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70 TOUCHES TO THE PORTRAIT




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70 TOUCHES TO THE PORTRAIT

DUBNA
2026

Compiled by

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COMPILERS' NOTE

March 26, 2026 marks the 70th anniversary of the establishment of the Joint Institute for Nuclear Research (JINR), an international intergovernmental scientific research organization. Those who are familiar with JINR activity, and especially those lucky enough to work here, call it, both in thought and aloud, shortly and simply "our Institute".

What does the 70th anniversary mean for our Institute — an international organization that unites a community of thousands of professionals who have dedicated their lives to the challenging task of serving science and who represent different generations of scientists, engineers, and workers from dozens of countries worldwide?

It probably means summing up the results, dreams for the future, a heightened collective self-awareness, and a reflection on a highlighted moment between the past and the future in the common creative work that has no end.

The first quarter of the 21st century was the time of rapid changes in global trends in scientific knowledge of the fundamental properties of matter, in science in general, and the intensification of global socioeconomic and geopolitical processes, thus forming a dramatically changing landscape in which our Institute exists and steadily develops. The variability of this landscape is not surprising, but it occasionally poses serious challenges for our Institute. These challenges have always been overcome due to the Institute's strict fulfilment of its mission to unite scientists from different countries to perform large-scale scientific research.

This book is a comprehensive self-portrait of the Institute, compiled line by line from numerous episodes as seen by the JINR community itself. This is an inside view which does not claim to be a narration of JINR's scientific history in the 21st century, but rather a collective testimony for future work by historians of science — the history of our Institute remains to be studied and written. The book focuses exclusively on science, leaving socioeconomic and geopolitical circumstances aside. Thoughtful, informed, and right-minded readers will easily complete the picture themselves.

The Joint Institute for Nuclear Research was founded in 1956 with the aim to unite the material and intellectual resources of its 11 Member States to study the fundamental properties of matter. The establishment of JINR responded to the post-war desire of states to move to peaceful development and integrate the scientific potential of many countries to implement research programs of a scale and complexity unfeasible at a national level, yet essential to achieving the national development goals of each Member State.

JINR currently unites 15 states in Europe, Asia, Africa, and Latin America. Cooperation agreements have been signed with eight countries at the governmental level.

JINR ranks firmly among the top three in the list of several dozen intergovernmental scientific organizations. In November 2021, the Arab Republic of Egypt became a JINR Member State. In 2023–2025, government-level research coordination agreements were signed with the United Mexican States, the People's Republic of China, and the Federative Republic of Brazil; the cooperation with the Republic of South Africa, the Republic of Serbia, and the Republic of India has strengthened over these years. JINR continues its fruitful participation in scientific collaborations at CERN. In 2023, the General Agreement between JINR and IAEA was updated. Contacts with the Arab Atomic Energy Agency are also developing. JINR actively collaborates with international organizations and associations, particularly UNESCO, IUPAP, and IUPAC. In general, JINR's collaboration encompasses hundreds of scientific organizations and universities in more than 60 countries. The JINR Scientific Council and Programme Advisory Committees, which constitute the Institute's expert base, currently include over 80 leading scientists from 35 countries across four continents. Training of highly qualified personnel for the Member States, educational activities at all levels, facilitating the transformation of scientists' and specialists' creative work into innovations, and the dissemination of information about the achievements of modern science and their impact on the socioeconomic development of the humanity are essential components for reaching the Institute's goals.

In conclusion, we would like to quote from the Sofia Declaration on the value of international scientific and technological integration, adopted by the Committee of Plenipotentiaries in 2021 at its November session in Sofia (Bulgaria): "We adopt the present Declaration and call on all interested countries and scientific organizations, sharing and supporting ideas of the value of international integration in science and technology, to join multilateral research activities carried out within JINR framework in the name of peaceful scientific, technological, social, economic and cultural development of all countries on all continents on planet Earth — our common home."

HIGH ENERGY PHYSICS

The JINR research program in the field of high energy physics includes several main areas, the most important of them is the construction and operation of the complex of superconducting rings for heavy-ion colliding beams — the NICA (Nuclotron-based Ion Collider fAcility) complex for fundamental and applied research located at VBLHEP. The goal of the project is to study nuclear matter formed in heavy-ion collisions, its phase transition under extreme conditions of high temperature and density, and to investigate the spin structure of protons and neutrons. The NICA complex comprises an injection unit, a chain of accelerators, including the upgraded Nuclotron, the Booster and the Collider, experimental facilities, engineering infrastructure, and a cryogenic station.

Fundamental research at JINR is performed within the framework of extensive international collaborations, including participation in experiments at the NICA accelerators and in "external" experiments carried out at leading research centers such as CERN (Geneva, Switzerland), FNAL (Batavia, USA), BNL (Brookhaven, USA), IHEP of CAS (Beijing, China), and others.

CONSTRUCTION OF THE NUCLOTRON

In the early 1970s, the JINR Laboratory of High Energies began the development of a new accelerator complex dedicated to provide physicists with a base for "home" experiments at the front line of science. A long-term research program was prepared, focusing on relativistic nuclear physics. It was also planned to study the interactions of relativistic multiply charged particles with matter to develop measures for the safety of astronauts and spacecraft. The beam system of the new complex was designed for biomedical beams. These tasks have remained relevant after half a century and are being addressed at a new level at the BM@N and MPD facilities and in specialized experimental areas for research under the ARIADNA collaboration program (Fig. 1).



Fig. 1. Infrastructure of the NICA complex

The accelerator complex, which included a linear and two cyclic accelerators, was named the Nuclotron. The concept of the accelerator's main ring was based on the most advanced trends in accelerator design and construction at the time. Unlike the Serpukhov synchrotron, it was proposed to use a magnetic system with separated functions (orbit formation is carried out by dipole magnets with a uniform rotating field, and beam focusing is performed with specialized quadrupole magnets), as it was implemented in the giant synchrotrons then under construction at FNAL and CERN. The dipoles were superconducting magnets of the "cos θ" type with a maximum field induction of up to 6 T. At the same time, it was possible to place a synchrotron with a magnetic rigidity of 150 T·m in the Synchrophasotron cable tunnel, which corresponds to the heavy-ion energy of up to 50 GeV/nucleon. The accelerator's intermediate ring, located in the same tunnel, was assumed to accelerate partially stripped ions to the energy of approximately 750 MeV/nucleon, ensuring the charge exchange efficiency of 90% or higher. For the efficient operation of the complex, the control system was designed with the extensive use of electronic computers, in accordance with the then-popular concept of a "cybernetic" accelerator. The expected intensity of the accelerated beam was estimated about $10^{12}/Z$ nuclei per second (where Z is the charge number of the nucleus).

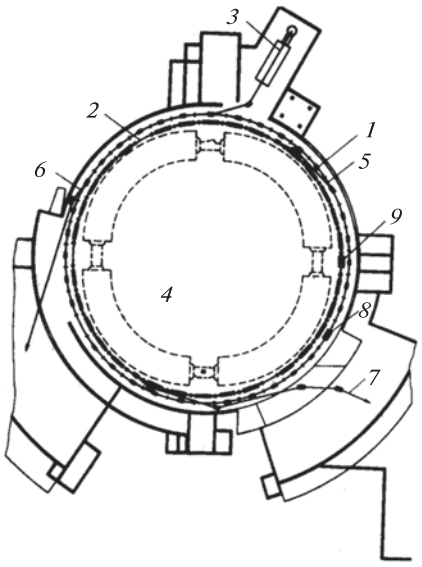
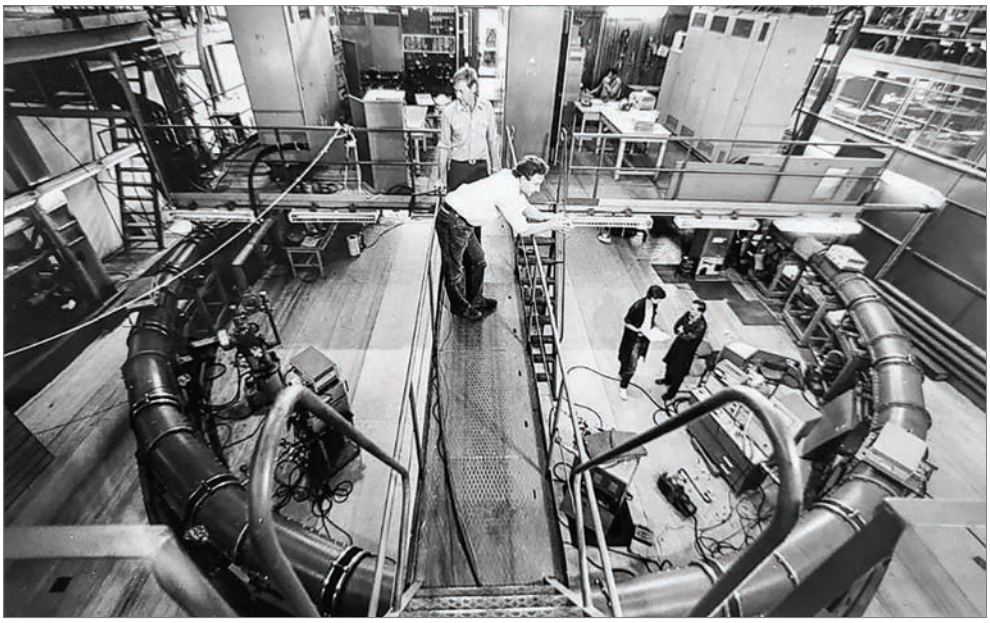


Fig. 2. Schematic diagram of the Nuclotron — a cryogenic accelerator of relativistic nuclei: 1 — intermediate accelerator ring (IAR); 2 — main accelerator ring (MAR); 3 — injector; 4 — existing Synchrophasotron; 5 — system of beam extraction from IAR and input into MAR; 6 — nuclear beam extraction from IAR to experimental pavilion No. 1; 7 — beam extraction from MAR to experimental pavilion No. 2; 8, 9 — accelerating cavities

This project (Fig. 2) was published in JINR communication[1] and presented by A. M. Baldin at a number of conferences, including the international ones. However, the first attempts to design powerful magnets showed that the cost of their development and manufacture was substantially greater than the laboratory's financial level, and 6-T magnets were still beyond the technical potential of humanity at that time.

In 1973, Igor Aleksandrovich Shelayev proposed radical simplification of the design and reduction of the cost of magnet production by using a yoke made of iron and shaped like a window frame to form the magnetic field in the dipoles. The winding was made from a Rutherford-type cable — a rectangular cable twisted from supercon-

[1] *Alekseev V. P., Baldin A. M., Beznogih Yu. D. et al.* Prospects for Research in Relativistic Nuclear Physics at LHE JINR (Considerations on the Development of the Accelerator Complex). JINR Commun. 9-7148. Dubna, 1973.



Installation of the superconducting injector of the Nuclotron. I. A. Shelayev and V. S. Alfeyev in the foreground

ducting wires and wrapped in electrically insulating material. The magnet was immersed in a bath of boiling helium for cooling. The gain for this simplification was a reduction in the maximum achievable field, which was expected to be 2.2–2.5 T.

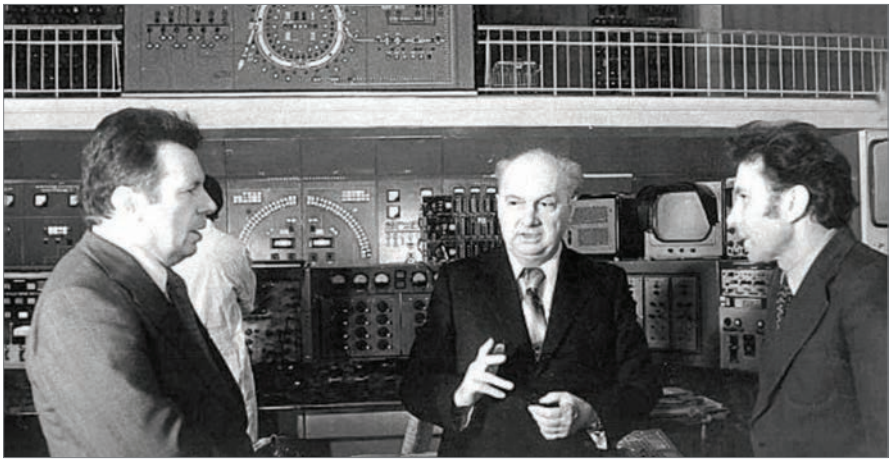
In 1974, the Laboratory designed and manufactured the first model "window frame" magnet with a superconducting winding and an immersion cooling system and successfully tested it on a cryogenic bench made for this purpose. The weak point of this relatively simple-to-manufacture and inexpensive magnet was its cooling system: the magnet was housed in a complex and unreliable cryostat with a large volume of liquid helium inside a helium vessel. Only operating experience in a real accelerator with a magnetic system based on such magnets could reveal how critical this drawback was.

Another significant change to the initial concept of the accelerator complex was required, as it became clear during the preliminary design studies, that it was physically impossible to accommodate two accelerators — the intermediate accelerator and the main one — in the existing tunnel. Following the recommendation from a meeting of experts from the JINR Member States held in 1977, a team of specialists from JINR, KIAE, NIIEFA, and MRTI developed a design for a heavy-ion accelerator complex[2], which supposed its phased construction. The first phase was to launch a first-stage cyclic accelerator (heavy-ion synchrotron), and to conduct further ion acceleration in the synchrotron, which would later be replaced by the Nuclotron. Thus, the development of the Booster synchrotron began, during which it repeatedly changed its magnetic structure type, parameters, and location.

[2] *Baldin A. M. et al.* Heavy Ion Accelerator Facility. JINR Commun. 9-1796. Dubna, 1978.

In 1979, a project for a small accelerator based on immersible magnets, the superconducting injector of the Nuclotron, was developed as a possible prototype of the Booster and to test the operational properties of immersible magnets. This accelerator, with all the necessary engineering systems, was located in building No. 205. It was planned to use a direct-action accelerator based on a pulse transformer with a maximum voltage of 750 kV as an injector. The project was not completed, but invaluable experience was accumulated during its implementation in the design, manufacture, and testing of magnets, and this required significant development of cryogenic technique.

Efforts to improve the design of superconducting magnets continued simultaneously with these works. In 1977, Anatoly Alekseevich Smirnov proposed constructing an excitation winding from a tubular superconductor with a channel for pumping liquid helium. A model dipole magnet with a "window frame" yoke was developed and manufactured under his leadership, with dimensions and working aperture sizes similar to the dipoles of the superconducting injector of the Nuclotron. The magnet was named the CSD-1 (circulating superconducting dipole). During testing, all the necessary requirements for the tubular cable were formulated, and its design was developed using commercially available components. By the end of 1983, the full-scale dipoles CSD-2 and CSD-3 had been made and tested. This is how magnets, later called "Dubna" magnets, or "Nuclotron-type" magnets, were developed[3]. These magnets are capable of operating both in a cycle with a field growth rate of up to 8 T/s and with long "tables", providing long stretching during slow extraction and the opportunities of carrying out experiments on a circulating beam in operating modes with an internal target or on colliding beams. The relatively small amount of helium in the accelerator's magnetic system and the high permissible pressure in the cooling channels of the magnets ensure high safety of the system in emergency modes and during rapid warming-ups.



At the control panel of the Synchrophasotron. A. A. Smirnov, A. M. Baldin, and I. B. Issinsky

[3] *Smirnov A. A.* The Nuclotron Is a New Technology of the Synchrotron Superconducting Magnet System // Part. Nucl. 2001. V. 32, No. 1. P. 96–142.

The next goal was to assemble and test the superperiod (octant) of the Nuclotron magnetic-cryostat system to verify the adopted technical solutions and confirm the opportunity of stable cryostatting of a large number of magnets connected in parallel to helium lines.

In January 1986, the project "Reconstruction of the Magnetic System of the Synchrophasotron to a Superconducting One — the Nuclotron" was approved. The Director of the laboratory A. M. Baldin and the Chief Engineer L. G. Makarov were appointed its leaders.





L. G. Makarov. Unveiling of a memorial plaque in honor of his 90th birthday. 2013

Leonid Grigorievich Makarov became the true soul of the project: thanks to his inexhaustible energy and ability to maintain the team's enthusiasm, all sections of the Nuclotron's dipole and quadrupole magnetic-cryostat modules were launched into serial production, manufactured and subsequently underwent comprehensive individual testing on a specially designed bench in a very short time — from 1987 to 1993. In February 1990, tests of the Nuclotron's magnetic system octant — a chain of 16 sections of cryogenic magnetic modules, twelve dipole and four quadrupole magnets connected in series — were successfully completed. Cooling from room temperature to helium temperature took 17 h and was accomplished using the KGU-1600/4.5 facility located in building No. 205.

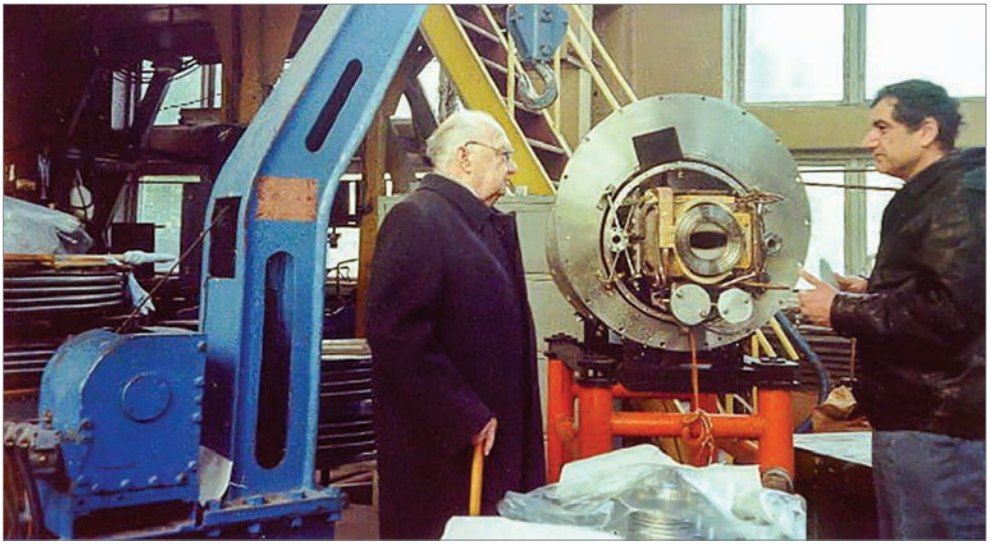
The creation and launch of superconducting accelerators required significant development of liquid helium production technology. By 1991, LHE had four operating KGU-1600/4.5 facilities. Three of them, combined into a single cryogenic supply system for the Nuclotron and capable of operating on a common collector to deliver liquid helium to the consumer, provided a total capacity of 1500 l/h. At the suggestion of the management of the Orenburg Helium Refinery, joint production of liquid helium to be transported into 40 000-liter automobile containers was established. In 1993, 32 containers were filled and sent for export, i.e., more than 1 million liters of liquid helium were produced. This additional use of the Nu-

clotron cryogenic system provided an influx of extra-budgetary financial resources that helped complete the creation of the new accelerator under the extremely difficult economic conditions of 1992–1993.

The first turns of beams at the Nuclotron were achieved in March 1993, followed by an intense period of tuning and optimization of the accelerator's operating modes. The work was complicated by the fact that, due to financial constraints, the project was not fully implemented: the beam diagnostic system was incomplete, a specialized power supply system was missing, and many systems were implemented at the level of working models.



General view of the Nuclotron



Testing the elements of beam extraction from the Nuclotron on a cryogenic test bench. A. M. Baldin, H. G. Khodzhibagiyan. 1999

During the early years of the operation of the Nuclotron, physical research was performed at the internal target station. In 1999, a system for slow beam extraction from the Nuclotron to building No. 205 was made, and experiments on fixed targets began[4]. In 2002, a polarized deuteron beam was accelerated at the Nuclotron. Currently, operating together with a Booster, it is the main accelerator of the NICA complex for fundamental and applied research. Its magnetic system has been in reliable service for over 30 years, and although no significant degradation of its parameters has been observed, the time for its replacement with a more modern one is approaching. Work in this direction is being fulfilled as part of the New Nuclotron project.

In spite of difficult economic times, a modern, specialized accelerator of relativistic nuclei with energies up to 6 GeV/nucleon was built in Dubna. The Nuclotron was the first superconductivity-based accelerator in Europe to study relativistic nuclei. This accelerator made it possible to continue physical research with relativistic nuclei, initiated at the Synchrophasotron, in both fundamental and applied science. A number of important physical results were obtained, significant to understand the structure of matter, to apply nuclear beams in medicine, power engineering, radiobiology, and to study the radiation resistance of electronic components.

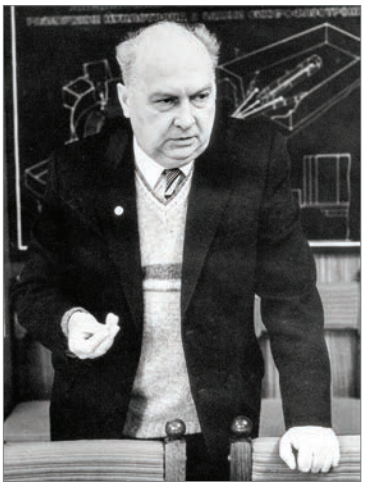
THE BIRTH OF RELATIVISTIC NUCLEAR PHYSICS. EXPERIMENTS AT THE NUCLOTRON

One of important areas of modern particle and nuclear physics is relativistic nuclear physics. This field appeared in the early 1970s because of the need to solve a number of practical problems, certain theoretical developments and success in accelerating nuclei to relativistic velocity in Dubna (USSR) and Berkeley (USA). Practical interest was primarily driven by the development of space exploration. Studying the effects of cosmic radiation, which is dominated by relativistic nuclei, on biological objects and electronics is particularly important to provide the safety of manned space flights. Understanding the laws of interaction between relativistic nuclei is also essential to construct models of the formation and evolution of the Universe, as well as to study the internal structure of stars. Recently, power engineers have also become interested in relativistic nuclei, hoping to realize the idea of making a safe nuclear reactor controlled by charged particle beams, as well as the idea of destroying nuclear wastes by means of the beams of charged particles and nuclei.

Relativistic nuclear physics can be defined as the field of nuclear physics that studies the interactions of nuclei under the condition that $p^2/m^2 \gg 1$, where p and m are the momentum and mass of the interacting objects, respectively.

The first experiments related to relativistic nuclear physics at JINR were performed at the Laboratory of Nuclear Problems in the late 1950s. The momentum spectra of secondary particles were measured depending on the magnetic field of a deflecting magnet. The work was carried out under the supervision of M. G. Mesh-

[4] *Smirnov A. A., Kovalenko A. D.* Nuclotron — Superconducting Accelerator of Nuclei at LHE JINR (Creation, Operation, Development) // Part. Nucl., Lett. 2004. V. 1, No. 6 (123). P. 11–40.



Director of the Laboratory of High Energies A. M. Baldin



Head of the work on the discovery of the nuclear cumulative effect V. S. Stavinsky

cheryakov. As a result, a process was discovered in which protons with the energy of 675 MeV knocked out the most weakly bound nuclei — deuterons — from various nuclei (Li, Be, C, O). This was very surprising, since at that time the prevailing view was that elastic and inelastic processes of interaction of high-velocity protons occur with individual nucleons that make up nuclei.

Usually, the question of the possibility of transferring high energy from a compound nucleus to an individual nucleon was answered negatively: considerations were put forward regarding the "looseness" of the nucleus and the low probability of concentrating the energy of a group of nucleons on a single nucleon. This problem was first considered by A. M. Baldin in his work[5], where he made certain predictions based on the analysis of experimental data and gave a positive answer to the question posed. Experimental confirmation of this conclusion was required.

The formation of secondary particles during the interaction of relativistic nuclei involving a group of nucleons was called the nuclear cumulative effect. In 1970, the simplest nuclei, deuterons, were accelerated to the energy of 4.5 GeV/nucleon at the Synchrophasotron in LHE JINR[6]. The presence of a deuteron beam in Dubna made it possible to carry out the first experiments with relativistic nuclei. The nuclear cumulative effect was first observed[7] at the Synchrophasotron by a group of authors headed by V. S. Stavinsky.

The cumulative effect is a consequence of the manifestation of quark-gluon degrees of freedom and multiquark configurations in nuclei. The existence of the cumulative nuclear effect indicates that nucleons in nuclei, under certain conditions, behave differently than in a free state. In 1980, A. M. Baldin introduced the concept

[5] *Baldin A. M.* // Bull. Lebedev Phys. Inst. Moscow, 1971. P. 35.

[6] *Beznogih Yu. D., Zinoviev L. P., Issinsky I. B., Kazansky G. S., Mikhailov A. I., Moroz V. I., Pavlov N. I., Puchkov G. P.* Acceleration and Ejection of a Deuteron Beam from the JINR Synchrophasotron. Second JINR Prize in the section "Scientific and Methodological Works", 1970.

[7] *Baldin A. M. et al.* // Nucl. Phys. 1973. V. 18, Iss. 1. P. 79.



Awarding ceremony of the Lenin Prize 1988 in the Kremlin

of the "quark-parton structure function of a nucleus"[8] by analogy with the concept of the quark-parton structure function of a hadron. The results of experiments on hadron–nucleus and nucleus–nucleus interactions showed that the quark-parton structure function of a nucleus $G(X)$ was not reduced to a set of structure functions of free nucleons and was a new object characterizing the quark-gluon state of a nucleus. The results of the insight into the role of quark-gluon degrees of freedom in nuclei, developed by him, were included in the cycle of joint works "New quantum number — color and establishment of dynamic regularities in the quark structure of hadrons and atomic nuclei", which was awarded the Lenin Prize in 1988 (A. M. Baldin, P. N. Bogoliubov, V. A. Matveev, R. M. Muradyan, A. N. Tavkhelidze).

V. S. Stavinsky's group performed detailed studies of the inclusive production of mesons in the rear hemisphere in collisions of 8.9 GeV/c protons with nuclei ranging from helium to uranium at the Dubna Synchrophasotron. These measurements found important properties of the nuclear structure function $G(X)$. Experimental data on the cumulative production of particles on nuclei cannot be explained within the traditional concept of nuclei, which consist of a set of individual quasi-free nucleons. They can provide a good basis to explain the phenomenon within the concept of multiquark states existing in nuclei. The properties of the cumulative effect prove that nuclear structure functions are independent objects of hadron physics. Experiments with relativistic nuclei established the limits of the proton–neutron model of the nucleus.

The process of interaction between two nuclei can be written as follows:

$$\mathrm{I} + \mathrm{II} \rightarrow 1 + 2 + \ldots, \qquad (1)$$

where I and II are the colliding nuclei; 1, 2 ... are secondary particles formed as a result of the collision of nuclei. A. M. Baldin offered an invariance method to ana-

[8] *Baldin A. M.* // Proc. Conf. on Extreme States in Nuclear Systems. Dresden, 1980.

lyze multiple particle production, in which process (1) is considered in space, the points of which are four-dimensional velocities $u_i = p_i/m_i$, where p_i is the four-dimensional momentum and m_i is the mass of the i-th particle. The variables on which the probability distributions (cross sections) depend were chosen to be dimensionless positive relativistically invariant quantities:

$$b_{ik} = -(u_i - u_k)^2 = -(p_i/m_i - p_k/m_k)^2 = 2(p_i p_k/m_i m_k - 1) = 2(u_i u_k - 1),$$

where the indices i and k take the values I, II, 1, 2, 3 ... (the numbers of all objects participating in the reaction (1)). The values b_{ik} have the meaning of relative distances between the participants of the interaction in the space of four-dimensional velocities.

A. M. Baldin proposed to classify nuclear interactions using the variable b_{ik}. The following three areas were singled out according to this classification:

1) the $b_{ik} \approx 10^{-2}$ area, corresponding to the interaction of nuclei as systems of weakly bound nucleons (this is the area of classical nuclear physics);

2) the $0.1 < b_{ik} < 1$ area, which is intermediate (in this area, quark degrees of freedom begin to play a significant role in the reconstruction of hadron systems);

3) the $b_{ik} \gg 1$ area, in which nucleons lose their significance as quasiparticles of nuclear matter and nuclei should be considered as quark-gluon systems.

In experiments at the Synchrophasotron, the value of $b_{ik} \approx 5$, at which quark-gluon degrees of freedom began to appear.

Thanks to the availability of nuclear beams at the Synchrophasotron (p, d, He, C, Mg, S), a new scientific direction began to develop at JINR — relativistic nuclear physics[9]. These studies required higher-quality beams of relativistic nuclei with a wider range of nuclei and higher energy than those at the Synchrophasotron. In connection with this, A. M. Baldin proposed to build a new specialized accelerator of relativistic nuclei — the Nuclotron. The first run of cooling the Nuclotron ring to a temperature of 4.5 K took place in March 1993, and on March 26, beam circulation in the Nuclotron ring was achieved. In July 1993, the first experiments were carried out on the Nuclotron's internal deuteron beam with the energy of 200 MeV/nucleon, and in 1994 a Nuclotron physical run was carried out with a deuteron beam with momenta of 3.8 and 6.2 GeV/c. The experiments were prepared by the SPHERE (headed by A. I. Malakhov) and SYaO (headed by V. A. Nikitin) collaborations. The spectra of secondary particles were measured using the $\Delta E{-}E$ techniques. Figure 3 shows the spectra of secondary particles obtained in this run.

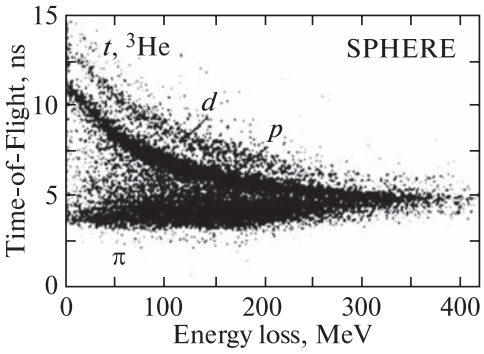
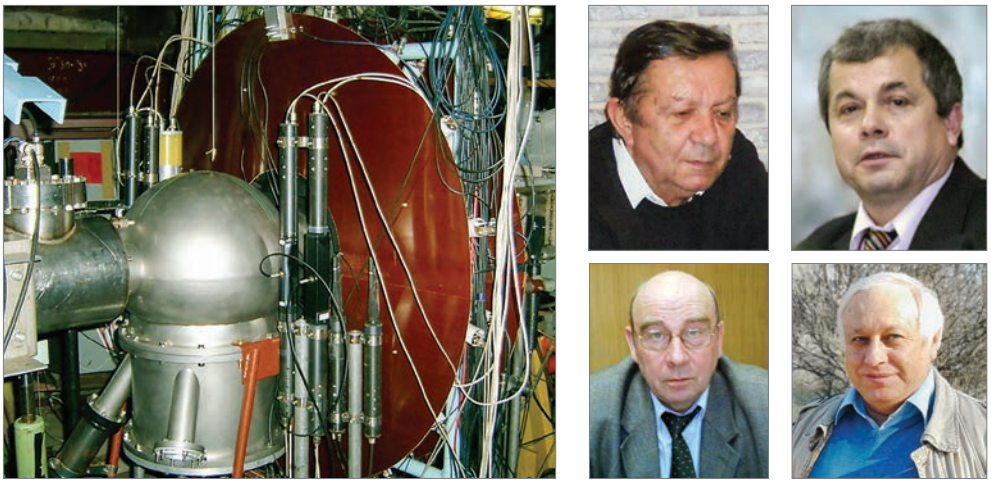


Fig. 3. Spectra of secondary particles during the interaction of the Nuclotron's internal deuteron beam with a momentum of 6.2 GeV/c with a thin gold target

[9] *Baldin A. M. et al.* Acceleration and Ejection of Deuterons of the Dubna Synchrophasotron. JINR Preprint P9-5442. Dubna, 1970.



The Nuclotron internal target station and project managers: J. Kliman, A. I. Malakhov, Yu. S. Anisimov, and Š. Gmuza



System for slow beam extraction from the Nuclotron and project managers: E. A. Matyushevsky, A. D. Kovalenko, I. B. Issinsky, and Yu. I. Tyatyushkin

A special internal target station was done to carry out regular research on the internal beams of the Nuclotron[10]. This work was carried out under the supervision of Yu. S. Anisimov with the active participation of colleagues from Slovakia and the Czech Republic and received the JINR First Prize for 2000.

The next step was to construct a system for slow beam extraction from the Nuclotron, allowing for physical experiments to be performed on external facilities. This system was made in 2002 under the supervision of A. D. Kovalenko and E. A. Matyushevsky, despite the financial difficulties of the time. This work also earned JINR First Prize for 2002. The system for beam extraction from the Nuclotron significantly expanded the opportunities for physical experiments.

Work on the Krion heavy-ion source had been successfully completed under the supervision of E. D. Donets by this time. This made it possible to produce beams of heavy ions up to Xe at the Nuclotron. E. D. Donets's group received the prestigious international Brightness Award for this work, which is awarded biennially for the most important achievements in the physics and technology of ion sources.



Laureates of the international Brightness Award. E. D. Donets, D. E. Donets, V. V. Salnikov, and E. E. Donets

As a result of the above-mentioned work, about 15 physical facilities began operating on the Nuclotron beams (Fig. 4).

The set of nuclei accelerated at the Nuclotron and the intensities of the extracted beams in the period 1993–2010 are presented in Table 1. Later, the intensities of heavy nuclei increased sharply and Xe nuclei are already extracted with the intensity of $5 \cdot 10^7$ ions per cycle.

Two accelerators operated at LHE until 2002: the Synchrophasotron and the Nuclotron. The Synchrophasotron was shut down after polarized deuterons were obtained at the Nuclotron. Figure 5 shows the graph of the Synchrophasotron and Nuclotron operation by year. By 2006, the Nuclotron's operation time ex-

[10] *Malakhov A. I. et al.* Potentialities of the Internal Target Station at the Nuclotron // Nucl. Istr. Meth. A. 2000. V. 440, Iss. 2. P. 320–329.

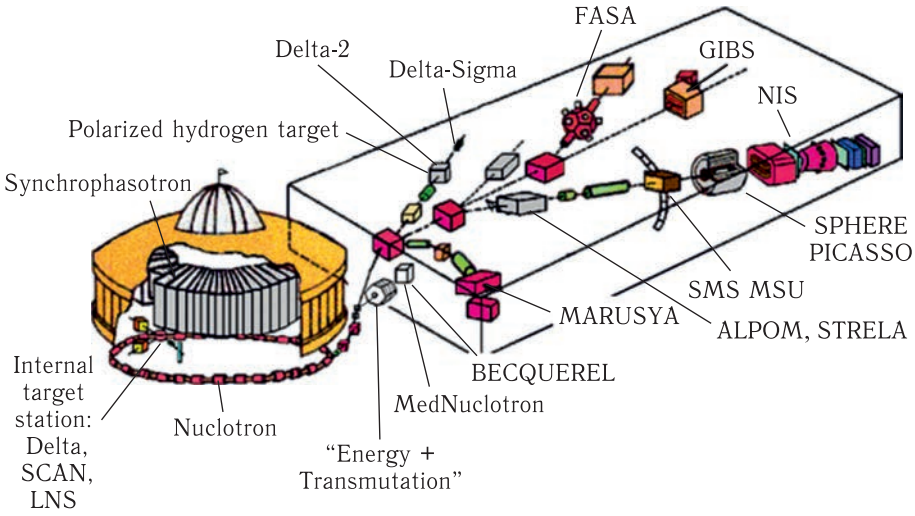


Fig. 4. Layout of physical facilities at the Nuclotron in 1993–2010

Table 1. Intensities of the Nuclotron extracted beams in 1993–2010

p	d	$\vec{d}$	t	^{4}He	^{7}Li	^{10}B	^{12}C	^{24}Mg	^{40}Ar	^{56}Fe	^{84}Kr	^{124}Xe
$2\cdot10^{10}$	$5\cdot10^{10}$	$3\cdot10^{8}$	$4\cdot10^{5}$	$8\cdot10^{8}$	$2\cdot10^{9}$	$2\cdot10^{10}$	$6.5\cdot10^{8}$	$1.2\cdot10^{8}$	10^{8}	10^{6}	10^{3}	10^{3}

ceeded 2500 h, and it was planned to increase this time beyond 3500 h. However, these plans were adjusted downwards due to the start of work to prepare the NICA collider complex project.

After the creation of the internal target station and the slow beam extraction system at the Nuclotron, the active phase of physical experiments began. Nuclotron users included dozens of scientific centers from Russia, from JINR member and non-member states (Fig. 6).

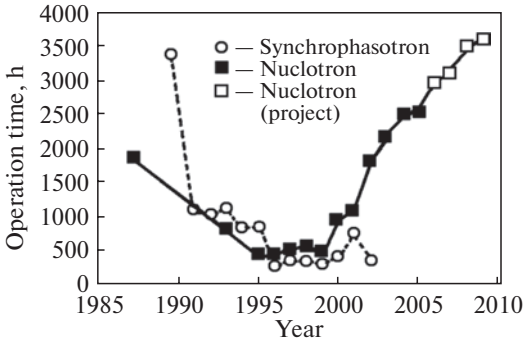


Fig. 5. Operation time of the Synchrophasotron and Nuclotron by year

Numerous comments and thanks were received for the beams provided. For example, Professor P. Picozzo from Italy wrote in March 2001: "The work was very effective with excellent results. I would like to thank the staff of the Accelerator Department for providing us with a very good beam and for their kindness."

In January 2002, Professor R. Brandt (Germany) noted in his letter: "The Nuclotron run was excellent (we reached the intensity goal of $6\cdot10^{13}$ protons in about 6 h, while the plan was 18 h). The international group (seven countries participated, and in addition, targets for China and Yugoslavia were irradiated) cooperated very successfully."

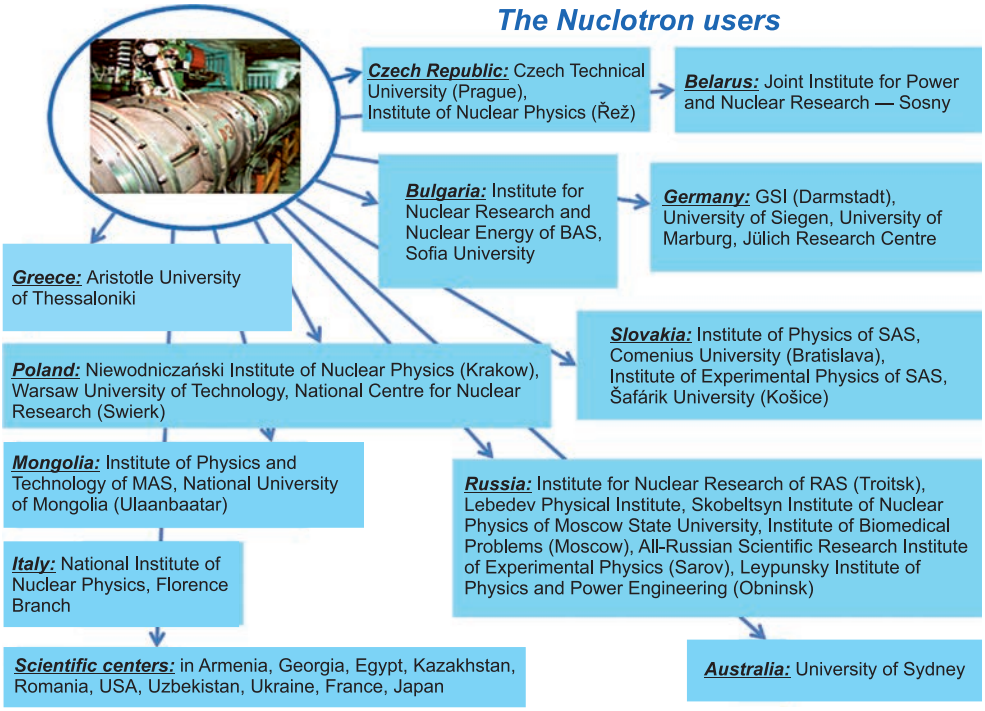


Fig. 6. The Nuclotron users

The following areas of work can be highlighted, which began at the Synchrophasotron and continued at the Nuclotron, starting in 1993:

— cumulative effect (DISK, SPHERE, PICASSO, MARUSYA);
— the structure of the nucleon (STRELA, NIS);
— the structure of the nucleus (FASA, BECQUEREL, SCAN);
— the influence of the nuclear environment on the production of particles (Delta, SCAN);
— modification of nuclear matter (FASA);
— exotic nuclei (GIBS, SCAN);
— polarization effects (TPD, PICASSO, LNS, ALPOM, STRELA, MARUSYA);

In addition, work was carried out in the following applied areas:

— radiobiology (LRB JINR and IMBP, Moscow);
— radiation medicine (MedNuclotron);
— the effect of radiation on electronics (PAMELA);
— safe nuclear energy ("Energy + Transmutation").

The DISK facility was improved for a more detailed study of the cumulative effect (Fig. 7). This work was headed by Yu. A. Panebrattsev.

A further step in this direction was made with the proposal of a new project — the 4π-facility SPHERE (Fig. 8). The project was headed by A. I. Malakhov.

Only the first stage of the SPHERE project, which included only the forward spectrometer, was implemented due to difficult economic conditions in the 1990s.

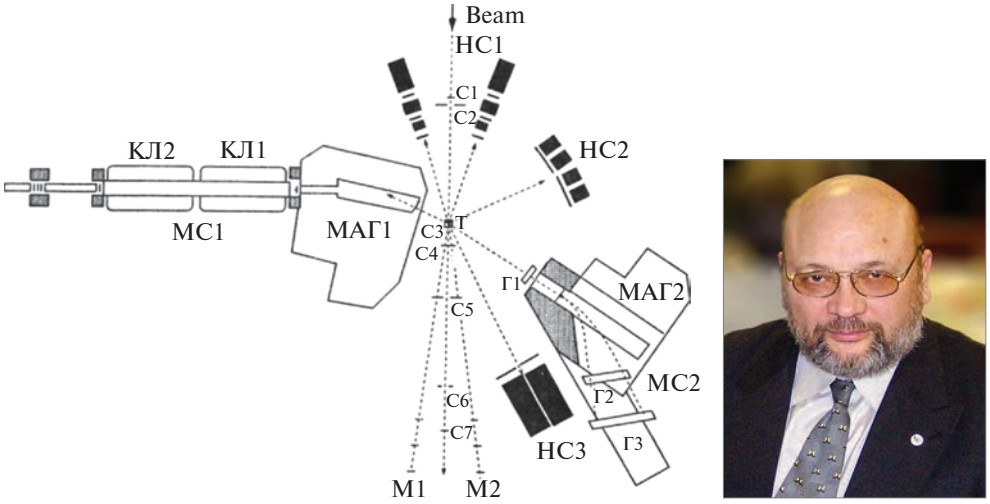


Fig. 7. The DISK facility diagram and the Group Leader Yu. A. Panebrattsev

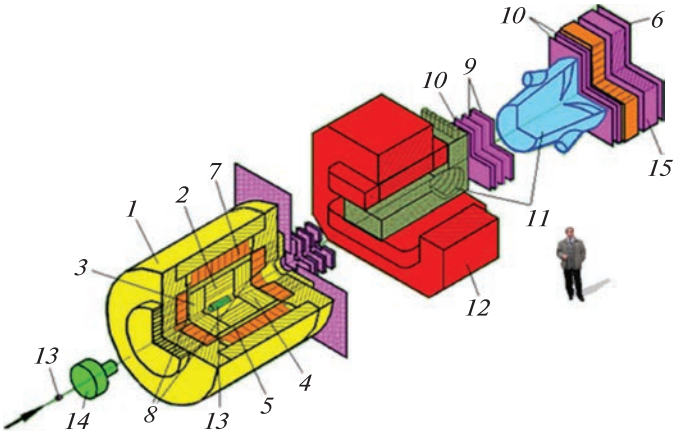


Fig. 8. Schematic diagram of the SPHERE facility: 1 — superconducting solenoid with an iron yoke; 2 — central cylindrical drift chamber; 3 — rear drift chambers; 4 — front drift chamber; 5 — cylindrical scintillation hodoscope; 6 — muon scintillation hodoscope; 7 — electromagnetic calorimeter; 8 — front and rear scintillation hodoscopes; 9 — proportional chambers; 10 — scintillation hodoscopes; 11 — threshold gas Cherenkov counters; 12 — dipole magnet; 13 — targets; 14 — beam absorber; 15 — muon filter

It carried out a series of physical studies of the interactions of relativistic nuclei with a momentum of 4.5 GeV/nucleon:

— the exponent in the A-dependence of the cross-section of fragmentation of relativistic deuterons into cumulative π^- mesons on the nuclei of carbon, aluminum, copper and lead was measured;
— studies of the behavior of the spectra of cumulative π^- mesons depending on the multiplicity of accompanying charged particles fragmenting from the target nucleus were carried out on a beam of relativistic deuterons and carbon nuclei;

— for the first time in the world, the production of cumulative muon pairs during the fragmentation of relativistic deuterons in the process $d + Pb \rightarrow \mu^+\mu^- + ...$ was observed, and the cross section of this process was estimated.

Below are the most striking results obtained at the Nuclotron in the 2000s.

First of all, this is the discovery in 2005 of parametric X-ray radiation produced by relativistic carbon nuclei passing through a silicon crystal[11]. The leaders of this experiment were A. D. Kovalenko and A. M. Taratin. Such radiation had previously been observed with protons. It turned out that the signal amplitude strongly depended on the type of ion, which opened up opportunities to make a new type of particle detector. Figure 9 shows the X-ray spectra in a silicon crystal from protons and carbon nuclei.

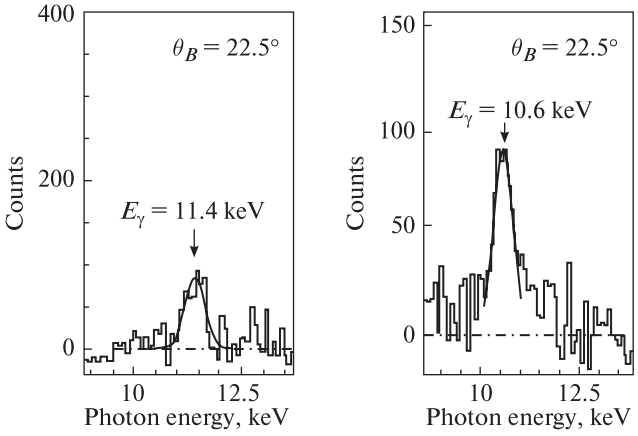


Fig. 9. Spectra of parametric X-ray radiation in a silicon crystal from protons with the energy of 5 GeV (left) and carbon nuclei with the energy of 2.2 A GeV (right)

The next important result was the discovery of tensor polarization of unpolarized deuterons when passing through matter. The effect was theoretically predicted by V. G. Baryshevsky (Belarus) and discovered at the Nuclotron by a group led by L. S. Zolin and A. G. Litvinenko[12]. Figure 10 shows the dependence of the tensor polarization P_{zz} on the thickness of the carbon target. A noticeable polarization of the deuteron beam after passing the target is visible. The results of this experiment indicated the possibility of obtaining a polarized beam in a cheap way without using the complex equipment.

The results of the SCAN experiment obtained by the group headed by S. V. Afanasiev to search for exotic η-mesic nuclei, are of equal interest. Using the Nuclotron's internal deuteron beam on a thin carbon target, indications were obtained of the existence of η-mesic nuclei, where one nucleon is replaced by a η meson[13]. Figure 11 shows a diagram of the SCAN facility and the spectrum of invariant masses of protons and pions, indicating the existence of η-mesic nuclei.

[11] *Adischev Yu. N. et al.* First Observation of Parametric X-Rays Produced by Moderate Relativistic Protons and Carbon Nuclei in Si Crystals // Nucl. Instr. Meth. B. 2006. V. 252. P. 111–117.

[12] *Azhgirei L. S. et al.* Measurement of Tensor Polarization of a Deuteron Beam Passing through Matter // Phys. Part. Nucl. Lett. 2010. V. 7. P. 27–32.

[13] *Afanasiev S. V. et al.* Search for η-Mesic Nuclei in the Reaction d + C at JINR // Phys. Part. Nucl. Lett. 2011. V. 8, No. 10. P. 1073–1077.

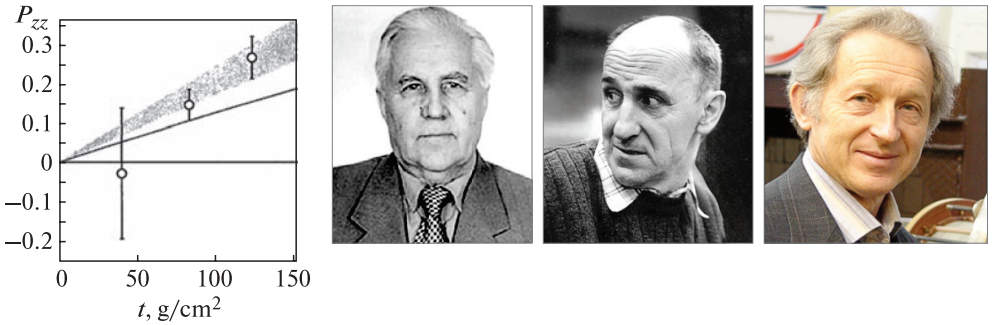


Fig. 10. Dependence of the tensor polarization of deuterons with a momentum of 5.5 GeV/c on the thickness of the carbon target. On the right: the leaders of the experiment L. S. Zolin, A. G. Litvinenko and V. G. Baryshevsky, who theoretically predicted the effect under study

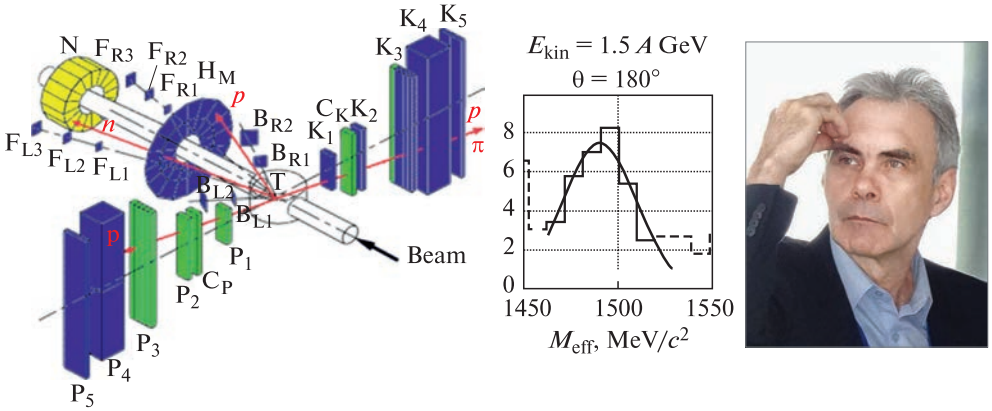


Fig. 11. SCAN facility diagram and the spectrum of invariant masses of protons and pions. On the right is SCAN project manager S. V. Afanasiev

It is also necessary to note the presence at the Nuclotron of unique beams of secondary light nuclei, including radioactive nuclei absent in nature. The work to obtain such beams was carried out on the initiative of P. I. Zarubin by V. A. Monchinskii and P. A. Rukoyatkin. These beams provide fundamental research into the structure of the family of light nuclei[14].

The BECQUEREL experiment applies an old but reliable method of detecting particles using nuclear photoemulsions. This method is significantly inferior to electronic methods in terms of statistics but still shows record-breaking coordinate accuracy in recording charged particle tracks, making it unique for search experiments.

One of the objectives of the BECQUEREL experiment (supervised by P. I. Zarubin, Fig. 12) is to study, in a relativistic approach, the clustering of light stable and radioactive nuclei, the features of the isotopes ^{7,9}Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N, and to

[14] *Zarubin P. I.* "Tomography" of the Cluster Structure of Light Nuclei via Relativistic Dissociation // Lecture Notes in Physics. Clusters in Nuclei. Springer Intern. Publ. 2013. V. 875, No. 3. P. 51–93.

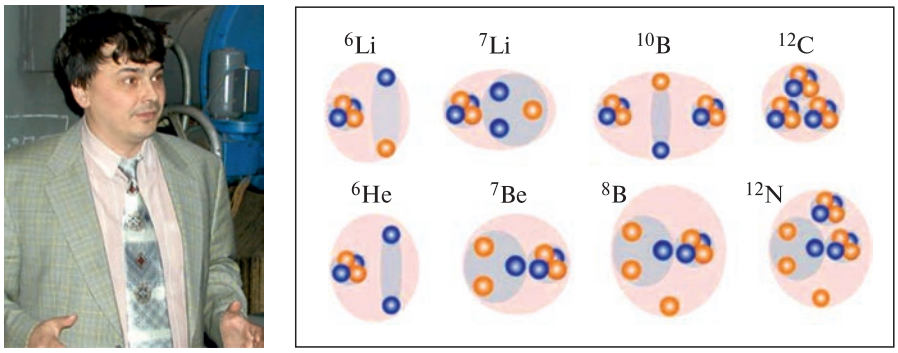


Fig. 12. BECQUEREL project manager P. I. Zarubin. On the right is an illustration of the cluster structure of light nuclei

measure the probability of their dissociation channels. The opportunity to investigate the existence of the so-called Hoyle state in the ^{12}C nucleus is of great interest.

The observation of the effect of increasing pion yields with increasing target mass in the internal beam of protons and deuterons of the Nuclotron had a very interesting result[15]. The increased pion yield was observed on copper and gold nuclei in the region of beam particle energies of ~350 MeV/nucleon (Fig. 13). The effect was absent on lighter nuclei, which indicated its nuclear nature. The experiment was carried out under the supervision of V. A. Krasnov and A. B. Kurepin.

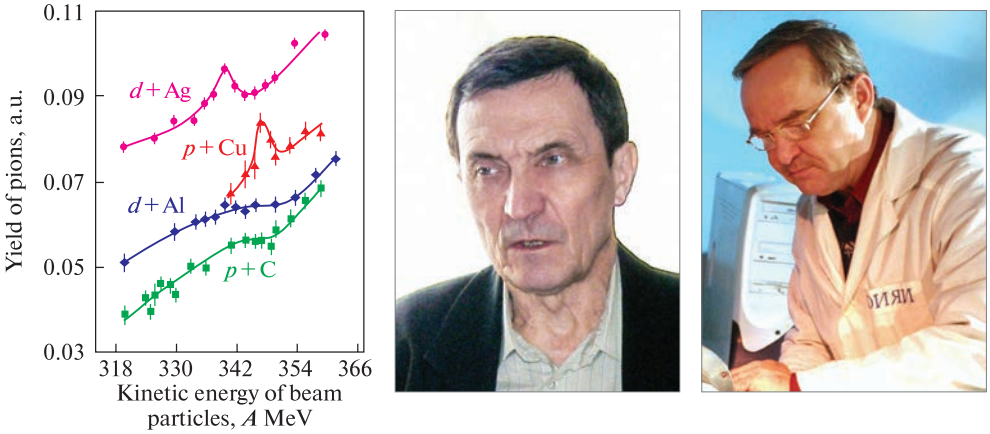
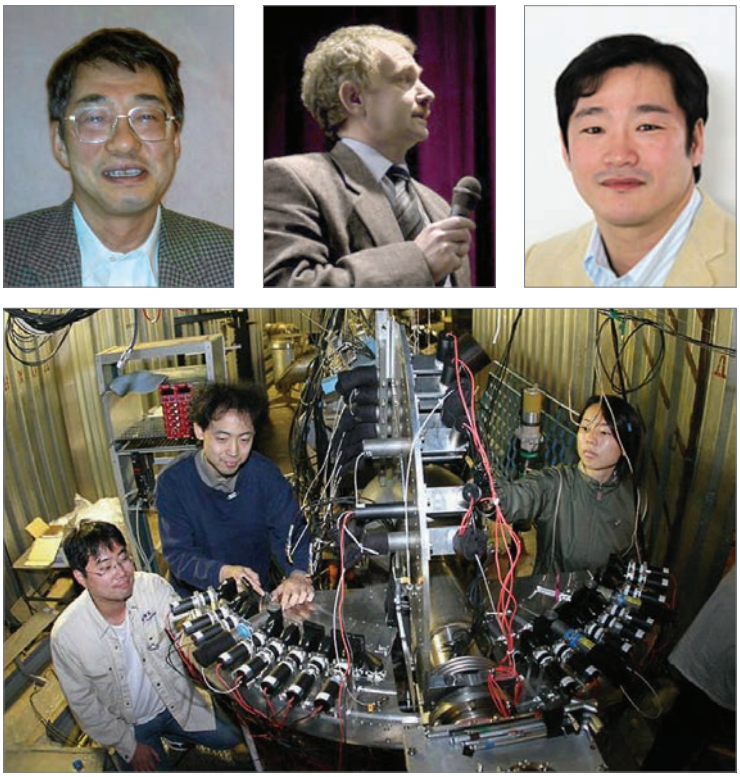


Fig. 13. Pion yield for C, Al, Cu, and Ag targets for a proton and deuteron beam with a kinetic energy of ~350 MeV/nucleon. Leaders of the experiment A. B. Kurepin and V. A. Krasnov

Joint experimental program LNS/DSS to study the light nuclei spin structure started at the RARF (RIKEN, Japan) and LHE/LHEP accelerator complexes in 1999 under the leadership of V. P. Ladygin, H. Sakai (Japan) and T. Uesaka (Japan). The first experiment of this program was to examine the angular dependences of

[15] *Livanov A. N. et al.* Search for Resonant Structure in the Pion Production Reaction on the Nuclotron Internal Beam // Intern. J. Mod. Phys. A. 2007. V. 22. P. 604–607.



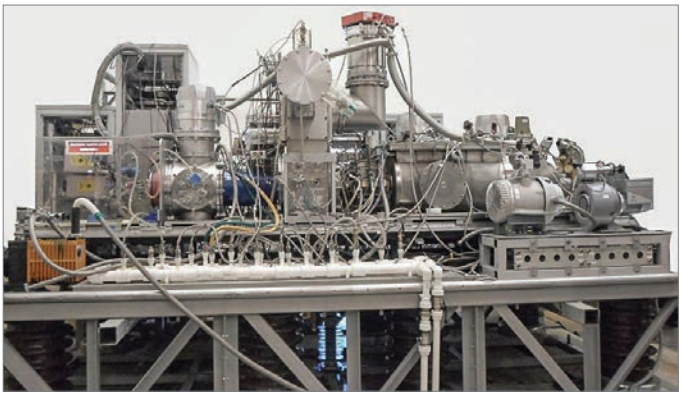
Top: H. Sakai, V. P. Ladygin, and T. Uesaka. Bottom: Japanese physicists prepare for operation the facility at the Nuclotron's internal target station

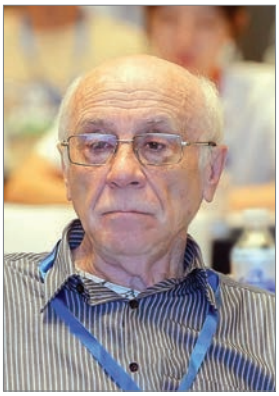
the full set of deuteron analyzing powers A_y, A_{xx}, A_{yy}, and A_{xz} in the reactions $d + d \to {}^3\mathrm{He} + n$ and $d + d \to {}^3\mathrm{H} + p$ at the energy of 140, 200, and 270 MeV at RARF. For the first time in the world, the spin structure of tritium was measured at small internucleon distances. The second part of the experimental program to study the cross-sections and deuteron analyzing powers in deuteron–proton elastic scattering was carried out on the internal target of the Nuclotron. In the first series of measurements, experimental data on the analyzing powers of A_y, A_{yy}, and A_{xx} were obtained at the energy of 880 and 2000 MeV. All these results are significant to understand the origin of three-nucleon forces in the nucleus.

At present, the analysis of the experimental data is continued on the analyzing powers A_y, A_{yy}, and A_{xx} in deuteron–proton elastic scattering[16] obtained in the second series of measurements at the energy of 400–1800 MeV.

With the commissioning in 2016–2017 of the SPI (Source of Polarized Ions), a source of polarized protons and deuterons developed under the supervision of V. V. Fimushkin in collaboration with the INR RAS, the capabilities of physical experiments on polarized beams at the Nuclotron have significantly improved. The intensity of polarized deuterons obtained was $2 \cdot 10^9$ per cycle.

[16] *Ladygin V. P. et al.* Angular Dependences of the Deuteron Analyzing Powers in Elastic *dp* Scattering at Large Transverse Momenta // Phys. Part. Nucl. 2022. V. 53. P. 251–255.





New source of polarized protons and deuterons.
Head of work on the source V. V. Fimushkin

The STRELA facility was made under the supervision of N. M. Piskunov, V. V. Glagolev, and G. Martinska (Slovakia) to study charge-exchange reactions. This facility is a single-arm magnetic spectrometer, whose main elements are drift chamber blocks serving as coordinate detectors. Using this facility, differential cross sections of the charge-exchange reaction $dp \to (pp)n$ were measured at a momentum of 1.75 GeV/c per nucleon for small momentum transfers. The ratios of the differential cross section of the charge-exchange reaction $dp \to (pp)n$ to the cross section of the elementary process $np \to pn$ were obtained in order to estimate the spin-dependent part of the $np \to pn$ charge-exchange amplitude. The $np \to pn$ amplitude turned out to be predominantly spin-dependent.







The leaders of the STRELA experiment (left to right): N. M. Piskunov, G. Martinska, and V. V. Glagolev

An unexpected energy dependence[17] of the ratios of differential neutron cross sections $R_{dp}(0°) = [(d\sigma/d\Omega)(nd)]/[(d\sigma/d\Omega)(np)]$ on a bound and free proton at

[17] *Sharov V. et al.* Measurements of the Ratio R_{dp} of the Quasi-Elastic $nd \to p(nn)$ to the Elastic $np \to pn$ Charge-Exchange Process Yields at Zero Proton Emission Angle over the 0.55–2.0-GeV Neutron Beam Energy Region // Eur. Phys. J. A. 2009. V. 39. P. 267–280.



Fig. 14. Dependence of $R_{dp}(0°)$ on the kinetic energy of neutrons and the leaders of the Delta-Sigma experiment (left to right): L. N. Strunov, V. I. Sharov, and F. Lehar (France)

zero emission angle in the energy range from 0.55 to 2 GeV was observed in the charge-exchange reaction $np \to pn$ (Fig. 14) in 2005.

Previously obtained world data showed a sharp decline in this ratio with increasing the incident deuteron energy. The experiment performed at the Nuclotron demonstrated with high precision that the R_{dp} value remained virtually unchanged with increasing the neutron energy up to 2 GeV. One of the participants in this experiment, F. Lehar, wrote in the weekly "Dubna: Science, Cooperation, Progress" regarding this result: "Yes, the LHE JINR physicists have closed one door in physics. As it often happens, they simultaneously opened the other, more reliable doors and posed new questions in their field of science. I am confident that these questions will be not less important than the previous ones, which were addressed over the course of half a century."

PROJECT OF THE NICA ACCELERATOR COMPLEX

In 2002, the next steps in developing the LHE accelerator complex were proposed to construct the Booster (was planned to begin in 2004, with commissioning in 2007), and then moving on to the construction of superconducting rings for colliding beam experiments (Fig. 15). At the time, this proposal was almost unnoticed. The Laboratory's financial resources did not allow it to maintain even the existing basic facilities in the working order, much less dream to build new accelerators.

In 2002, the final run of the Synchrophasotron took place. The veteran that had made JINR famous departed without a farewell ceremony: gradually deteriorating, it awaited its fate for six years until an order was issued for its partial dismantling. Thanks to the valiant effort of its maintenance personnel, the Nuclotron continued operation on several experimental programs but never approached its design parameters. Consequently, its existence was virtually invisible on the global landscape of high-energy physics.

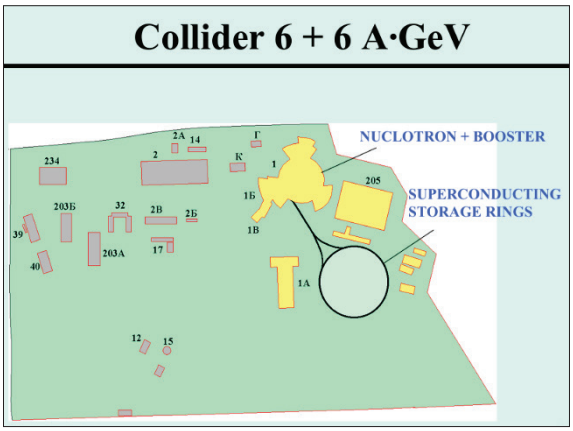


Fig. 15. A slide from the report of LHE Director A. I. Malakhov at the 92nd session of the JINR Scientific Council on June 6, 2002

When Alexei Norairovich Sissakian became the Director of JINR, he posed the question of the future of LHE in a strict manner: either the Nuclotron would be decommissioned and the laboratory staff would concentrate on external experiments or a scientific task of high priority would be formulated for which the Member States would agree to allocate funds to complete the accelerator complex project and its further development.

This task appeared[18]. With increasing energy of colliding heavy nuclei, a number of experiments at CERN and BNL in the early 2000s indicated the formation of a special state of hot and dense nuclear matter — quark-gluon plasma. The opportunity of experimental study of this "new" physics inspired theorists: a hypothetical phase diagram was constructed for the possible states of matter formed in the collision of two heavy nuclei, the most interesting area of which was the transition of hadronic matter to a quark-gluon state via a mixed phase. Scientists from the JINR Laboratory of Theoretical Physics played a significant role in the development of these concepts[19]. In some publications, the region of the diagram corresponding to the mixed phase was even called the "Dubna Glade". According to calculations, it was achieved at a relatively low energy in the center-of-mass system of colliding nuclei — approximately 10 GeV/nucleon. This energy was accessible in both fixed-target experiments and colliding beams. Several workshops and roundtables were held, including in Dubna. These discussions led to beam energy scanning programs at the RHIC collider (BNL) and the NA61/SHINE experiment at CERN; and the CBM (Compressed Baryonic Matter) experiment was included in the FAIR accelerator complex project in Darmstadt. The proper place was also found for the Dubna accelerator complex. The fact is that the luminosity of a colliding beam experiment in this energy range was limited by space charge effects in colliding clusters and was inversely proportional to the square of the facility's

[18] *Agapov N. N., Kekelidze V. D., Kovalenko A. D., Lednický R., Matveev V. A., Meshkov I. N., Nikitin V. A., Potrebenikov Yu. K., Sorin A. S., Trubnikov G. V.* Relativistic Nuclear Physics at JINR: From the Synchrophasotron to the NICA Collider // Phys. Usp. 2016. V. 186, No. 4.

[19] *Sissakian A. N., Sorin A. S., Toneev V. D.* // Proc. 33rd Intern. High Energy Physics Conf., ICHEP'06, Moscow, Russia. 2006. V. 1. P. 421; nucl-th/0608032.



In the Nuclotron's linear injector hall, Nobel Prize laureate David Gross marks the point on the phase diagram corresponding to the mixed phase

perimeter. Therefore, all other things being equal, a collider with a small perimeter could outperform RHIC in luminosity by more than hundred times.

Two groups of accelerator specialists were organized to develop alternative concepts for the new accelerator complex: one led by Alexander Dmitrievich Kovalenko, the second one — by Igor Nikolaevich Meshkov. The prepared projects were optimistic both in terms of the commissioning timeframe and the cost of the installation, which was significantly reduced by the possibility of placing a collider with a perimeter of 200–250 m in the existing experimental building. The NICA center (Nuclotron-based Ion Collider fAcility — the name given to the planned accelerator complex) was organized to combine the efforts of the developers, with Alexander Savelyevich Sorin, an employee of the Laboratory of Theoretical Physics, appointed as its head. Before the start of full-scale work, it was necessary to demonstrate in practice the Nuclotron's ability to operate within its design parameters. The Accelerator Department, headed by Grigory Vladimirovich Trubnikov, was established at LHE in 2007 to address this problem. By this time, he had already served for two years as Deputy Chief Engineer at JINR and had proven to be a competent specialist in charged particle accelerators and a talented organizer. Another organizational decision was the merger of two laboratories — LHE and LPP. Vladimir Dimitrievich Kekelidze, a world-renowned experimental physicist, was elected Director of the new laboratory, named the Laboratory of High Energy Physics.

Since 2006, the NICA project has been discussed at seminars and workshops in Russian and foreign scientific centers. In 2008, it was presented at leading inter-

national accelerator and physics conferences[20]. In 2009, the project was approved by the JINR Scientific Council and included in the Seven-Year Plan for the Development of JINR by a decision of the session of the Committee of Plenipotentiaries of the Governments of the JINR Member States. It was necessary to build a new linear accelerator, an intermediate superconducting synchrotron, complete the modernization of the Nuclotron, construct two collider rings with two beam collision points, and two experimental facilities — MPD (Multi-Purpose Detector) and SPD (Spin Physics Detector) to implement the project. JINR and the Russian Federation had not built facilities of this scale for several decades.



Laureates of the Russian Federation Government Prize: A. N. Sissakian, G. V. Trubnikov, A. D. Kovalenko, H. G. Khodzhibagiyan, and B. Yu. Sharkov

Following the successful completion of the Nuclotron[21] upgrade, a group of JINR staff, together with ITEP staff, received the Russian Federation Government Prize in 2010 for the construction of a new generation of heavy-ion accelerators

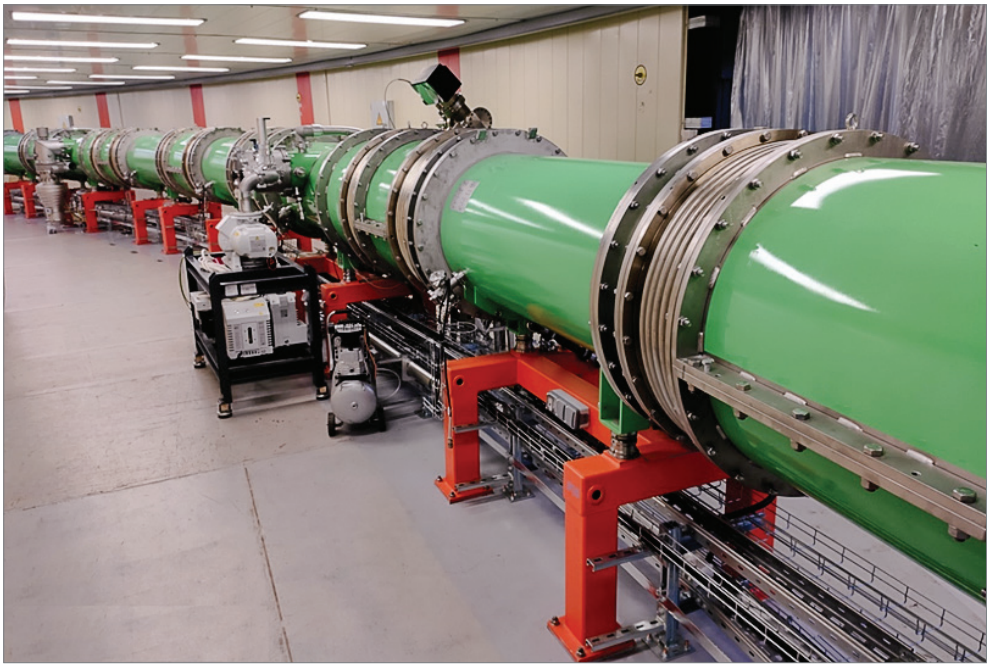
[20] *Sissakian A. et al.* Design and Construction of Nuclotron-Based Ion Collider Facility (NICA), Conceptual design report. Dubna: JINR, 2008; *Trubnikov G. et al.* Project of the Nuclotron-Based Ion Collider Facility (NICA) at JINR // Proc. EPAC 2008, Genoa, Italy, 2008. P. 2581.

[21] *Agapov N. N., Butenko A. V., Karpinsky V. N., Khodzhibagiyan H. G., Kovalenko A. D., Sidorin A. O., Trubnikov G. V., Volkov V. I.* Results of the Nuclotron-M Project // Phys. Part. Nucl. Lett. 2012. V. 43, No. 4. P. 474–491.

for relativistic nuclear physics and innovative nuclear energy technologies. Work on the creation of superconducting magnets for synchrotrons and the results of the Nuclotron upgrade were awarded Russian Federation State Prizes.

2016 was one of the most productive years. The first beam was obtained at the new heavy-ion linear accelerator, and a line for the assembly, testing, and certification of superconducting magnets was launched, inspired by Hamlet Georgievich Khodzhibagiyan. Booster and Collider magnets were subsequently manufactured on this line. The new KGU-1000 facility was also commissioned, after which the cryogenic plant's capacity allowed for the supply of liquid helium to all the facilities of the complex. The first runs were realized with the LU-20 preinjector, based on RFQ (spatially uniform quadrupole focusing), and a polarized beam source. Thus, the spin program returned to the complex after a pause of more than a decade.

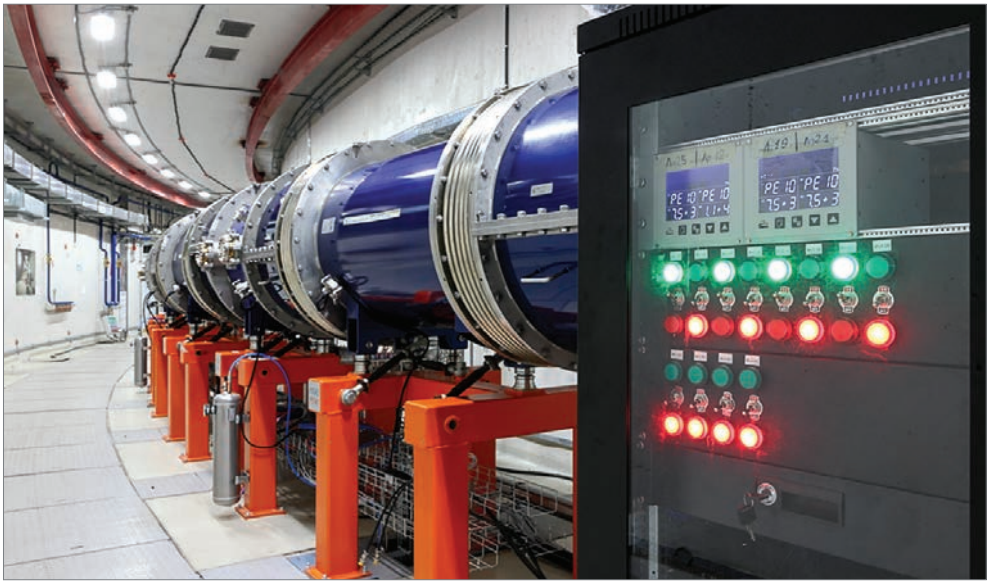
This very year was also the most saturated in the project's history. During the development of the technical design for the complex, it became clear that the Collider with its systems and areas for assembling and testing the detectors could not be accommodated in the existing experimental hall. The decision was made to construct a new, spacious building, which more than doubled the cost of the project. The JINR budget did not have the necessary funds, and the Directorate made the decision at its own risk. At the same time, vigorous efforts were underway at all levels, including the State Duma and the Government of the Russian Federation, to include the project in the program for mega-science facilities in the Russian Federation. As a result, in 2016, JINR Director V. A. Matveev and RF Minister of Science and Education D. V. Livanov signed an agreement between JINR and the Government of the Russian Federation on the construction and operation of the



Superconducting Booster synchrotron



The VBLHEP Accelerator Department in the Synchrophasotron hall after the first commissioning session on the NICA Booster



Testing the magnetic-cryostat system of the Collider

NICA complex of superconducting rings for colliding beams, which finally determined the future prospects of the project. Construction of the Collider building began.

The COVID-19 pandemic and sanctions policy of Western countries certainly impacted the construction schedule of the complex. However, all difficulties were overcome. In 2020, the first accelerated beam was produced in the Booster[22], and installation of the Collider magnets began. During commissioning, physical studies were carried out on the Nuclotron's extracted beams — at the SRC (Short Range Correlations) and BM@N (Baryonic Matter at Nuclotron) facilities — and applied research was performed under the ARIADNA (Applied Research Infrastructure for Advanced Developments at NICA fAcility) collaboration program.

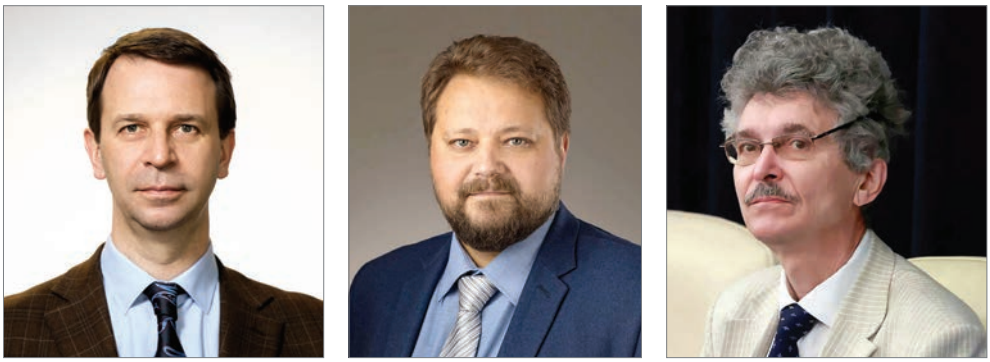
Currently, assembly of the magnetic-cryostat system of the Collider is being completed and its testing has begun, the operating modes of all systems of the complex are being optimized, and preparations for operation with the beam of the first experimental facility on the Collider ring, the MPD detector, are being completed.

The success of the employees in building the complex did not go unnoticed in 2023, A. I. Malakhov was awarded the P. A. Cherenkov Prize of the Russian Academy of Sciences for a series of studies in relativistic nuclear physics conducted at JINR and foreign centers and forming the basis of the physics program of the



President of the Russian Academy of Sciences G. Ya. Krasnikov presents the P. A. Cherenkov Prize of the Russian Academy of Sciences to Professor A. I. Malakhov

[22] *Butenko A. V., Brovko O. I., Galimov A. R., Gorbachev E. V., Kostromin S. A., Karpinskii V. N., Monchinskii V. A., Meshkov I. N., Sidorin A. O., Syresin E. M., Trubnikov G. V., Tuzikov A. V., Filippov A. V., Khodzhibagiyan H. G.* NICA Booster: A New Generation Superconducting Synchrotron // Phys. Usp. 2023. V. 193, No. 2. P. 206–225.



Laureates of the 2024 V. I. Veksler Prize of the Russian Academy of Sciences. G. V. Trubnikov, A. V. Butenko, A. O. Sidorin

NICA accelerator complex; in 2024, the V. I. Veksler Prize of the Russian Academy of Sciences was awarded to a scientific team from the Joint Institute for Nuclear Research — G. V. Trubnikov, A. V. Butenko, and A. O. Sidorin — for a series of works "Multifunctional Complex of Heavy Ion Accelerators — Injector of the NICA Collider".

CRYOGENICS AND SUPERCONDUCTIVITY IN THE NICA MEGAPROJECT

The scientific school of cryogenics[23], which has been continuously developing since JINR foundation, made it possible to make the world's first superconducting fast-cycling synchrotron to accelerate heavy ions — the Nuclotron. In March 1993, it was cooled to 4.5 K for the first time, and its operation began, continuing to the present day. More than 60 accelerator runs have already been conducted, with magnets cooled to liquid helium temperature, followed by warming to room temperature, and several tens of millions of excitation cycles with the current up to 6 kA.

The Nuclotron's cryogenics was distinguished by a large number of previously unused technologies and solutions. They are described in such key terms as fast-cycling superconducting magnets, cryostatting with a two-phase vapor-liquid helium flow, an unusually short time of cooling the system to operating temperatures, parallel connection of more than a hundred superconducting magnets along the boiling helium flow, vapor-liquid helium turboexpanders, screw helium compressors with a compression ratio of over 25 in just two stages, and others. Each of above points marked a new and important step in the development of liquid helium and superconducting magnet technologies[24].

[23] *Agapov N. N.* Scientific School of Cryogenics at the Laboratory of High Energies // Part. Nucl., Lett. 2004. V. 1, No. 6(123). P. 70–79.

[24] *Agapov N. N.* Cryogenic Technologies of the Nuclotron — Superconducting Accelerator of Relativistic Nuclei // Phys. Part. Nucl. 1999. V. 30, No. 3. P. 761–804.

In the 2010s, VBLHEP was actively pursuing the next stage of accelerator technology development based on superconducting magnets. As part of the NICA project, which includes new accelerators — a Booster synchrotron and a Collider, work began to improve the design of Nuclotron-type magnets for these tasks and construct a unique complex to assemble and test superconducting magnets. Construction of the new accelerators is currently in its final stage. Below is a brief description of the components of the Nuclotron, Booster, and Collider[25], the production complex for their assembly and testing, and the liquid helium supply system[26] for these facilities.

The Nuclotron uses simple and cost-optimal magnets in which the field is generated by means of an iron yoke. They are characterized by minimal consumption of superconductor, although they are limited in the conditions of iron saturation by a magnetic field of about 2 T. The main elements of such magnets are a superconducting winding and the iron yoke, which provides a highly homogeneous magnetic field and perceives the magnetic forces affecting the winding. The superconducting cable (Fig. 16) is based on a cupronickel tube with a diameter of 5×0.5 mm, inside which the boiling vapor-liquid flow of helium passes for cooling. A superconductor is spirally wound on this tube. This superconductor is a copper wire matrix with a diameter of 0.5 mm, containing 1045 thin niobium–titanium fibers 10 μm thick. They are pressed to the cooling tube using a bandage wire to ensure good thermal contact. The cable has electrical insulation made of two layers of polyamide and two layers of glass tape impregnated with epoxy compound.

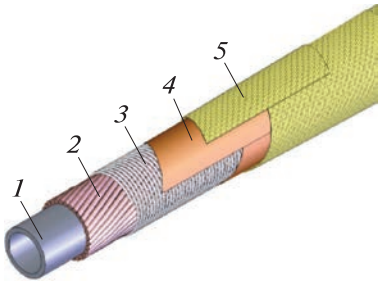


Fig. 16. Structure of the Nuclotron superconducting cable: 1 — cupronickel tube; 2 — superconducting wire; 3 — bandage wire; 4 — polyamide tape; 5 — glass tape impregnated with epoxy compound

The rated current of such a superconducting cable is 6 kA, the transition of the magnets to a normal state is observed when a current of about 7.5 kA is applied. The ring magnetic-cryostat system consists of 96 dipoles and 64 quadrupoles, made on the cable described above.

The cross section of the dipole and quadrupole magnets is shown in Fig. 17. The magnets have a modular construction. The dipole iron yoke consists of two symmetrical parts connected with bolts and assembled from 0.5-mm-thick electrical steel plates. The quadrupole yoke has four symmetrical parts. The accelerator's

[25] *Khodzhibagiyan H. et al.* Development of Superconducting Accelerator Magnets at JINR // Natural Sci. Rev. 2024. Iss. 1. 6.

[26] *Agapov N. et al.* Cryogenics for the Future Accelerator Complex NICA at JINR // Part. Nucl., Lett. 2014. V. 11, No. 4(188). P. 760–767.

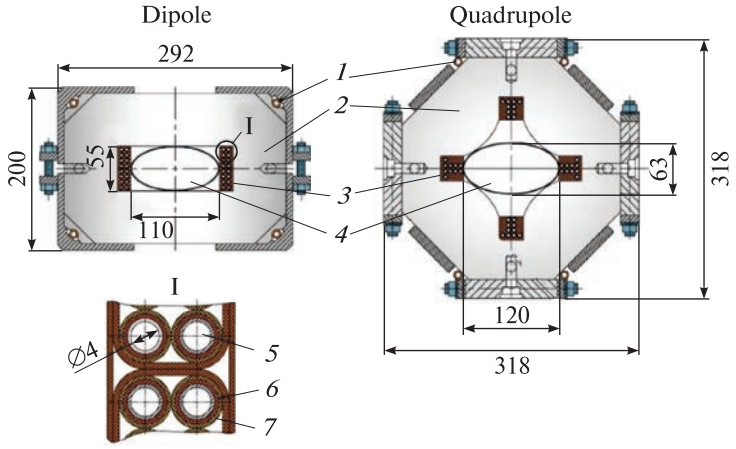


Fig. 17. Cross sections of the dipole (left) and quadrupole (right) of the Nuclotron: 1 — cooling tube of the iron yoke; 2 — magnet yoke; 3 — winding; 4 — beam chamber; 5 — cooling tube; 6 — SC wire; 7 — electrical insulation

magnetic optics elements, as well as the forward and reverse flow helium collectors, are located in an annular cryostat formed by horizontal cylindrical stainless steel sections.

Additionally, a heat shield cooled with liquid nitrogen is located around the entire perimeter of the annular cryostat. The cylindrical sections have lengths corresponding to the lengths of the magnets and, when being assembled, form single magnetic-cryostat units (Fig. 18), interconnected by bellow joints. The magnetic element suspension system is implemented using eight rods located at the ends of these units. The design of the rods ensures that, despite thermal deformations after cooling down to operating temperatures, the spatial position of the magnetic axis remains unchanged.

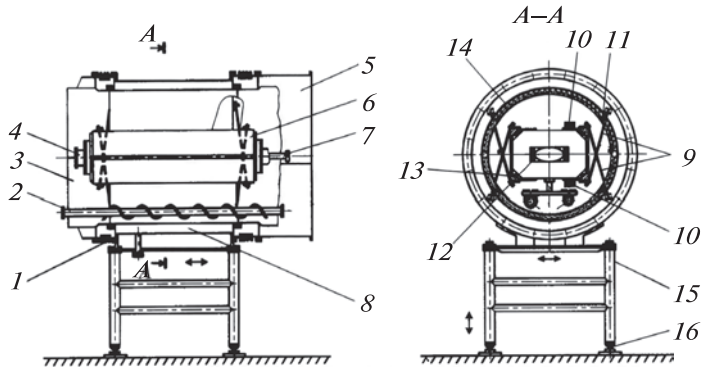


Fig. 18. Magnetic-cryostat unit of the Nuclotron: 1 — bellows; 2 — helium collectors; 3 — heat-insulating shield; 4 — vacuum chamber of accelerated particles; 5 — coupling; 6 — iron yoke; 7 — liquid nitrogen pipeline; 8 — vacuum casing; 9 — rod; 10 — superconducting cable for electrical connection of magnets; 11 — heat bridge; 12 — winding; 13 — tube for cooling the yoke; 14 — heat insulation; 15 — stand; 16 — adjustment jack



Production complex for assembly and testing of magnets for the NICA accelerators

Flexible bellows elements are attached to the ends of the vacuum housing via cap flanges, allowing the units to be moved for adjustment. The structure is mounted on a stand equipped with an adjustment device. The vacuum housings of the units are connected with detachable couplings. These provide access to the electrical and cryogenic connections located in the short spaces between the magnets.

The magnets of the NICA accelerator complex were developed based on many years of experience gained during the operation of the Nuclotron. All of them were manufactured at VBLHEP and underwent an extensive testing program, the main one being cryogenic testing. This program consisted of several stages: cooling the magnet to the temperature of 4.5 K, training the superconducting winding, magnetic measurements at liquid helium temperature, measuring static heat gain and dynamic heat release, hydraulic resistance of the cooling channel, searching for "cold" leaks, and heating. A special production complex was made at the Laboratory to carry out this work, which was officially commissioned in November 2016.

The complex includes an incoming inspection area, superconducting cable and winding production areas, a shop for magnet assembly, room-temperature magnetic measurements, leak checks of the magnet helium lines, and installation of superconducting magnets in the cryostat. During the final stage, the products were tested at the operating temperature of 4.5 K and current of up to 12 kA, which was provided by specially developed helium refrigerators and devices to supply the current to the magnet windings. The production plan included the manufacture of approximately 450 magnetic-cryostat units: 88 dipole and quadrupole units for the Booster, 186 for the Collider, and up to 175 for the SIS100 synchrotron of the FAIR project. This plan for the NICA complex magnets was fully implemented.



The magnetic-cryostat units of the NICA accelerators. Left to right: the Booster dipole and quadrupole, the Collider dipole

The designs of the superconducting magnets of the Booster and Collider are shown in Figs. 19, 20, and their characteristics are given in Tables 2 and 3. The main features are that the Booster dipoles have a curved shape with a radius of curvature of about 14 m, and the Collider magnets are made with two apertures for colliding particle beams.

In connection with the development of new accelerators for the NICA project, the cooling capacity of VBLHEP cryogenic system was significantly increased from 4000 to 10 000 W. Russia's largest liquid helium production complex, which had been operating for the needs of the Nuclotron since 1993, was supplemented by a number of new industrial units, the prototypes of which were designed and manufactured according to JINR specifications. These prototypes, commissioned and

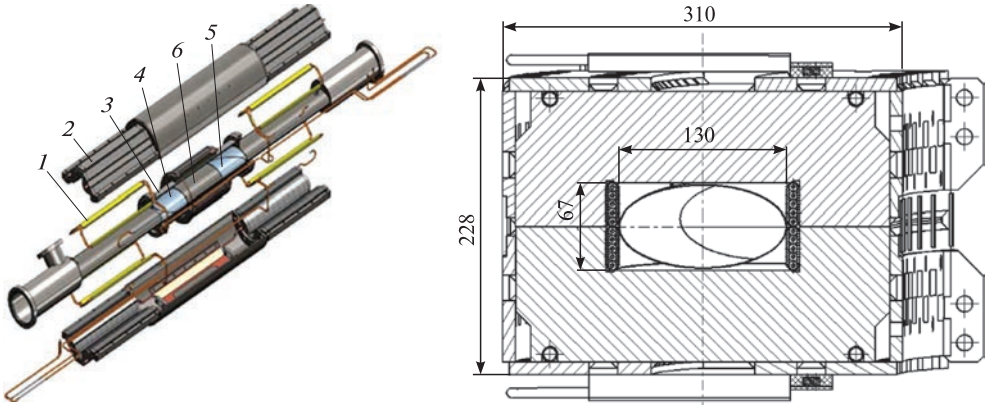


Fig. 19. Design of the superconducting magnets of the Booster. Left — a quadrupole doublet, right — a dipole magnet. 1 — half-coil; 2 — half-yoke; 3 — beam pipe; 4, 5 — beam position monitors; 6 — correction magnet

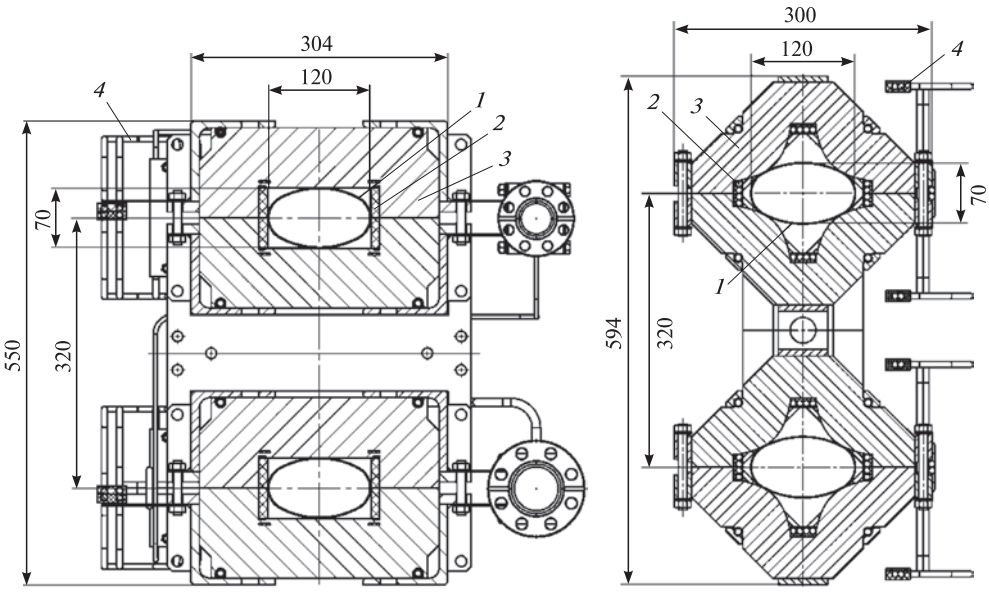


Fig. 20. Cross-section view of the dipole (left) and quadrupole (right) of the NICA collider. 1 — beam pipe; 2 — SC coil; 3 — iron yoke; 4 — bus-bars

Table 2. Main characteristics of the Booster magnets

Parameter	Dipole	Quadrupole
Number of magnets	40	48
Maximum magnetic field, gradient	1.8 T	21.5 T/m
Effective length of magnet, m	2.2	0.47
Beam pipe aperture, mm	128/65	128/65
Radius of curvature, m	14.09	—
Total mass, kg	1030	110

Table 3. Main characteristics of the Collider magnets

Parameter	Dipole	Quadrupole
Number of magnets	80+8[a)]	86+12[b)]
Maximum magnetic field, gradient	1.8 T	23.1 T/m
Effective length of magnet, m	1.94	0.47
Beam pipe aperture, mm	120/70	120/70
Distance between colliding beams, mm	320	320
Total mass, kg	1670	240

[a)] Special dipoles for converging particle beams at interaction points.
[b)] Single aperture quadrupoles around interaction points.

thoroughly tested by JINR staff, became the basis for serial production in response to the current need for import substitution.

The schematic flow of the NICA cryogenic complex is shown in Fig. 21. Its main elements were manufactured by JSC "R&D Geliymash" (Moscow) and JSC "NIIturbokompressor" (Kazan):

— helium liquefier with a capacity of 1000 l/h, the largest in terms of productivity in Russia;
— liquid helium transport tank with a capacity of 40 m^3;
— satellite helium refrigerators with a cooling capacity of up to 2000 W;
— two-stage screw compressors processing 6600 cubic meters of gaseous helium per hour with an output pressure of 30 atm.

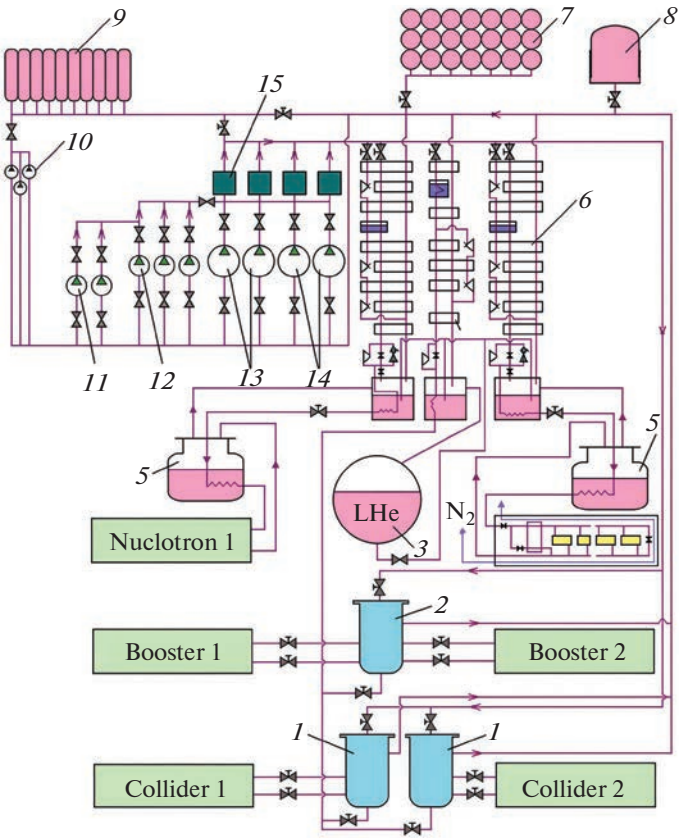


Fig. 21. Schematic flow diagram of the cryogenic helium supply system of the NICA accelerator complex: 1 — RSG-2000/4.5 satellite refrigerators of the Collider (2 pcs.); 2 — RSG-2000/4.5 satellite refrigerator of the Booster; 3 — 40-m^3 cryogenic helium tank KTsG-40/0.5; 4 — helium liquefier OG-1000; 5 — Nuclotron separators (2 pcs.); 6 — KGU-1600/4.5 helium refrigerators (2 pcs.); 7 — 1000-m^3 gas holder; 8 — 20-m^3 gas holder; 9 — 20-m^3 compressed-helium reservoirs (10 pcs.); 10 — piston compressors 6GSh-1.6-2/1.1 (3 pcs.); 11 — piston compressors 2GM4-12/31 (2 pcs.); 12 — piston compressors 305NP-20/30 (3 pcs.); 13 — screw compressors "Kaskad-110/30" (2 pcs.); 14 — screw compressors "Kaskad-80/25" (2 pcs.); 15 — draining and oil-purification units MO-800 (4 pcs.)

This equipment provides the increased cooling capacity necessary to maintain operating temperatures and the ability to rapidly cool superconducting magnets of approximately 290 t from ambient temperature to 4.5 K. The Booster and Collider cryostatting system utilizes satellite refrigerators located near the accelerator rings. They utilize liquid helium supplied through pipelines from the central liquefier. These refrigerators, consisting almost entirely of heat exchangers, are characterized by multimode operation, high reliability, and ease of operation. Less reliable components requiring constant personnel attention are concentrated in one location — the central cryogenic station. This operating scheme requires the minimum of cryogenic pipelines while maintaining high energy efficiency.

The layout of the new cryogenic complex equipment is shown in Fig. 22. It is distributed across several VBLHEP buildings, connected by the necessary process pipelines: the central cryogenic station in building 1B, the satellite refrigerator room in the Collider building, and two compressor stations. A significant portion of the equipment is installed and operated outdoors: helium and nitrogen gas holders with a capacity of 1000 m^3 each, liquid helium and nitrogen tanks, and receivers to store gases under pressure.

The central cryogenic station houses two KGU-1600/4.5 helium refrigerators, the Nuclotron's cryostat half-rings, an OG-1000 helium liquefier, a Booster satellite refrigerator, and fine purification units for gaseous helium supplied under pressure from the compressors. Liquid nitrogen production units designed to recondense vapors escaping from the heat shields of the cryostats and the accelerator magnets current leads are also located here. The construction of such a closed-loop

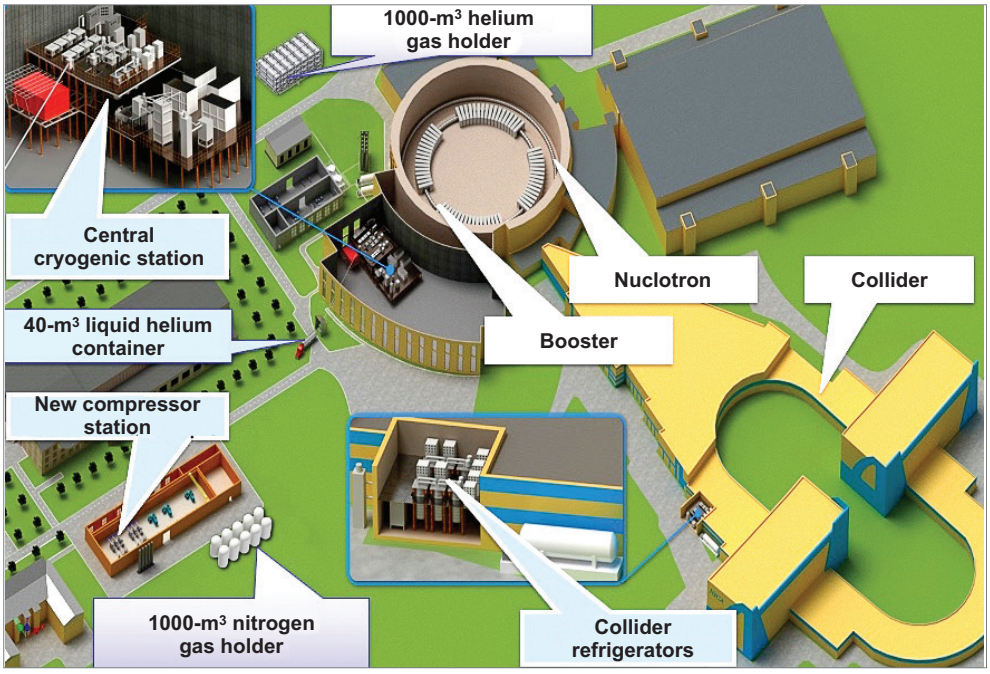
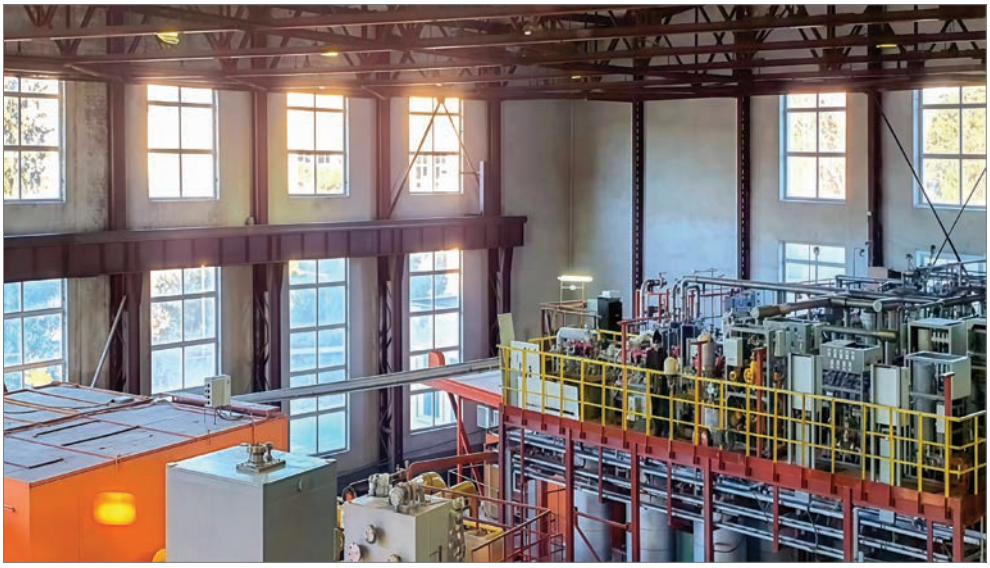


Fig. 22. Layout of equipment of the NICA cryogenic complex



The central cryogenic station of VBLHEP in building 1B



The building of the new compressor station of the NICA complex



Screw compressors "Kaskad-110/30" in the new compressor station

nitrogen system eliminates nitrogen emissions into the atmosphere and significantly reduces operating costs at the NICA complex.

A new building was constructed to house the compressor equipment. It comprises two new-generation helium screw compressors, the design of which incorporates years of experience of operating similar machines during Nuclotron runs. The building also locates three nitrogen turbocompressors, which are part of a closed-loop nitrogen vapor recondensation system. The installed capacity of the electric motors in the new compressor station is 7.6 MW.

In concluding the description of cryogenic and magnetic technologies of the NICA megaproject, it should be noted that their development is ongoing. New progress is expected in the near future: magnetic elements for accelerators and physical instruments using high-temperature superconductivity. Four quadrupoles

have already been manufactured and tested at the Laboratory's production complex, and plans are underway to make a model dipole and a full-scale one for the so-called "New Nuclotron", which will operate at temperatures up to 50–80 K.

EXPERIMENTS AT THE NICA ACCELERATOR COMPLEX

The experience of constructing and operating the Nuclotron allowed the design of the NICA collider complex, which is currently being implemented, with the Nuclotron remaining its "heart": ion beams accelerated at the Nuclotron will fill the Collider's opposing rings and then collide at two points. The MPD (Multi-Purpose Detector) and SPD (Spin Physics Detector) facilities will be located in the beam crossing zones.

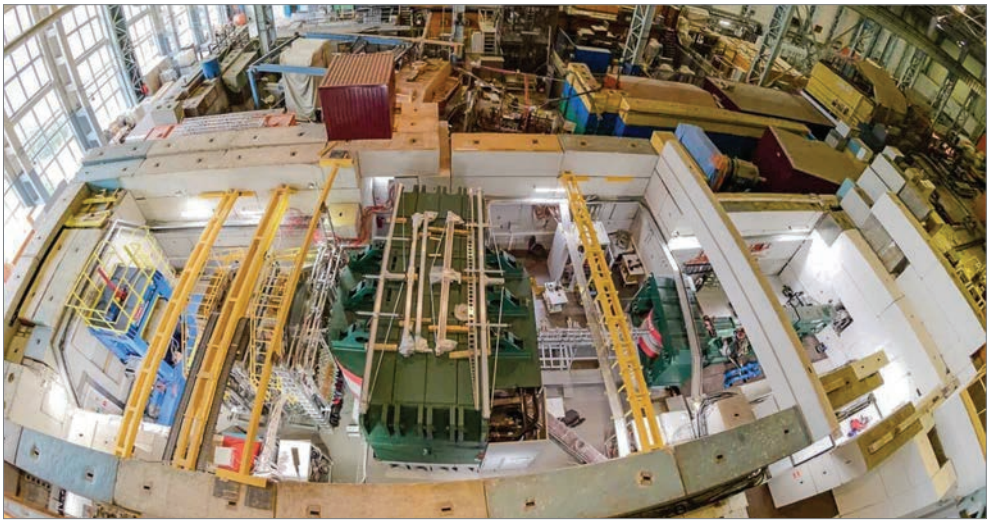
The study of collisions of heavy relativistic nuclei has always been an important part of the JINR scientific program and has been discussed at various meetings and conferences. These discussions resulted in the proposal in 2007 of projects to upgrade the Nuclotron accelerator and build a new relativistic ion collider, NICA, with the MPD experimental facility to study the properties of hot and dense baryonic matter. The project was initiated by A. N. Sissakian, theoretical support was provided by V. D. Toneev, and the accelerator part of the project was developed by I. N. Meshkov. Simultaneously, the infrastructure for fixed-target experiments was developed.

THE BM@N EXPERIMENT

The intensities of accelerated nuclei at the Nuclotron increased significantly with the commissioning in 2021of the superconducting Booster synchrotron located inside the Nuclotron yoke. A new, modern, universal BM@N (Baryonic Matter at Nuclotron) facility, led by M. N. Kapishin, began operating on the extracted beam.

The BM@N physics program includes studies of the equation of state of nuclear matter, its thermodynamic parameters, and the dynamics of nuclear collisions; the properties of hadrons in dense media; the production of cascade hyperons near the threshold; and the production of hypernuclei in collisions of heavy-ion beams with various fixed targets at energies up to 4.5 *A* GeV.

The BM@N experimental program began in 2015, when the first deuteron beam collisions with targets were recorded. At that time, the feasibility of beam transport to the target in the facility was tested. The question was not to obtain physical results; only three proportional chambers created at VBLHEP and two drift chambers obtained from CERN, previously used in the NA48 experiment, were available. But year after year, thanks to the work of many people, the experimental facility was modified and filled with detectors. New detector subsystems were made to register charged and neutral particles, for their identification and calorimetry. At the same time, the physics program was developed and the software



Panoramic view of the BM@N facility

for both operating the detectors and processing and analyzing the experimental data was updated.

The first heavy-ion physics run was carried out in the winter of 2022–2023. During the run, more than 500 million events of xenon ion interactions with a cisium-iodine target were collected at two beam energies — 3.0 *A* and 3.8 *A* GeV. Thanks to the data monitoring system, the team could already see event parameters in real time during the run, right down to the mass distributions of the produced charged particles. Even before applying the detailed calibrations, we observed a higher-quality peak from Λ hyperons in the invariant mass spectrum of pion and proton pairs than was obtained in previous test runs.

The scheme of the facility used for data collection in 2022–2023 is shown in Fig. 23. The main components of the facility[27] include the SP-41 analyzing magnet (*0*), the inner tracking system consisting of Forward Silicon Detectors (FSD) (*8*) and Gas Electron Multipliers (GEM) (*9*), the external tracking system consisting of Drift Chambers (DCH) (*12*) and Cathode Strip Chambers (*10*, *17*), the ToF-400 and ToF-700 Time-of-Flight detectors (*11*, *13*), the Scintillation Wall (ScWall) (*14*), and the Forward Hadron Calorimeter (*20*).

Each detector meets the latest requirements and deserves a separate discussion, but it is worth noting the main tracking system, consisting of unique gas electron multipliers (GEMs) with three strengthening layers (triple GEMs). These detectors are the largest GEM detectors used in physical experiments in the world (the area of one plane is approximately 0.75 m^2).

Currently, the international collaboration of the BM@N experiment includes more than two hundred people from five countries. The head of the collaboration is R. Lednický, the technical coordinator is S. M. Piyadin, and M. M. Merkin is the

[27] *The BM@N Collab.* // Nucl. Instr. Meth. A. 2024. V. 1065. P. 169532.

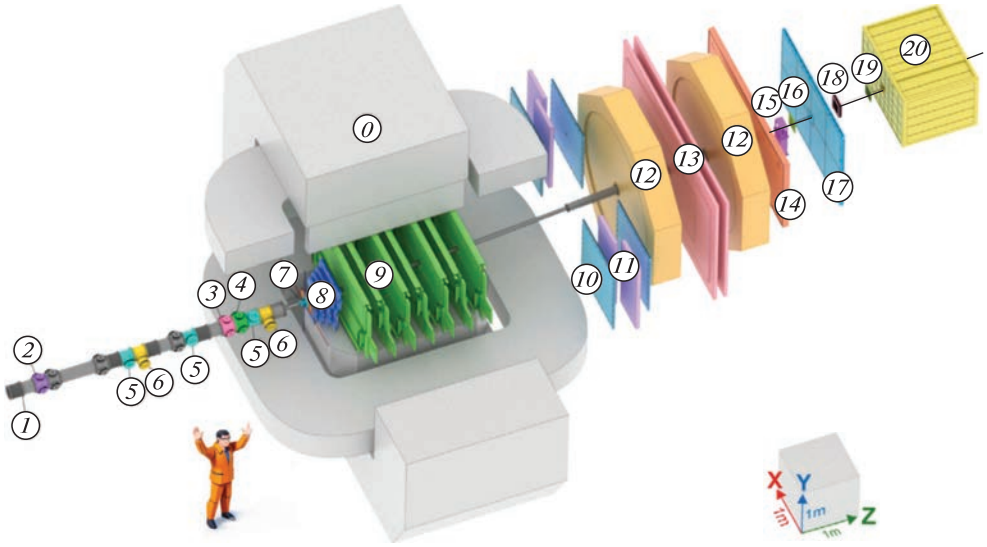


Fig. 23. Schematic view of the BM@N facility in the 2022–2023 run with the xenon ion beam

Chairman of the Council of institutes. The collaboration is preparing and upgrading the facility for the next experimental runs and analyzing the already collected experimental data. Thus, the results of the production of π^+ and K^+ mesons in argon-nucleus interactions at an energy of 3.2 A GeV have already been published[28]. Publications are being prepared on the analysis of the production of Λ hyperons and short-lived neutral kaons, light ions, the measurement of proton, deuteron and Λ hyperon fluxes, the neutron yield and the determination of the centrality of the interaction. Two employees have already defended their PhD theses based on the experimental data obtained, and several more are on their way.

The BM@N experiment is quite young and the large number of young people among the participants in the collaboration makes it possible to look confidently to the future and be ready to solve new engineering, technical and physical problems.

THE MPD EXPERIMENT

The NICA accelerator complex and the MPD (Multi-Purpose Detector) experimental facility are in the final stages of construction, with the first heavy-ion beams expected in 2026. The main scientific objective of the MPD experiment is to study the properties of strongly interacting matter at extremely high baryon densities, achieved at heavy-nucleus interaction energies of $\sqrt{s_{NN}} = 4–11$ GeV in the collider mode and/or at $\sqrt{s_{NN}} = 2.4–3.5$ GeV in the fixed-target experiment mode. The primary goal of the MPD experiment is to search for signals indicating the onset of deconfinement, a first-order phase transition, and the critical point of strongly interacting matter. To achieve this goal, it is planned to implement a

[28] *The BM@N Collab.* // JHEP. 2023. V. 174.

scanning program for the energy and size of colliding nuclei at the NICA collider, measuring a large number of signals for each measured system, including:

— the yield of strange mesons, (multi)strange baryons and antibaryons;
— fluctuations of multiple particle production, transverse momentum, relative particle yield;
— angular correlations and collective fluxes of identified hadrons;
— pulse correlations (femtoscopy);
— production of lepton pairs and soft direct photons;
— polarization phenomena.

Calculations have shown that the highest baryon density is achieved in nuclear collisions in the NICA energy range, making the MPD facility particularly well suited for these tasks. This energy range is also important for modern astrophysics. Model calculations have shown that during neutron star mergers, nuclear matter reaches densities and temperatures similar to those produced by heavy-ion collisions at NICA. Thus, MPD offers a unique opportunity to complement the study of neutron star mergers by obtaining data from a ground-based laboratory experiment. The ability to study collisions of various nuclear systems at NICA is expected to significantly expand the results of the energy scanning program for a single Au + Au system at the RHIC collider, which ended in 2021.

To conduct these studies, the MPD detector facility must ensure efficient identification of nuclear collision products and measurement of their parameters at high loads over a wide region of phase space. To achieve this, the MPD experimental facility includes:

— a tracking system for measuring tracks of charged particles and their momenta in the range of 0.1–2 GeV/c;
— a time-of-flight system for particle identification, capable of separating protons, π mesons, K mesons and electrons in the momentum range of 0.1–3 GeV/c;
— a system of trigger and determination of the coordinates of the primary interaction vertex with an accuracy of 100–200 μm and secondary decay vertices with an accuracy of 10–20 μm;
— detectors for recording gamma quanta in the energy range of 50–2000 MeV.

The maximum size of the facility along the beam is determined by the arrangement of the magnetic lenses of the Collider storage rings and cannot exceed 9 m in order to ensure good focusing of the beams in the region of their collision. The diameter of the central detector is the result of a compromise between the need for a sufficient time-of-flight baseline and track length for accurate determination of the particle type and their momentum, on the one hand, and high requirements for the homogeneity of the magnetic field and a reasonable cost of the magnetic system, on the other. The track length must not be less than 1 m along the radius and the number of points on the track must not be less than 50 in order to obtain the required momentum resolution of 3% in the particle momentum range up to 2 GeV/c. With such a momentum resolution and time-of-flight measurements on a 1.5 m baseline with an accuracy of 100 ps, it will be possible to separate 90% of the pions and kaons produced in collisions of gold ions with the energy in the center-of-mass system of 11 GeV/nucleon.

The facility must cover a geometry close to 4π. The tracking system must operate in a uniform magnetic field with an induction of 0.2–0.5 T for accurate particle momentum measurements. Obviously, it was preferable to use a superconducting solenoid magnet to obtain such a field in the specified volume.

The MPD facility that meets these requirements is shown in Fig. 24. The detector consists of a cylindrical section and two end sections located in the magnetic field. The cylindrical section consists of various types of detectors surrounding the beam collision region, which include a tracking system, a time-of-flight system, and an electromagnetic calorimeter.

A time-projection drift chamber (TPC, headed by S. A. Movchan) was proposed as the main tracking system. It should be complemented by an internal track-

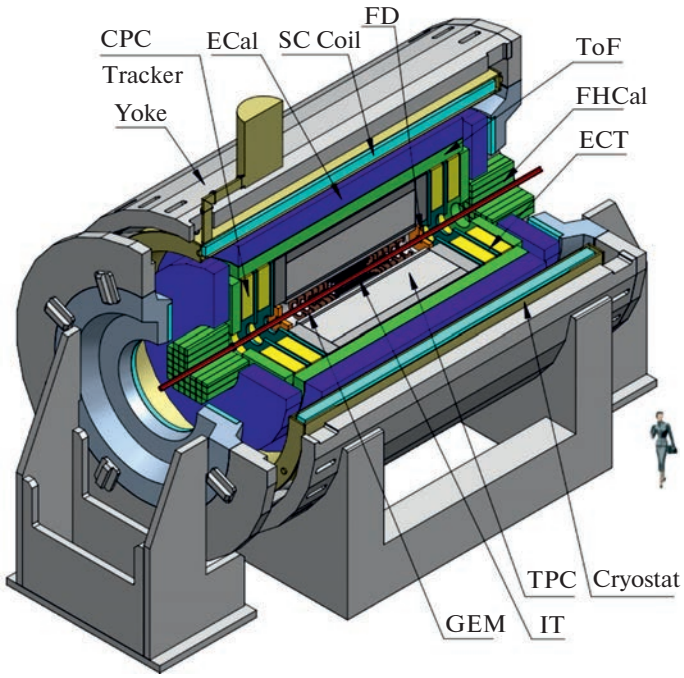


Fig. 24. MPD facility diagram, full version

ing system based on silicon semiconductor detectors (ITS, headed by Yu. A. Murin) surrounding the beam collision region. Both detectors can ensure accurate reconstruction of charged particle tracks and their momenta, as well as determination of the decay vertices of short-lived particles. The internal detector should have at least six layers surrounding the beam interaction region to reconstruct secondary decay vertices of charm mesons and baryons.

A time-of-flight system (ToF, led by V. A. Babkin) is used in addition to the TPC to identify particles. It enables the identification of charged particles with momenta up to 2 GeV/c over a wide pseudorapidity range. The fast forward detector (FFD, led by V. I. Yurevich) provides the starting signal for the time-of-flight system and has a time resolution of at least 50 ps.

An electromagnetic calorimeter with projection geometry (ECal, headed by I. A. Tyapkin) is used to identify electrons and photons and measure their energies. The calorimeter's high granularity (4 × 4 cm), along with good energy and time resolution, will significantly improve the particle identification capabilities of the MPD detector. The calorimeter, optimized in design and cost, is based on a multilayer absorber-detector "shashlyk"-type assembly.

To expand the particle detection region in the forward pseudorapidity region to $|\eta| \sim 2$, where the TPC tracking efficiency decreases, it is necessary to add forward spectrometers, including end-cap tracking systems (ECTs) based on proportional straw tubes, proportional chambers with cathode readout, or detectors based on GEM structures. ECTs should be located at both ends of the MPD directly behind the TPC readout chambers. It is also proposed to use a time-of-flight system similar to the ToF in the cylindrical part of the MPD to identify particles in the angular range $|\eta| > 1.2$.

Fast forward detectors (FFD) and forward hadron calorimeters (FHCal, headed by A. P. Ivashkin) are used to register particles emitted at very small angles $1.2 < |\eta| < 2$. These detectors are used in the trigger (headed by S. N. Bazylev) to determine the centrality of the collision and reconstruct the interaction point of the beam nuclei.

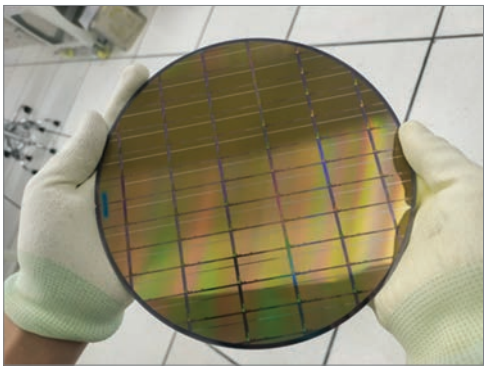
Thus, three regions with a characteristic measurement method and accuracy can be distinguished in the MPD structure under consideration: the central part $|\eta| < 1.2$, the forward region $1.2 < |\eta| < 2$, in which the particle momentum is measured rather roughly ($dp/p \sim 4–10\%$), and the region $2 < |\eta| < 3$, where the integral parameters of the event are measured.

To optimize the design and commissioning time of the facility, it was advisable to build it in stages. At the first stage, the basic configuration is assembled, which should include subsystems such as the TPC, the cylindrical part of the ToF, FFD, FHCal, and the cylindrical part of the ECal. The inner tracking system (ITS), the forward tracking system, and the end ToFs can be included in the complete configuration and manufactured at the second stage. In the basic configuration, the facility can efficiently identify secondary particles and measure their momenta in the pseudorapidity range $|\eta| < 1.2$.

In 2020–2025, the main components of all detector subsystems for the MPD base configuration were manufactured. These included the time-projection chamber (TPC), time-of-flight system (ToF), electromagnetic calorimeter (ECal), fast forward detector (FFD), and forward hadron calorimeter (FHCal). Assembly, testing, and calibration are currently underway. Extensive work was completed on the assembly and commissioning of the facility's superconducting magnet (led by K. A. Mukhin). At the end of 2024, the magnet was cooled for the first time to the operating temperature of liquid helium (4.5 K). Preparations for magnetic field measurements are currently underway. Multilevel platforms with clean rooms for the electronics and control systems of the detector subsystems were developed and built, and the layout of a huge number of cables and pipes of various diameters was optimized (led by A. A. Fediunin). The first stage of the MPD facility launch with beams in 2025–2026 is expected to use Xe and Bi nuclei, which ensure more reliable operation of the NICA accelerator complex

during its commissioning. In its basic configuration, the MPD facility will make it possible to measure particle momenta and identify them in the pseudorapidity range up to $|\eta| < 1.2$.

The creation of the MPD facility is inevitably accompanied by the introduction of cutting-edge technologies for particle detection, previously unavailable at JINR. The most striking illustration of this is the project to construct a six-layer MPD vertex tracker from monolithic active pixel sensors (MAPS) to identify the decay products of short-range D^0 and D^+ mesons. Six billion pixels make it possible to detect the path of secondary charged particles with a spatial accuracy of better than 10 μm. These charmed particles are considered one of the most promising probes of "new" physics for research in high-energy heavy nucleus collisions. The implementation of this project required the development of technologies for the production of ultra-lightweight mechanical structures from composite materials with integrated cooling system elements and the construction of high-tech areas for the precision assembly of ITS system modules and supermodules. And, most importantly, joint work was initiated with Chinese partners from the Central China Normal University (CCNU, Wuhan) and the University of Science and Technology of China (Hefei) on the design and production of specialized, highly integrated circuits, previously unavailable in Russia, designed for particle detection, aggregation, and transmission of the tracker's massive volume of generated data to the servers of the remote online MPD farm. The photo shows one of 12 silicon plates with the first MAPS MICA prototypes, manufactured at one of the state-owned enterprises in China and successfully tested on stands with radioactive sources.



Silicon plate with chips of the first MICA prototype (courtesy of Prof. Xiangming Sun, CCNU, Wuhan)

In recent years, a comprehensive performance study program for the MPD facility in its baseline configuration has been performed. Using Monte Carlo simulations of the experimental setup with full event reconstruction, the efficiency of measuring the yields and angular distributions of various particle types, including light mesons and hyperons, resonances, light nuclei and hypernuclei, direct photons, and dileptons, was investigated. It has been shown that the MPD facility in its baseline configuration will measure collective fluxes and particle correlations as a function of collision centrality, transverse momentum, and particle velocity with high efficiency. The capabilities of the MPD facility for operation with a fixed target have been also investigated, that will significantly expand the range of energies available to study and solve the problem of the low frequency of nuclear collisions, which is the most important thing during the launch of the Collider. The results of these studies have been presented at prestigious international

conferences and published in peer-reviewed journals, including two collaborative publications[29].

A concept for a future upgrade of the MPD facility is currently being developed, including the installation of forward spectrometers containing tracking stations and particle identification detectors. The addition of forward spectrometers will increase the MPD detector's pseudorapidity acceptance to $|\eta| < 2.0$. This will also enable an even more detailed study of the QCD phase diagram at the MPD, using for the first time three-dimensional scanning of the following variables: collision energy, interacting system size, and particle velocity. Implementation of this project will increase the sensitivity of measured signals to changes in the QCD phase diagram.

More than 500 scientists and engineers from 39 institutes and universities in 12 countries are participating in the MPD project. A large, functioning international collaboration has been formed at JINR on the MPD project, which has stood the test of time over the six years of its existence. The MPD collaboration is led by V. G. Riabov, and the MPD project managers are V. D. Kekelidze and V. M. Golovatyuk.

The team of project participants undoubtedly possesses high scientific qualifications in the development of modern detector equipment, as well as extensive experience in carrying out experiments to study collisions of relativistic heavy ions at the SIS, Nuclotron, SPS, RHIC and LHC accelerators, in processing experimental data and simulating processes.

THE SPD EXPERIMENT

The main goal of the "Spin Physics Detector" project at the NICA collider is to study the spin structure of nucleons. A comprehensive answer must be obtained to the question of how the spins of the quarks and gluons that make up the nucleon, as well as their internal motion, form the nucleon spin. Particular attention in the proposed measurements will be given to the gluon component. This project combines the experience of "home" experiments with polarized beams and the experience of JINR's participation in spin physics experiments at leading world centers. More than 150 employees of four JINR laboratories — DLNP, VBLHEP, BLTP, and MLIT — are participating in the project, as well as more than 200 scientists and specialists within the SPD collaboration from more than 30 scientific centers in Russia, Europe, Asia, Africa, and America.

In 2014, a working group headed by I. A. Savin and including A. V. Guskov, A. V. Efremov, A. D. Kovalenko, V. V. Kukhtin, A. P. Nagaytsev, D. V. Peshekhonov, O. V. Teryaev, N. D. Topilin, and O. Yu. Shevchenko prepared a Letter of Intent that formulated the measurement program and described the proposed experimen-

[29] *Abgaryan V. et al. (MPD Collab.)*. Status and Initial Physics Performance Studies of the MPD Experiment at NICA // Eur. Phys. J. A. 2022. V. 58, No. 7. P. 140; e-print: 2202.08970 [physics.ins- det];
Abdulin R. et al. (MPD Collab.). MPD Physics Performance Studies in Bi + Bi Collisions at $\sqrt{s_{NN}} = 9.2$ GeV // Rev. Mex. Fis. 2025. V. 71. 041201; e-print: 2503.21117 [nucl-ex].



SPD collaboration at a meeting in Yerevan, 2025

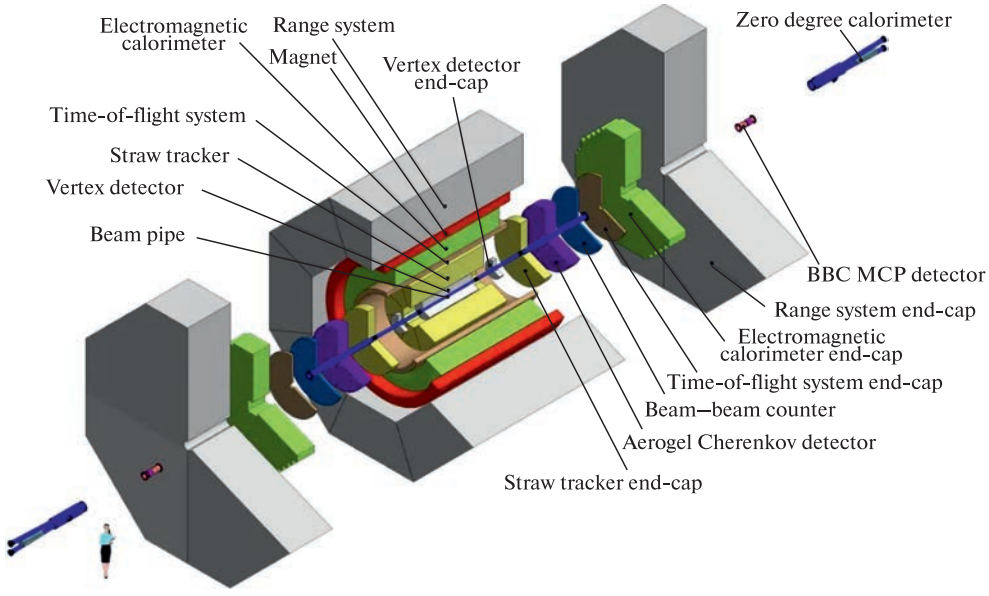


Fig. 25. Scheme of the SPD facility

tal facility. A series of thematic conferences DSPIN (Dubna) and SPIN-Praha (Czech Republic) played a major role to develop the SPD project. In 2018, under the leadership of R. Tsenov, preparation of the conceptual design of the detector began, and by 2021 the physics program of the experiment was finalized. In the summer of 2021, the international SPD collaboration was formed, with A. V. Guskov (JINR) and V. T. Kim (PNPI) elected as co-leaders. In 2024, the technical design

of the SPD detector[30] underwent an independent international review and was approved by the JINR management. The work on this voluminous and complex document was coordinated by JINR staff members G. D. Alekseev, V. A. Anosov, L. G. Afanasyev, A. A. Baldin, O. P. Gavrishchuk, A. V. Guskov, D. V. Dedovich, I. I. Denisenko, T. L. Enik, A. S. Zhemchugov, N. I. Zamyatin, G. D. Kekelidze, A. Yu. Korzenev, A. V. Kulikov, V. P. Ladygin, D. N. Nikiforov, D. A. Oleynik, V. V. Tereshchenko, H. G. Khodzhibagiyan, and V. B. Chmil.

The SPD project (Fig. 25) is currently in the preparatory stage of developing subsystems for the first phase of the experiment. The work is underway both in JINR laboratories and at participating institutes. New research teams are joining the international collaboration. The groundwork laid provides confidence in the successful implementation of ambitious plans.

EXPERIMENTS AT THE LARGE HADRON COLLIDER

The Large Hadron Collider (LHC), operating at CERN (Geneva, Switzerland) since 2009, is the largest and most powerful accelerator ever built. Its operation and the results it produces have been the main hopes of particle and fundamental interactions physics in recent decades. The physics programs of the two largest multipurpose experiments at the LHC — ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) — are aimed at solving such high-priority problems as confirming the mechanism of electroweak symmetry breaking, testing the Standard Model of particle interactions and finding ways to unify three fundamental interactions, solving the problem of baryogenesis and the mass hierarchy of elementary particles, searching for candidate particles for dark matter, and many others. In addition, the physics program of experiments includes a whole range of research aimed at studying the laws of interaction of nuclei at high energies, research into a new state of nuclear matter — quark-gluon plasma, and much more.

The multipurpose ATLAS and CMS detectors at the Large Hadron Collider were built primarily to discover the Higgs boson and study its properties, as well as to search for "new" physics beyond the Standard Model (SM). The first objective was successfully achieved: the Higgs boson was discovered in 2012, but a detailed study of its properties and the search for "new" physics require hundreds of times more data.

THE ATLAS EXPERIMENT

The list of authors of the Letter of Intent (CERN/LHCC/92-4) for the multipurpose ATLAS experiment at the LHC, published in October 1992, already included 50 participants from JINR. The JINR staff contributed to the creation of *all* detector systems of the ATLAS facility. Only a few countries and major research

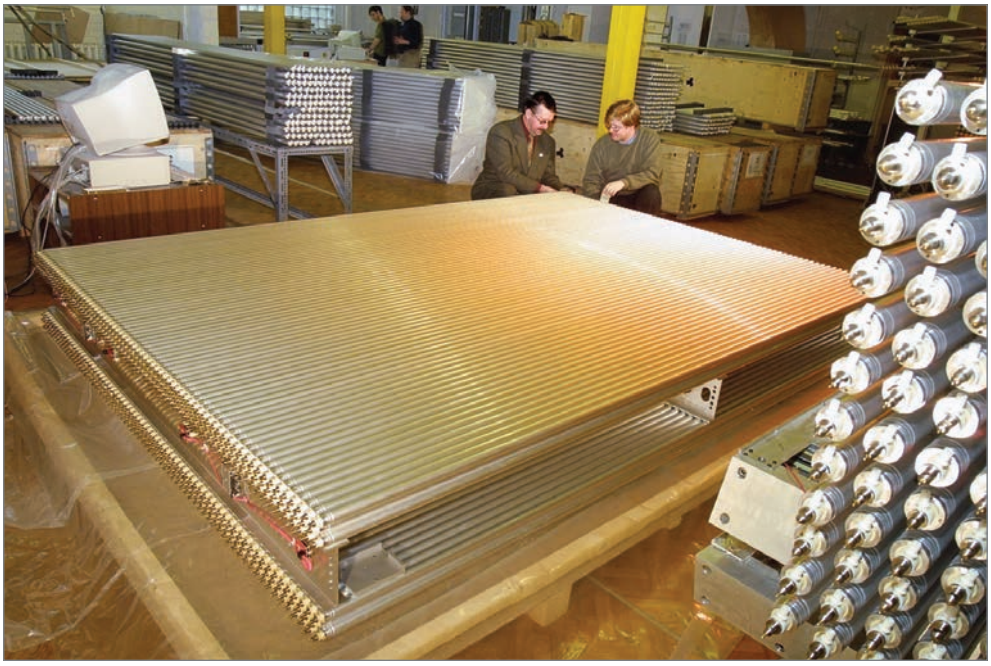
[30] *Abazov V. et al. (SPD Collab.)*. Technical Design Report of the Spin Physics Detector at NICA // Natural Sci. Rev. 2024. Iss. 1. 1.

centers could afford this. Development of the magnetic system, muon spectrometer, and trigger system of ATLAS, the hadron scintillation calorimeter, the liquid-argon hadron calorimeter, and the straw-tube transition radiation tracker are among the most significant JINR contributions.

Participation in the creation of the muon system

The staff of the Dzhelepov Laboratory of Nuclear Problems joined during the design phase of the ATLAS facility. During discussions at CERN about the optimal design for the ATLAS muon detector system, G. D. Alekseev proposed using drift tubes with increased operating gas pressure as coordinate detectors for this system. Increasing the operating gas pressure in a drift detector improves its coordinate resolution. To convince colleagues, a prototype of such a detector was quickly manufactured and beam-tested at DLNP (Z. V. Krumstein, G. A. Shelkov). The results were so persuasive that the collaboration adopted this design as the primary one to make coordinate detectors for the ATLAS muon system.

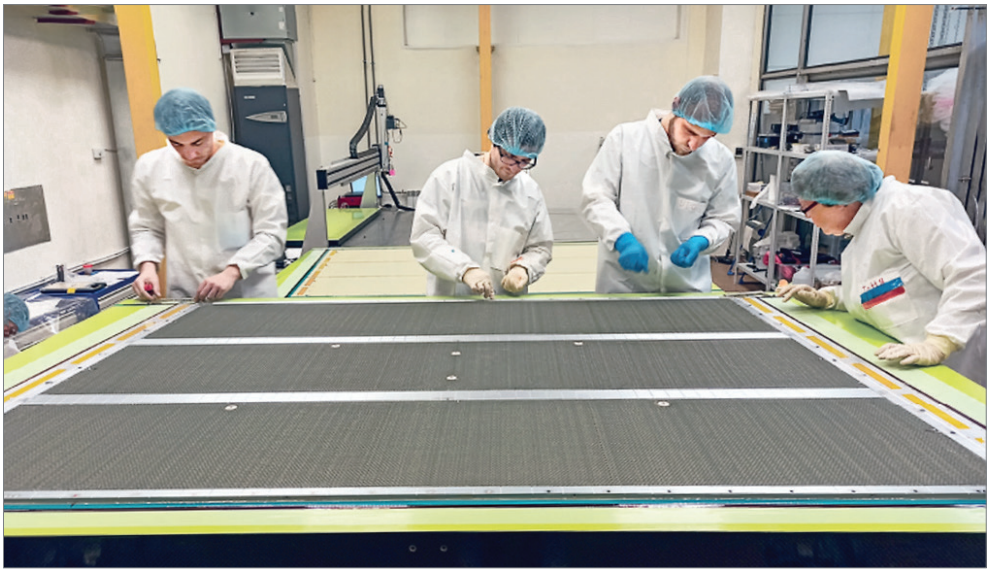
The ATLAS muon system required the production of 1200 muon chambers of various geometries, consisting of approximately 400 000 individual drift tubes. The DLNP JINR team was responsible for the manufacture of approximately 65 000 individual drift detectors (approximately 16% of the total quantity) for its 86 BMS and BMF muon chambers and BOS/F chambers assembled at MPI (Munich). The facility to manufacture and test both individual detectors and complete BMS/F chambers was located in the building that once housed the best Soviet computer, the BESM-6. These detectors are still operating reliably in the facility.



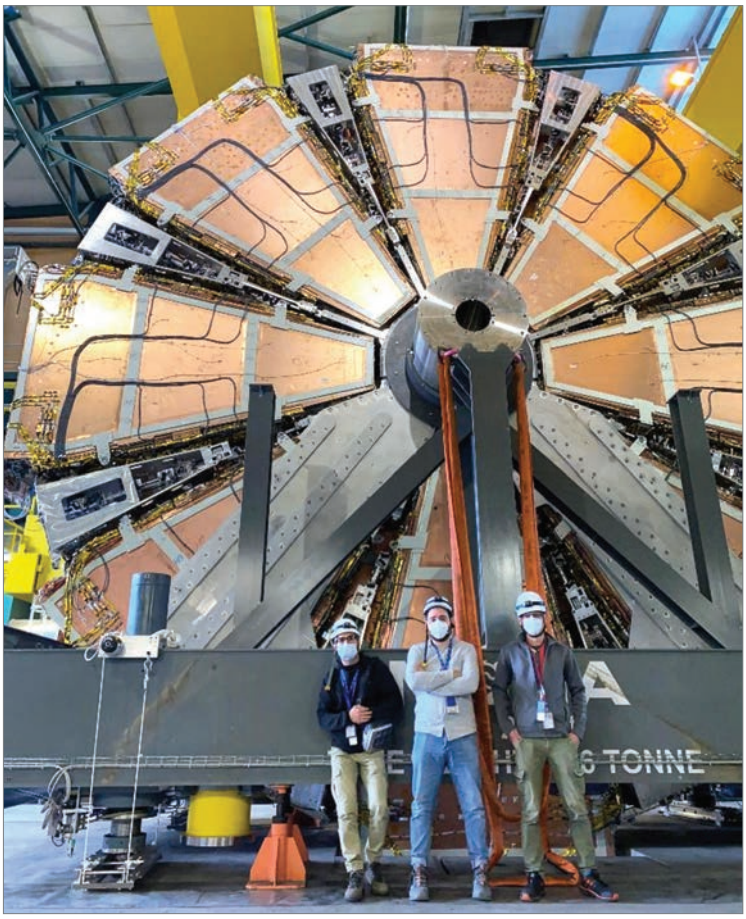
G. A. Shelkov and A. V. Guskov are preparing the next in turn muon chamber for shipment to CERN



Installation of the first BMS chamber, manufactured at DLNP JINR, into the ATLAS detector



Micromegas readout panel production. Left to right: R. V. Sotenskii, L. A. Gongadze, I. V. Liashko, T. O. Rudenko



Staff of DLNP DCB in front of the NSW "A" before its lowering into the shaft of the ATLAS experiment. CERN, July 2021. Left to right: L. A. Gongadze, B. Buadze, I. Minashvili

Active participation in the ATLAS upgrade continued following the discovery of the Higgs boson and the completion of the first phase of the LHC operation. To accommodate the increased radiation loads and enhance background suppression in the first-level trigger, it was necessary to replace (phase 1 of the upgrade) the existing muon and cathode strip chambers on the most heavily loaded inner end sections of the muon spectrometer (the so-called Small Wheels) with faster-response Micromegas chambers with a resistive coating.

The production and testing areas for Micromegas detectors for the ATLAS New Small Wheels (NSW) were prepared as a result of significant development and supplying the ATLAS muon chamber areas with new modern equipment.

The Muon Group of the DLNP Department of Colliding Beams (DCB) was responsible for the production and testing of Micromegas modules for the exterior of large NSW sectors. All 64 (plus two spare) readout panels and 32 Micromegas modules/quadruplets (plus one additional module) based on them, with a total



A group of employees of DCB DLNP participating in the upgrade of the ATLAS NSW at the site for the production of Micromegas readout panels

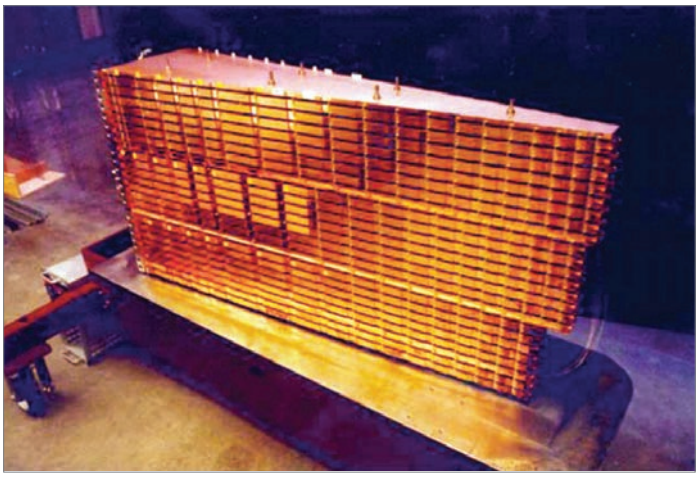
active area of 384 m^2 out of the 1200 m^2 allocated for the entire NSW, were to be produced and tested at JINR. The group successfully completed the task, and the manufactured Micromegas modules are currently operating smoothly in the ATLAS shaft.

In addition to the Micromegas detector production and testing site for the ATLAS NSW, DLNP JINR made the first full-cycle production facility in Russia for Micromegas detectors. It enables the development, manufacture, and certification of detectors of various configurations, tailored to specific task requirements. An example is the development of a cylindrical central detector based on Micromegas for the SPD NICA experiment. The technology has been refined and the first cylindrical prototype has been constructed.

Participation in the construction of a liquid-argon calorimeter

One of the important areas of work was the research and development of new calorimetry methods with liquid argon as the active medium. V. V. Kukhtin was appointed head of the JINR Liquid Argon Calorimetry Group at ATLAS. The JINR Liquid Argon Calorimetry Group included employees of four laboratories (LSHE, DLNP, FLNP, and FLNR) and worked in the following areas: component manufacturing, assembly, and beam testing of hadron end-cap calorimeter (HEC) modules; study of the radiation resistance of various structural materials and readout electronics of liquid argon calorimeters; study of changes in the purity of liquid argon under the influence of neutron and gamma-ray irradiation of the detector; development and manufacture of HEC front-end readout electronics elements; development and creation of a system to measure the temperature of liquid argon in a cryostat; simulation of physical processes.

M. Yu. Kazarinov supervised the fabrication of the ATLAS detector's liquid argon hadron calorimeter modules. The primary financial contribution of JINR



Full-scale module of the HEC liquid argon hadron calorimeter

was purchasing 80 t of copper sheet for the 25-mm-thick absorber plates. JINR assembled and tested one-third of the calorimeter modules and transported them to CERN, where, with the participation of JINR staff, the incoming modules were inspected and tested on the secondary particle beams of the SPS accelerator. The manufacture of the HEC wheels was the result of the joint efforts of six teams from Canada, four from Germany, three from Russia, and one from Slovakia. A mandatory step in this process included the fabrication of a full-scale prototype module and a "module 0". This approach ensured identical manufacturing practices across all laboratories, as confirmed by "cold" cryostat tests on test beams at CERN. In 1998, the construction of both the prototype and "module 0" was completed at JINR.

That same year, a clean room for assembling serial modules of the end-cap hadron calorimeter was prepared at DLNP JINR. The calorimeter's absorbers, made of pure copper, were manufactured at the JINR Experimental Workshop and at the Minsk MZOR plant in Belarus between 1999 and 2002. The modules were assembled at JINR, and the first serial module was sent to CERN in 1999. Twenty-five serial calorimeter modules — approximately 40% of the total number — were assembled at JINR. A. N. Lazarev, S. Shilov, A. B. Neganov, S. I. Kakurin, E. V. Serochkin, I. L. Pisarev, and A. Fedorov actively participated in this work.

JINR staff members also participated in runs on the secondary beams of the SPS accelerator to study the physical characteristics of the manufactured calorimeter modules. This demonstrated identity of the modules and their compliance with the design requirements.

Degussa PT100 platinum temperature sensors were selected to develop the liquid argon temperature measurement system (headed by Yu. A. Usov). Calibrating the sensors on a dedicated testbed improved the temperature measurement accuracy by an order of magnitude (up to 10 mK). Seven hundred calibrated sensors were selected, placed in two end-cap cryostats and electromagnetic calorimeters, and used in the ATLAS general cryogenics systems. V. I. Datskov, V. M. Drobin,

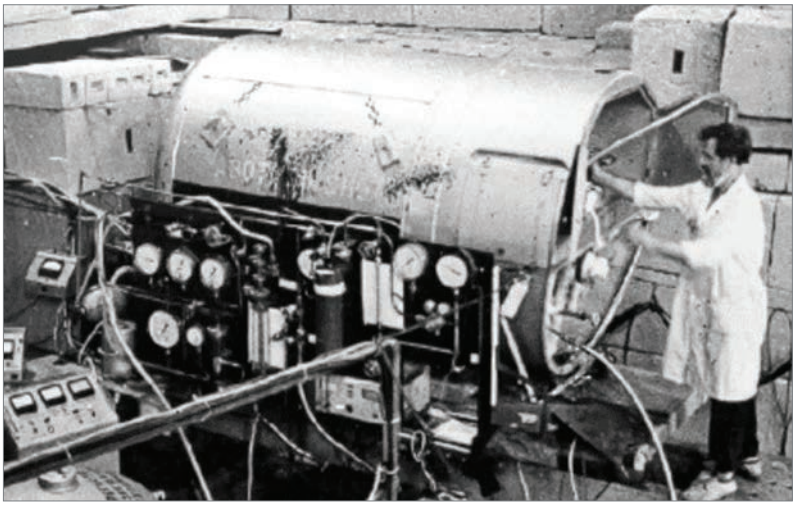
V. V. Kukhtin, A. B. Neganov, L. V. Petrova, and A. N. Fedorov contributed to the development of the liquid argon temperature measurement system.

To measure the calorimeter signal, special preamplifiers were developed in collaboration with colleagues from the Max Planck Institute for Physics (MPI, Munich, Germany) to operate under high background radiation conditions in a cryostat without free access for replacement when necessary. Along with the preamplifiers, the first prototypes of amplifier-shapers for the hadron calorimeter readout electronics were developed, manufactured, and tested (led by E. A. Ladygin). An electronic circuit to compensate for changes in the capacitance of the liquid argon calorimeter readout electrodes was developed, and 200 channels of electronic circuits for the pre-shapers were manufactured and mounted on circuit boards located along the outer radius of the calorimeter. A. A. Karev and V. P. Obudovsky also participated in this work.

Research of the properties of electronics began in 1993 and was carried out using high-intensity beams from pulsed fast-neutron reactors at FLNP JINR. A radiation resistance study of GaAs-based readout electronics components was performed, and various structural material for the ATLAS detector's liquid argon calorimetry was certified at neutron fluences of up to $7 \cdot 10^{16}$ cm^{-2} and associated γ doses of up to 300 kGy.

These studies showed that changes in the electronics and mechanical properties of the calorimeter electrodes caused by the total neutron and gamma-ray flux over 10 years of operation would not exceed the permissible 20%, which could be taken into account by appropriate calibration algorithms. This is supported by the results of a specially performed simulation of the expected degradation of the calorimetric signal based on the data obtained in radiation tests.

During the research, potential contamination of liquid argon caused by radiation damage to the calorimeter materials in the cryostat was tested. A special cryo-



Part of the facility for testing radiation resistance of elements of the ATLAS liquid argon calorimetry at the IBR-2 reactor. E. N. Kulagin (FLNP) checks cryogenic communications. 1998

genic facility was manufactured with the participation of L. B. Golovanov's group. The purity of liquid argon before and after irradiation was analyzed using an ionization chamber. It was shown that the level of contamination of liquid argon with electronegative impurities at high neutron fluence did not exceed 2 ppm.

Following the launch of the ATLAS experiment at the LHC, radiation tests of various detector components continued for subsequent upgrading the facility.

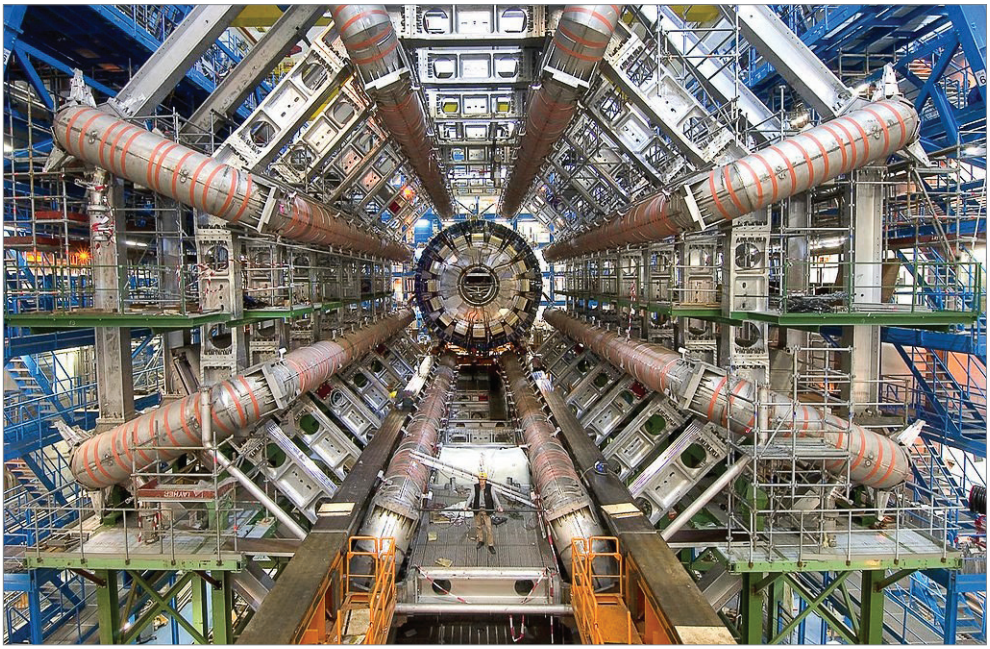
The FLNP employees V. V. Golikov, E. N. Kulagin, V. I. Lushchikov, E. P. Shabalin, M. V. Bulavin, DLNP employees A. N. Shalyugin and A. Lazarev, FLNR employee A. M. Rodin, VBLHEP employees S. M. Golubykh, N. A. Javadov, V. V. Kukhtin, E. A. Ladygin, V. F. Minashkin, V. P. Obudovsky, D. Salikhagich, and A. P. Cheplakov (work coordinator) made significant contributions to the successful implementation of the radiation tests. Considerable assistance in the implementation of the irradiation program was provided by F. Dydak, H. Oberlack (Germany), and C. Leroy (Canada).

The magnetic system

JINR staff made a significant contribution to the development of the ATLAS magnetic system, which includes a superconducting solenoid for the inner tracking system and a large "air toroid", whose magnetic field is generated by eight superconducting rings symmetrically positioned outside the calorimeter system, plus two end-cap toroids. The central solenoid magnet is relatively small (2.5 m in diameter and 5.3 m long), while the central toroid rings are the largest (over 25 m long), and the end-cap toroids are the heaviest (approximately 100 t). All magnets in the system were superconducting; they were manufactured one by one on the surface in a large experimental hall, tested, lowered into the shaft, and finally installed in the underground hall at a depth of 100 m.

The practical implementation of the toroidal magnetic system of the ATLAS facility became a top-priority task, for which a collaboration was established with key participants from CERN, JINR, CEA (Saclay, France), the Oxford Laboratory (UK), and LASA (Italy). It also included other institutes and companies which manufactured individual toroid components. This priority was determined by the fact that the toroidal system had to be assembled first, and all other ATLAS systems would be successively attached to its mechanical "warm structure". This work, in which the staff from JINR laboratories and the Experimental Workshop (initially approximately 25 technicians and engineers) played a significant role, became the JINR primary mission in 1998. Preparatory work began at CERN with the test facility for the assembled toroids, where the magnetic core manufactured in Dubna, simulating the magnetic field inside the ATLAS facility, was delivered and installed. This allowed one to test the assembled toroids under conditions as close as possible to the real ones.

The main work on toroid assembly began in 2002 with the production of a 25-m traverse at the JINR Experimental Workshop, which was used to move the toroids with minimal permissible deformation. A large number of various jacks and adjustable stands were also manufactured, on which large toroid components were mounted for further installation. Subsequently, the Experimental Workshop man-



Superconducting magnetic toroids in the ATLAS facility

ufactured and delivered to CERN numerous unique tools for magnet assembly, including devices to lower down the central toroids and various large platforms for assembly in the underground hall.

Considerable effort was made with regard to develop the welding technology for aluminum tubes used to supply liquid helium which cools the so-called cold mass of the toroids and ensures low-temperature superconductivity. The electric current in the toroids must reach 20 kA to generate the designed magnetic field inside the ATLAS facility. Strict quality requirements for the welds, each of them was subjected to X-ray inspection in multiple planes, were set to provide long-term operation of the toroids without access to the cooling lines within them.

After the central toroids were manufactured and tested, the intense process of installing them in the underground hall began. Overall, the work was completed in 2004–2005 in a record-breaking period of 13 months, with the mechanical structure elements arriving from Russia and Belarus virtually online while assemblying. During this period, materials delivered to CERN in over 60 heavy-load trucks were customs-cleared, accepted, unloaded, and quickly dispatched to the facility.

Work on the end-cap magnets continued in parallel. They were also assembled, tested, and lowered down into the underground hall on schedule, that allowed one to install all other detector subsystems in accordance with the overall ATLAS assembly plan.

This work was highly praised by the collaboration, and JINR, along with such giants as INTEL and ORACLE, was awarded a special ATLAS Prize. As P. Jenni (leader of the collaboration during the construction of the facility) emphasized at the conference in Montenegro in 2017, “JINR played a really fantastic role in the



Transporting an end-cap magnet to the ATLAS shaft

implementation of the toroidal magnetic system of the ATLAS facility". H. Ten Kate, head of the Magnetic Project, also stated there: "The creation, adjustment, launch, control, and upgrade of the ATLAS magnetic system was an exceptionally successful joint undertaking by the ATLAS collaboration and JINR". Significant contributions to this truly successful and important work were made by V. I. Danilov, N. P. Danilov, N. I. Zimin (leader of the JINR part), M. V. Kulikov, A. A. Lyubimtsev, and approximately 100 other employees of the JINR Experimental Workshop and laboratories.

It was the Dubna team, which showed an excellent performance when developing the ATLAS magnetic system, that was asked to install the safety valves when an accident due to problems with safe release of helium from the accelerator's superconducting magnet cooling system occurred during the LHC launch. This work was carried out both on the surface and in the LHC underground tunnel in unspoken competition with colleagues from Spain and Poland. Ultimately, the JINR team was selected to participate in the upgrade of superconducting magnets and superconducting compounds (SMACC) during the extended shutdown of the LS1 collider in 2013–2014. Six hundred and twelve emergency pressure relief valves were installed on more than half of the LHC dipole magnets, which today ensure the reliable and safe operation of the collider.

Following the completion of the ATLAS installation and commissioning, JINR continues to participate in its operation, upgrade, and research. This includes developing software for control and operating of the vacuum system, electrical circuits, sensor development, etc. JINR staff regularly participate in the opening and closing the facility in the ATLAS shaft during the winter shutdowns of the LHC.



Welding work to install emergency pressure relief valves in the LHC tunnel

Inner detector

The team from VBLHEP headed by V. D. Peshekhonov made a significant contribution to the development and construction of the transition radiation tracker (TRT) used in the ATLAS inner detector. JINR employees performed the research and development on thin-walled drift tubes and methods to read out information from them, participated in the development and testing of a prototype of the transition radiation detector — a tracker based on these tubes — and in the full-scale assembly of this detector, which is also used to identify electrons.

The group was responsible for the production of the ring submodules for the TRT and performed work on reinforcing straw tubes installed in the barrel and end-cap sections of the full-scale TRT. To fulfill these responsibilities, Class 10 000 cleanrooms with a total area of approximately 250 m^2 and a height of 7–8 m were prepared and equipped. Approximately 608 km of carbon fiber threads were glued to the straw tubes, and totally 91 993 straw tubes were reinforced, accounting for more than 50% of the total TRT requirements. Overall, 110 127 37-cm-long straw tubes and 45 062 49.7-cm-long straw tubes were manufactured at JINR.

Participation in physical research

New event detection and reconstruction systems, new algorithms to collect and process unprecedentedly large volumes of data have allowed the ATLAS facility to achieve the highest sensitivity and accuracy of experimental research since the commissioning of the collider.

The Higgs boson was discovered by the ATLAS and CMS experiments in 2012, and the primary experimental goal of these detectors was thus achieved after just two years of active data collection. Dubna physicists made a significant contribution to the first-ever studies dedicated to the physics of the Higgs boson, in par-

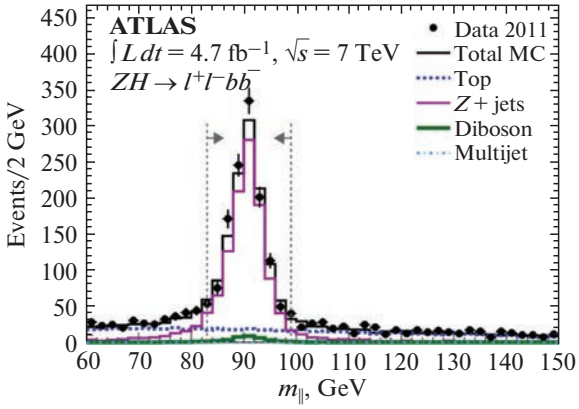


Fig. 26. First observation of the Higgs boson production in association with Z bosons in the two b-quarks decay channel

ticular, the first observations of the Higgs boson production[31] in association with gauge bosons (Fig. 26).

Even before the commissioning of the Large Hadron Collider (1994–2007), JINR staff were actively engaged in research into the physics of the Higgs boson, modeling its production processes in proton–proton collisions, and reconstructing potential decays in the detector. One of the first works was carried out by I. R. Boyko, K. V. Nikolaev, and G. A. Shelkov, dedicated to study the Higgs boson in decays to four muons based on a full simulation of the ATLAS facility[32], and the potential to detect the Higgs boson in the decay channel to a Z boson and a gamma-photon. During this period, active work was done to predict possible manifestations of physics beyond the Standard Model and their detection at ATLAS. A proposal was made to search for chiral bosons at the LHC using the ATLAS facility[33], a number of opportunities to detect supersymmetric particles were studied[34], and a detailed analysis of the prospects to study top quarks with the ATLAS facility was performed[35].

The results of numerous new experimental studies performed with the participation of JINR staff began to be actively published with the start of data collection. Experimental limits on the parameters of chiral Z^* bosons proposed in Dubna were obtained in their decays into pairs of leptons[36], and some of the first constraints on the parameters of supersymmetric particles[37] at the LHC were published (Fig. 27).

Precision measurements of the Standard Model parameters, as well as upgrade of detector reconstruction algorithms and improved modeling of experimentally observed processes, have become an important area of physical research. Exam-

[31] *ATLAS Collab.* // Phys. Lett. B. 2012. V. 718. P. 369–390.
[32] *Boyko I. R., Nikolaev K. V., Shelkov G. A.* // Part. Nucl., Lett. 2005. V. 2, No. 2(125). P. 7–20.
[33] *Chizhov M. V., Bednyakov V. A., Budagov Yu. A.* // Phys. At. Nucl. 2008. V. 71, No. 11.
[34] *Bednyakov V. A. et al.* // Phys. Part. Nucl. Lett. 2008. V. 5, No. 6. P. 520–530.
[35] *Khramov E. V. et al.* // Part. Nucl. 2008. V. 39, No. 1. P. 217–242.
[36] *ATLAS Collab.* // JHEP. 2012. V. 1211. P. 138.
[37] *ATLAS Collab.* // Phys. Rev. D. 2012. V. 86. 092002.

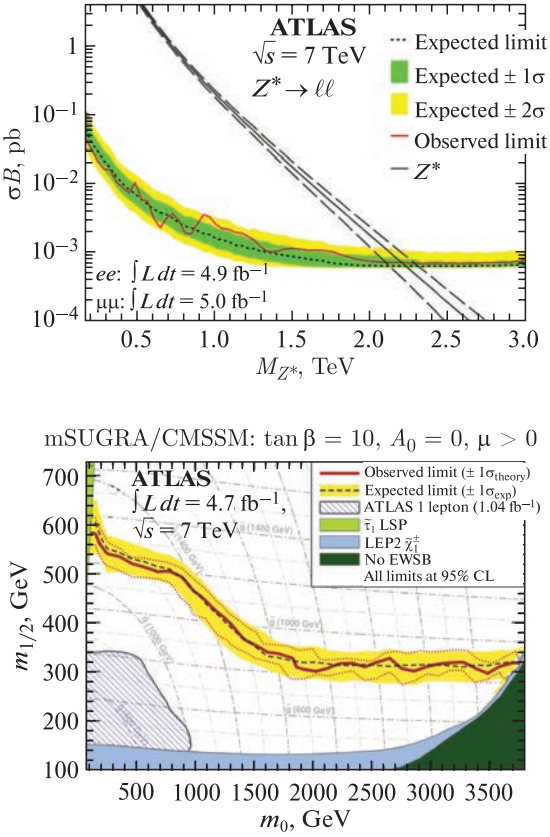


Fig. 27. Experimental limits on the admissible cross sections and masses of chiral Z bosons, the models of which were proposed at JINR (top); constraints on the parameters of supersymmetric particles (bottom)*

ples of such work include measuring parameters of Bose–Einstein correlations in high-multiplicity hadron track events[38], measuring production cross sections of charm and beauty hadrons and their properties[39], and measuring differential cross sections of gauge bosons in heavy-jet coproduction processes[40].

During several stages of the ATLAS upgrade (in 2013–2014 and 2019–2021), it became possible to further improve the reconstruction accuracy, the efficiency of selecting events of interest for physical analysis, and the stability of operation under high-intensity proton–proton beams. This significantly increased the measurement accuracy, in particular, demonstrating good agreement between the Higgs boson parameters and the values predicted by the Standard Model. JINR staff members obtained new results in measuring Yukawa interactions with heavy quarks and Higgs boson production cross sections in gluon or vector gauge boson

[38] *ATLAS Collab.* // Eur. Phys. J. C. 2015. V. 75. P. 466.
[39] *ATLAS Collab.* // Nucl. Phys. B. 2016. V. 97. P. 717–763; Phys. Lett. B. 2015. V. 751. P. 63–80.
[40] *ATLAS Collab.* //JHEP. 2020. V. 2020.07. 044.

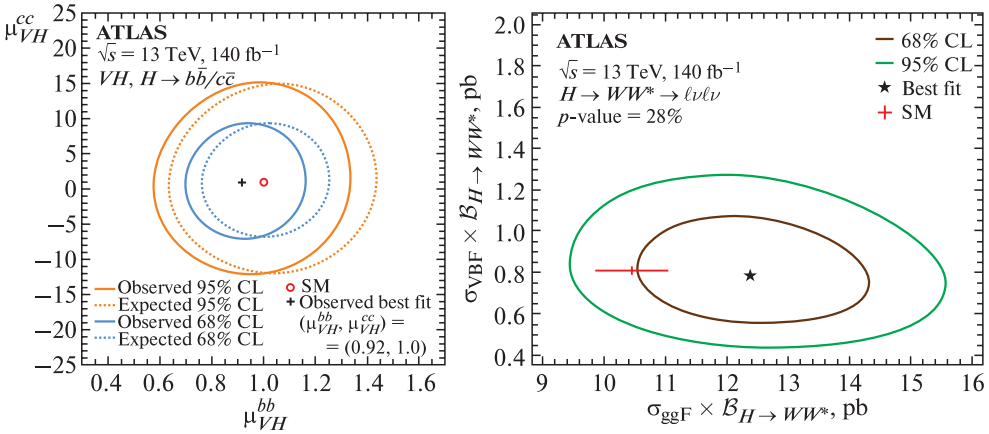


Fig. 28. Measurements of the observed values of the Higgs boson coupling with beauty and charm quarks (left), measurements of the cross sections of Higgs boson production in gluon or gauge boson fusion processes (right)

fusion processes (Fig. 28)[41]. They proposed a number of new kinematic variables which improved the efficiency of signal event selection in the channel with the decay of the Higgs boson into two *b*-jets as part of a study of the Yukawa interaction of top quarks by measuring the associated production of Higgs bosons with top quarks[42]. In addition, deep machine learning models were used to select events, and a number of new methods to optimize these algorithms were developed.

Although a number of previously popular theoretical extensions of the Standard Model have been in fact excluded by experiments at the LHC, the search for "new" physics at ATLAS, with the participation of JINR, continues actively. Using the latest experimental data, searches for quantum black holes in proton–proton collisions[43] were carried out, and new limits on their masses were obtained (Fig. 29). The opportunity of deviations from the Standard Model in the $W/Z/H$ boson and gamma-quantum decay channel was investigated[44].

The JINR team is actively studying the properties and spectra of beauty hadrons and light states, including searching for and measuring the properties of pentaquark and tetraquark states[45]. The parameters of two pentaquark states ($P_c(4380)$, $P_c(4450)$) have been measured in the $\Lambda_b^0 \to J/\psi Kp$ decays. A number of new data analysis methods have been proposed to increase sensitivity to the parameters of exotic states, and directions for further research on exotic hadrons at the ATLAS facility have been identified.

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[41] *ATLAS Collab.* // Eur. Phys. J. C. 2021. V. 81. P. 178; JHEP. 2025. V. 2025.04.075; Phys. Rev. D. 2023. V. 108. 032005.

[42] *Boyko I. R. et al.* // Part. Nucl., Lett. 2024. V. 21, No. 3. P. 592–603;
Boyko I. et al. // Phys. Part. Nucl. Lett. 2024. V. 21, No. 4. P. 615–618.

[43] *ATLAS Collab.* // Phys. Rev. D. 2024. V. 109. 032010.

[44] *ATLAS Collab.* // Phys. Rev. Lett. 2020. V. 125. 251802; JHEP. 2023. V. 2023.07.125.

[45] *Yeletskikh I. (ATLAS Collab.)* // Proc. 18th Intern. Conf. on B-Physics at Frontier Machines. PoS. 2020. V. 377; doi.org/10.22323/1.377.0010;
ATLAS Collab. // Phys. Rev. Lett. 2023. V. 131. 151902.

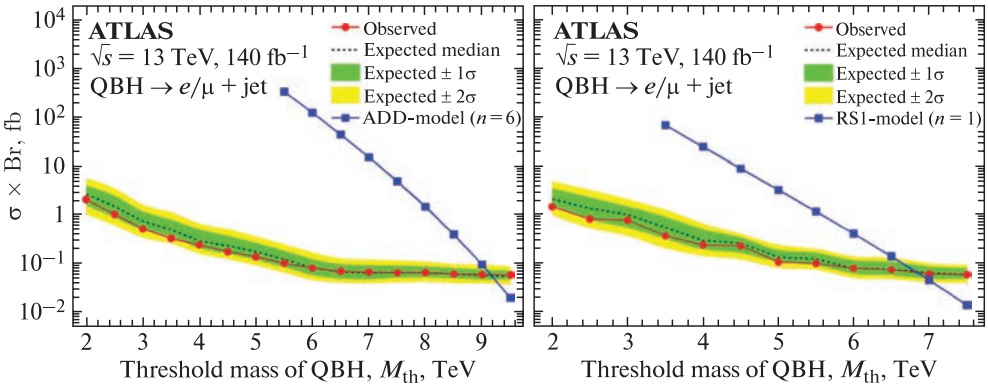


Fig. 29. Constraints on the cross sections and masses of quantum black holes for the Arkani—Dimopoulos—Dvali (left) and Randall—Sundrum (right) models

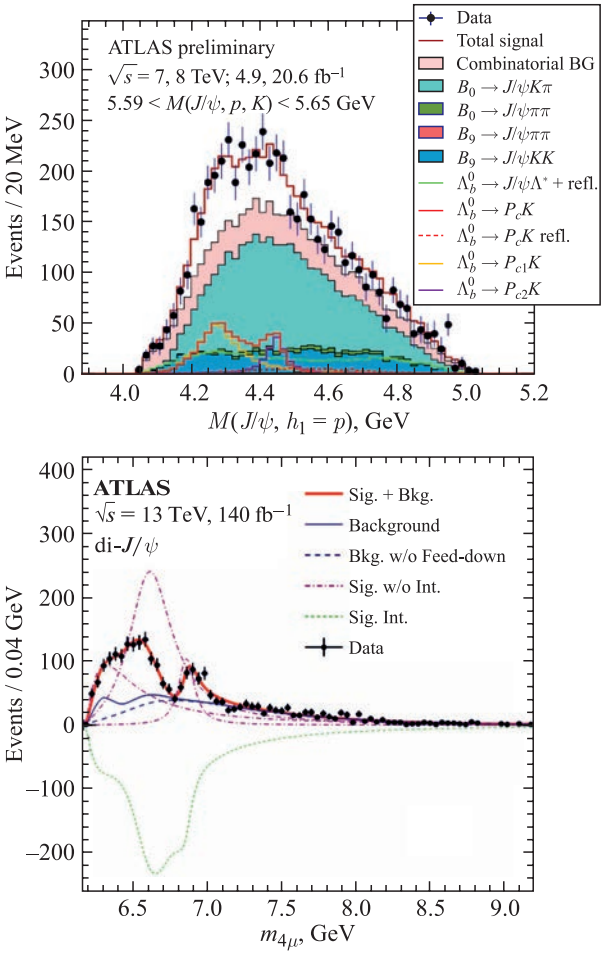


Fig. 30. Observation of pentaquark states with hidden charm (top) and fully charmed tetraquarks (bottom)



A. V. Gladyshev, I. Minashvili, T. S. Donskova, A. B. Arbuzov, D. V. Fursaev, M. Lavrova, T. V. Lyubushkina, A. V. Bednyakov at the ESHEP-2017 school

New resonances were discovered in the two J/ψ mesons or a J/ψ–$\psi(2S)$ pair decay channel with the participation of JINR physicists. These resonances are consistent with the hypothesis of the existence of fully charmed tetraquarks (Fig. 30).

The joint organization of schools for students and young scientists dedicated to physical research at the LHC has long been a good tradition between JINR and CERN.

The decisive contribution of JINR staff to the ATLAS experiment software, the operation of the facility, and the provision of safe working conditions is worth noting.

The experience gained over more than 30 years of JINR's participation in the ATLAS experiment — in detector design and upgrade, simulation, and data analysis — is actively used in other JINR projects.

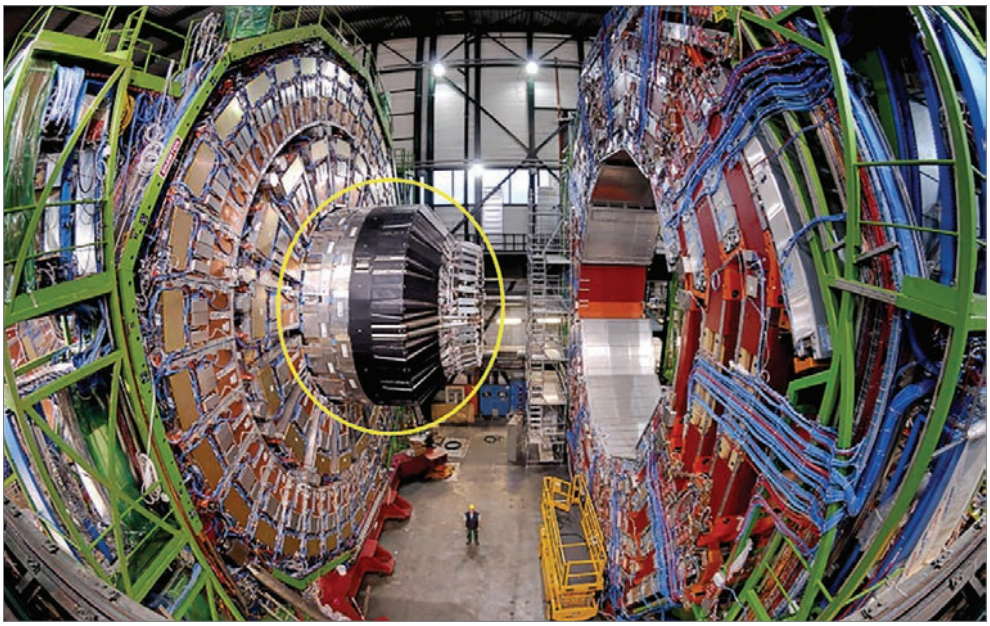
THE CMS EXPERIMENT

The Compact Muon Solenoid (CMS) — multipurpose detector at the Large Hadron Collider — was designed to perform comprehensive research in particle physics to understand the fundamental laws of nature. It is one of the two largest high-energy physics experimental facilities ever built, bringing together scientists and engineers from 210 scientific organizations in 48 countries.

Physicists from VBLHEP JINR have been participating in the CMS project since 1992, when the concept of the experiment was proposed and the Letter of Intent was signed.

In September 1994, the leading scientific centers of Russia participating in the CMS project, JINR and a number of JINR Member States united into the collaboration called RDMS (Russia Dubna Member States) and gathered more than 300 scientists and specialists from 20 institutes from seven countries. I. A. Golutvin became the Scientific Leader of the RDMS collaboration, and V. A. Matveev became the Chairman of the collaboration council. This form of participation in the CMS experiment allowed for the pooling of scientific, technical, and financial contributions from individual institutes and the involvement of industry from participating countries. RDMS institutes, in cooperation with CMS research centers, made a decisive contribution to develop the detectors for the internal end-cap systems of the CMS experimental facility (marked in the photo), including the Forward Hadron Calorimeter (HF), the Forward Shielding (FS), the End-Cap Muon System (ME), the End-Cap Electromagnetic Calorimeter (EE), and the Preshower Detector (ES). RDMS's main efforts were focused on the development of the Hadron Calorimeter (HE) and the Forward Muon Station (ME1/1) systems.

JINR scientists and engineers, together with other RDMS institutes and enterprises, made an invaluable contribution to the design, construction, installation, and commissioning of the end-cap hadron calorimeter, including the production of brass absorber plates and active elements — scintillation megatiles. Overall coordination of the calorimeter construction work was the responsibility of JINR and was carried out under the supervision of I. A. Golutvin. Employees of the N. A. Dollezhal Research and Development Institute of Power Engineering (NIKIET, Moscow), under the supervision of V. P. Smetannikov, were responsible for the design of HCal and its installation in the CMS facility. The calorimeter absorber plates were

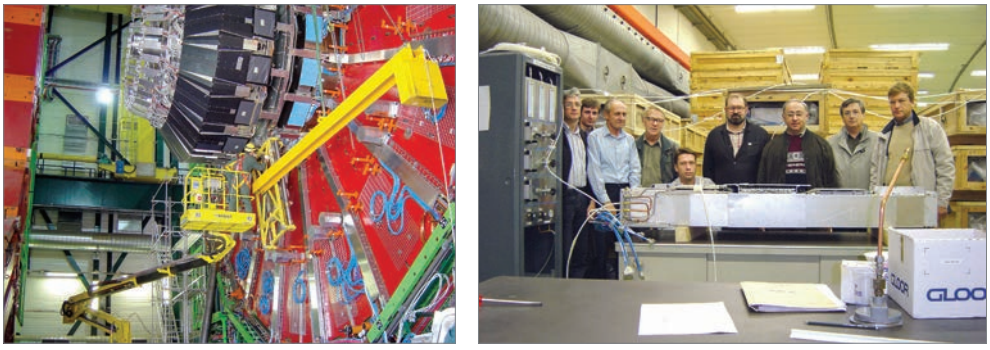


The internal end-cap system of the CMS experimental facility (circled) is the area of responsibility of the RDMS institutes

manufactured at the Izhora Plants in St. Petersburg. Weapons-grade brass, smelted from artillery shells, was used for this. Preliminary assembly of the absorber plates was carried out by employees of the National Scientific and Educational Center for Particle and High Energy Physics under the supervision of N. M. Shumeiko at the October Revolution Plant (MZOR, Minsk) to check their manufacturing accuracy. After checking, the absorber plates were delivered to CERN for installation of the calorimeter in the CMS experimental facility. The calorimeter scintillators were manufactured at the Institute for Single Crystals of the NAS of Ukraine (Kharkov) under the supervision of V. G. Senchishin, and employees of IHEP (Protvino) performed their assembly into megatiles, including quality control and calibration, under the supervision of N. E. Tiurin. Physicists and engineers from JINR and the RDMS institutes took a major part in the assembly and commissioning of the end-cap hadron calorimeter.

JINR assumed full responsibility to develop, manufacture, and install 76 cathode strip chambers (CSC) of the ME1/1 forward station of the CMS end-cap muon system into the CMS experimental facility. The development and manufacture of the chambers at VBLHEP JINR were supervised by Yu. T. Kiryushin. The ME1/1 CMS muon station project was coordinated by V. Yu. Karzhavin. The work was carried out in close collaboration with the RDMS institutes: the National Scientific and Educational Center for Particle and High Energy Physics (NCPHEP, Minsk) under the supervision of N. M. Shumeiko and the High Energy Physics Laboratory (Sofia) under the supervision of I. D. Vankov, whose employees participated in the development of the electronics for the muon detectors.

The ME1/1 forward muon station is one of the most complex parts of the facility. It is located inside a magnetic solenoid in front of an iron yoke in the region of a strong axial magnetic field (~ 3 T). The highest background of secondary particles, up to 1.5 kHz/cm^2, is reached in the station's location area. The coordinate accuracy of the ME1/1 muon station detectors plays a decisive role to provide the required momentum resolution of the CMS muon system. The chambers have the best characteristics in the muon system (spatial resolution ~ 50 μm, time resolution ~ 3 ns), which provides the accuracy of reconstructing the coordinates of the charged muon track and its referencing to the time of the event. The closest location of the ME1/1 chambers to the beam interaction point ensures the stitching of



Installation and testing of the ME1/1 forward muon station chambers

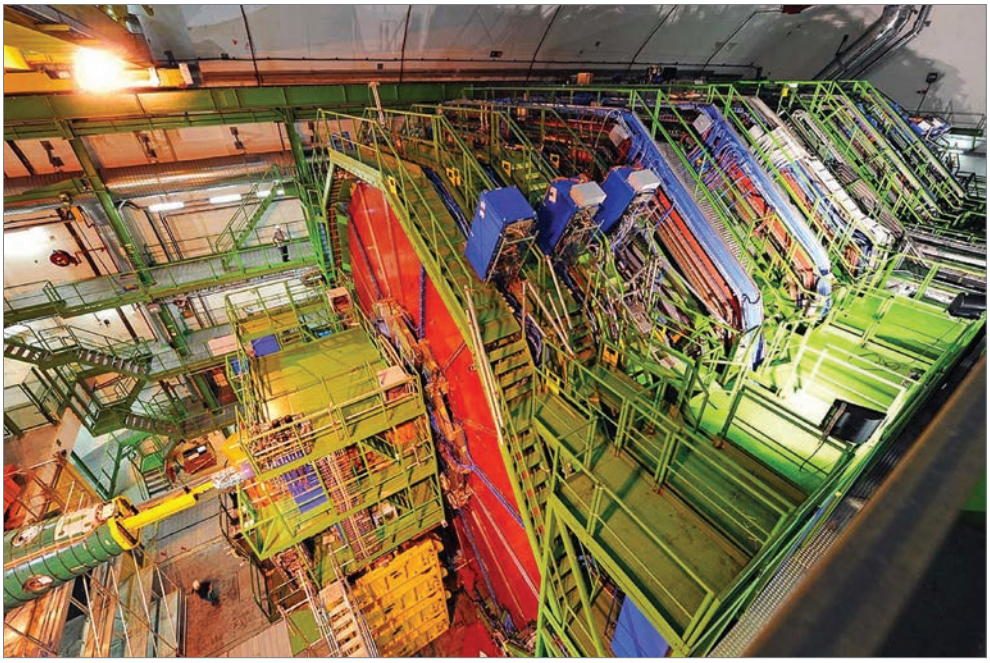
the track parts reconstructed in the muon system and in the tracker, and the extrapolation of the track to the interaction point. The ME1/1 chambers were manufactured at JINR and delivered to CERN, where, after comprehensive testing, they were installed in the CMS detector. The main contribution to develop the detectors was made by the VBLHEP staff: A. O. Golunov, N. V. Gorbunov, Yu. V. Ershov, Yu. T. Kiryushin, V. Yu. Karzhavin, A. M. Kurenkov, S. A. Movchan, P. V. Moisenz, V. V. Perelygin, D. A. Smolin, L. V. Svetov, V. S. Khabarov, S. V. Khabarov, and the staff of the NCPHEP V. A. Chekhovsky and A. V. Solin.

The CMS muon system, and especially the ME1/1 forward muon station detectors, played a key role in the discovery of the Higgs boson decay to four muons ($h_{125} \to ZZ \to 4\mu$), which was a fundamental achievement of the CMS experiment.

By 2008, the CMS facility was fully assembled and tested, moved to the underground experimental hall, mounted and prepared to receive data.

The first stage of LHC operation (LHC Run1) took place in the period 2009–2012 at energy $\sqrt{s} = 7$ and 8 TeV in the center-of-mass system of the colliding protons. A new stage (LHC Run2) at $\sqrt{s} = 13$ TeV started in 2015 and lasted until the second long stop (Long Stop 2, LS2) at the end of 2018. During this time, the integrated luminosity L_{int} of the data recorded in the CMS experiment was 190 fb^{-1}. It is expected that during the Run3 data collection period, until mid-2026, the experimental data statistics corresponding to $L_{\text{int}} \sim 500$ fb^{-1} at $\sqrt{s} = 13.6$ TeV will be obtained.

JINR staff members are actively involved in implementing the physics research program, maintaining the efficient operation of the facility, and performing ex-



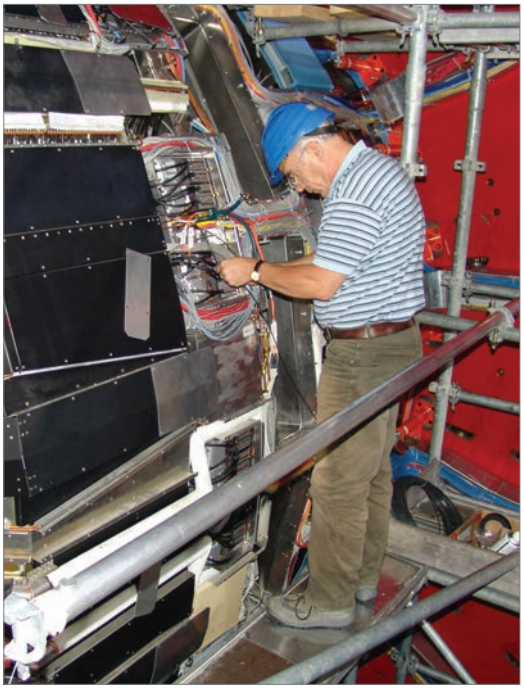
CMS detector subsystems were lowered down into the underground experimental hall for final assembly

perimental data collection runs. During two long technical stops of the LHC in 2013–2015 (LS1) and 2019–2022 (LS2), the CMS experimental setup was upgraded to provide the efficient operation of all systems under the LHC luminosity, which increased to $2 \cdot 10^{34}$ $cm^{-2} \cdot s^{-1}$. The HCal readout electronics system was replaced as part of the hadron calorimetry upgrade, including the replacement of



The chamber test bench (top). The upgrade of the end-cap muon system chambers (bottom)

the multichannel hybrid photodetector (HPD) with a new silicon photomultiplier (SiPM). This significantly increased the efficiency of the calorimeter by reducing noise and increasing the gain, as well as increasing the number of readout channels and adding timing information, which expanded the trigger capabilities of the experiment. The work of the first phase to upgrade the detector systems was carried out under the supervision of A. V. Zarubin. A special contribution to the upgrade of HCAL was made by VBLHEP staff members Yu. V. Ershov, P. D. Bunin, I. A. Golutvin, V. A. Smirnov, A. I. Malakhov, S. V. Afanasyev and NCPHEP staff members N. M. Shumeiko, I. F. Emelyanchik, A. V. Litomin.



Setting up HCAL readout electronics

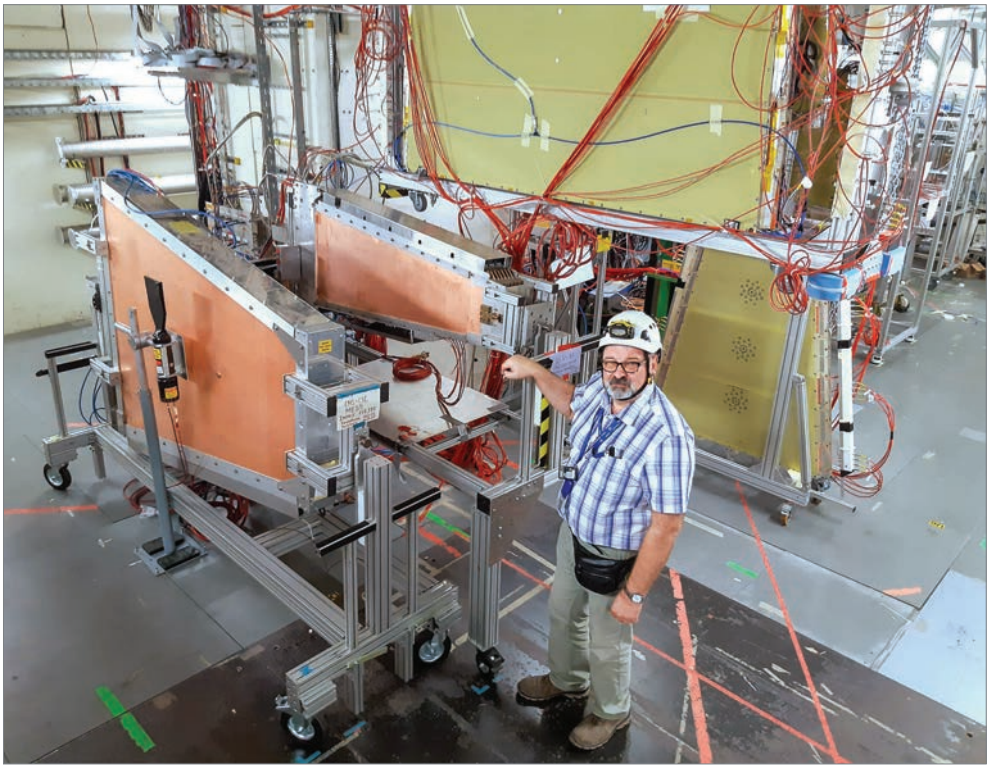
As part of the first phase of the CMS end-cap muon system upgrade, the ME1/1 chambers, located in the high-occupancy area, were also equipped with new, fast readout electronics. Additional readout electronics were installed on the chambers to improve the spatial resolution and increase the triggering efficiency. The second phase of the end-cap muon system upgrade, dedicated to the CMS transition to operation under LHC high-luminosity conditions (phase 2), required replacing the detector electronics of four muon stations: ME1/1, ME2/1, ME3/1, and ME4/1, with fast electronics that operate without dead time. Together with specialists from NCPHEP (Minsk), low voltage distribution and control modules for on-chamber electronics and the automated board setup bench were developed and manufactured, the cooling system for ME1/1 chambers was replaced, and the assembly, installation, and parameter testing of 180 chambers of the end-cap muon system were completed.

The analysis of experimental data showed stable and efficient operation of the CMS end-cap detectors. The CSC spatial resolution values obtained in proton–proton collisions during Run3 (2024) are in good agreement with the Run2 data (2018), indicating the stability of the detectors. The main contribution to the upgrade of the end-cap muon system was made by VBLHEP JINR staff members A. O. Golunov, N. V. Gorbunov, N. N. Evdokimov, Yu. V. Ershov, V. Yu. Karzhavin, A. Yu. Kamenev, A. M. Kurenkov, A. M. Makankin, S. E. Vasiliev, V. V. Perelygin, and NCPHEP staff members V. A. Chekhovsky, A. V. Kunz, Ya. D. Galkin.

Starting from 2030, the LHC will operate at high luminosity, up to $7 \cdot 10^{34}$ $cm^{-2} \cdot s^{-1}$ (High Luminosity LHC, HL-LHC phase), which will increase the statistics by more than one order, to $L_{int} \sim 3000$ fb^{-1}. This will significantly increase the sensitivity of the facility to various physical processes and research channels. During the third long-term stop LS3 (2026–2029), the second phase of the CMS upgrade is planned, the goal of which is to provide the efficient operation of all systems under the HL-LHC conditions. JINR's obligations at this stage of the upgrade include participation in the construction of the High-Granularity Calorimeter (HGCal) and the upgrade of the detectors of the CMS end-cap muon system. The work on the second phase of the CMS detector upgrade is carried out under the overall supervision of V. Yu. Karzhavin.

The results of research carried out by the JINR group to study the physical characteristics of the muon chambers to test their stability and efficiency under heavy loads with increasing LHC luminosity are of great importance at this stage of the facility upgrade. The effect of radiation aging of the detectors is being studied to assess the degradation of their parameters with increasing radiation load. The research is being performed at CERN at the GIF++ facility, where the chambers are irradiated in the H4 channel of the SPS accelerator muon beam and using a ^{137}Cs gamma source with an activity of 12 TBq. The research results show that degradation of the chamber characteristics is not observed at a charge of 890 μC accumulated per centimeter of the anode wire length, which is three times higher than the value expected for detector operation in the high-luminosity mode of the HL-LHC. The main contribution to the study of the characteristics of the detectors when operating under conditions of heavy loads expected in the high-luminosity mode was made by VBLHEP employees V. V. Perelygin, A. O. Golunov, A. Yu. Kamenev, and V. V. Palichik (MLIT).

The JINR team is participating in the construction of a High-Granularity Calorimeter (HGCal) as part of the CMS preparation for the HL-LHC operation mode. The JINR team is working on a test bench to verify the performance of the HGCal cassettes, which house the sensor elements. The cassettes will be tested under realistic conditions at the temperature of −30°C using cosmic rays. JINR has constructed two thermally insulated chambers to accommodate the racks containing the cassettes being tested. Scintillation trigger planes measuring 2.4×3.0 m are located on the top and bottom of the thermally insulated chamber. The main contribution to the development and construction of the test bench was made by VBLHEP employees S. V. Afanasyev, A. O. Golunov, N. V. Gorbunov, Yu. V. Ershov, A. I. Malakhov, V. Yu. Aleksakhin, P. D. Bunin, E. V. Sukhov, V. V. Ustinov in



The ME1/1 and ME1/2 chambers at CERN's GIF++ facility

cooperation with employees of Yerevan Physics Institute (Yerevan) under the leadership of A. Tumasyan.

JINR researchers have been actively involved in the development and implementation of the physical research program at CMS from the very beginning of the preparation of the experiment. Scientists from four JINR Laboratories (VBLHEP, MLIT, BLTP, DLNP) and institutes from seven JINR Member States (Armenia, Belarus, Bulgaria, Georgia, Czech Republic, Uzbekistan, Ukraine) were involved in the program at various stages.

Researchers from JINR and JINR Member States (Dubna Member States, DMS) in collaboration with Russian institutes continue to make remarkable contribution to the discovery and study of the Higgs boson properties in the decay channels into two neutral gauge bosons $h_{125} \to ZZ \to 4l$, the search for "new" physics, precision measurements of the Standard Model (SM) parameters, the study of QCD processes and heavy-ion interactions. Significant efforts were focused on the development of methods and software for online and offline selection and reconstruction of muons and muon pairs in the unique energy range up to several teraelectronvolts, techniques for studying and accounting experimental and theoretical systematic effects in the registration of muon pair production processes and QCD jets, as well as on calculations and simulation of physical processes and detector systems.

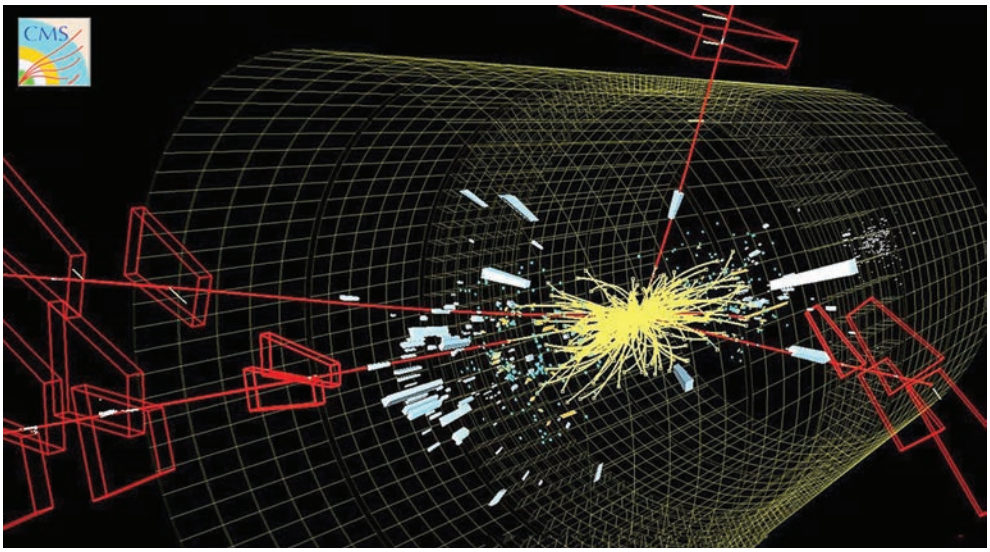


Bench for testing the performance and monitoring the characteristics of HGCal cassettes

It is especially worth mentioning the contribution of the teams of Yerevan Physics Institute (Armenia) under the supervision of A. Sirunyan and, subsequently, A. Tumasyan, the Institute of Nuclear Problems of the Belarusian State University (INP BSU, Belarus) under the direction of N. M. Shumeiko and then V. V. Makarenko, the Institute of Nuclear Physics of the Academy of Sciences of Uzbekistan under the leadership of B. S. Yuldashev. The preparation, implementation, and development of the program of JINR and JINR Member States participation in CMS research were managed and coordinated by S. V. Shmatov. An invaluable role in the formation of the JINR physics program in CMS was played by A. A. Belkov, I. M. Gramenitsky, I. A. Golutvin, V. F. Konoplyanikov, V. A. Matveev, and M. V. Savina.

One of the key areas of physical analysis, in which JINR scientists have been actively involved for over 20 years, is the study of the production and properties of muon pairs. This research became a priority for physicists from JINR and its Member States in the CMS experiment. It has brought together more than 70 DMS scientists including recognized specialists in theoretical elementary particle physics and quantum field theory, experts on data processing and analysis, elaboration of modern algorithms of reconstruction and selection of elementary particles, as well as detector technologies and methods of modern computing in high energy physics.

This study is of fundamental importance to test the Standard Model and search for "new" physics. The systematic study of processes involving high-energy muons (muons with large transverse momenta) in the final state was launched by JINR researchers on the initiative of I. A. Golutvin, V. F. Konoplyanikov, and S. V. Shmatov. The first justifications for this research were presented by V. V. Pa-



An example of a "golden" event of the Higgs boson decay into four muons (one muon in the cylindrical part of the muon system and three muons in the end part)

lichik, M. V. Savina, and S. V. Shmatov. The proposed program is an experimental development of revolutionary theoretical ideas on the quark-gluon structure of matter and the concept of asymptotic freedom of quarks, proposed in the works of N. N. Bogoliubov, B. V. Struminsky, A. N. Tavkhelidze, as well as Han, Nambu, and Miyamoto with the theory of color degrees of freedom of quarks. The works of V. A. Matveev, R. M. Muradyan, S. Drell and Tung-Mow Yan were focused on the theoretical description of the processes of lepton pair production at high energies. Later, in 2003–2009, a program was developed to search for signals of "new" physics beyond the SM in theories with extra spatial dimensions and with an extended gauge sector and to test the predictions of the Standard Model by measuring the characteristics of the Drell–Yan process. I. G. Altsybeev, I. I. Belotelov, V. F. Konoplyanikov, A. V. Lanyov, P. V. Moisenz, G. A. Ososkov, V. V. Palichik, M. V. Savina, O. V. Teryaev, and S. V. Shmatov made a decisive contribution to the preparation of the CMS Physics TDR (PhTDR). The role of a group of theoreticians from the INP BSU and the F. Skorina Gomel State University under the leadership of N. M. Shumeiko was invaluable. The results of their calculations of QCD and EW corrections of higher orders to muon pair production processes, always performed at a world-class level, became an integral part of the physical analysis and final results of the experiment. At different times the group included E. V. Dydyshko, V. L. Ermolchik, V. A. Zykunov, V. V. Makarenko, V. A. Mosolov, and J. Suarez.

The research has progressed rapidly following the launch of the LHC and the beginning of data taking. Over the fifteen years from 2010 to 2025, the data from the groundbreaking study at proton collision energy of 7, 8, and 13 TeV from the LHC Run1 and Run2 yielded new, unique results on the elementary particle interactions. These include the discovery and detailed study of the Higgs boson in the decay channel to four muons, the measurement of paired muon production processes

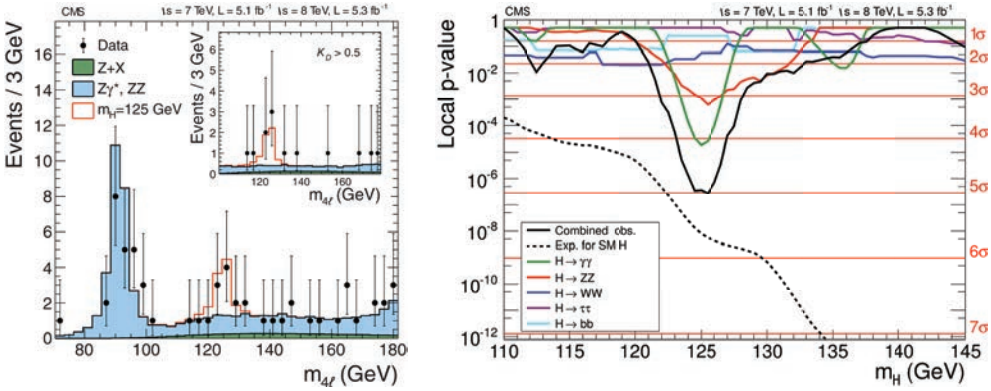


Fig. 31. Left: the first observation of Higgs boson in the $h \to ZZ \to 4l$ decay: distribution of the four-lepton invariant mass; right: the observed local p-value for the five decay modes and the overall combination as a function of the SM Higgs boson mass

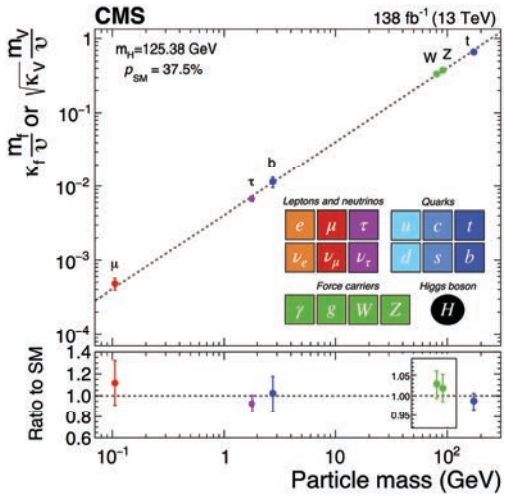


Fig. 32. Testing the universality of Higgs boson interactions: summary of the CMS measurements of the Higgs boson couplings to the other fundamental particles

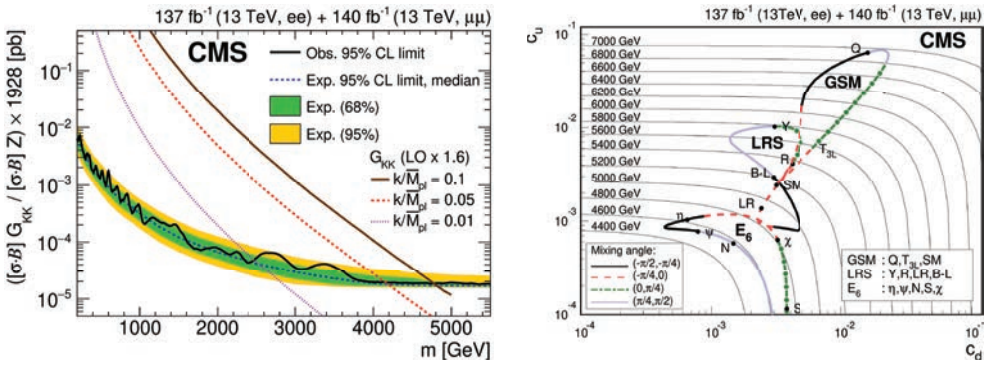


Fig. 33. Experimental constraints on the allowed cross sections, coupling constants, and masses of new resonances predicted by scenarios with extra spatial dimensions (left) and extended gauge models (right)

with record-breaking precision and the investigation of polarization phenomena in these processes, the establishment of unique model-independent constraints on the cross sections of physical processes beyond the SM, and fundamentally new experimental constraints on the model parameters of theories with extended gauge and Higgs sectors, strong gravity and extra dimensions, and candidate particles for "dark matter". V. Yu. Aleksakhin, D. V. Budkovsky, N. N. Voytishin, M. G. Gavrilenko, I. N. Gorbunov, I. A. Zhizhin, A. V. Lanyov, V. V. Palichik, V. V. Shalaev, and S. G. Shulga also made significant contributions to these results. Starting in 2021, the research program underwent a new development: traditional muon-pair signals began to be used to search for new scalar states predicted by non-minimal Higgs models and candidate particles for "dark matter". With this aim, the production of muon pairs began to be considered in channels of associated production with missing transverse energy. Within several years, world results were obtained, which were among the key results of JINR research in 2023–2025. At present, this direction is considered the most promising one and includes a group of specialists from JINR (Yu. V. Korsakov, O. L. Kodolova, A. N. Nikitenko, M. V. Savina, K. V. Slizhevsky, S. V. Shmatov) and a team from A. Alikhanyan National Laboratory (YerPhI) under the leadership of A. Tumasyan.

It is worth noting other areas of research by DMS physicists that have been implemented over the past 20 years. Among them are the study of multiple particle production to test QCD predictions and search for microscopic black holes (the work was initiated by M. V. Savina), the study of particle multiplicity in quark and gluon jets to test hadronization mechanisms (proposal of S. G. Shulga), the study of QCD properties in the process of associated jet and photon production (A. V. Zarubin, O. L. Kodolova, V. F. Konoplyanikov, N. B. Skachkov), and many others.

Achieving world-class results would have been impossible without the construction and continuous operation of the hardware and software environment for data processing and analysis. From the very beginning of the implementation of the physics research program, JINR specialists, under the WLCG (Worldwide LHC Computing Grid) project, have been working to build a grid infrastructure for the coordinated use of computing resources to process large volumes of experimental data. This resulted in the establishment of the Multifunctional Information and Computing Complex (MICC), which includes, among other things, Tier-1 centers for the CMS experiment and Tier-2 centers for a number of other experiments, as well as their integration into the global WLCG grid infrastructure. This titanic work was carried out at the Meshcheryakov Laboratory of Information Technologies under the supervision of V. V. Korenkov. Within the framework of the CMS project, the main contributions were made by N. N. Voytishin, A. O. Golunov, A. G. Dolbilov, I. A. Kashunin, V. V. Mitsyn, D. A. Oleynik, A. Sh. Petrosyan, R. N. Semenov, T. A. Strizh, V. V. Trofimov, and I. A. Filozova.

DMS physicists have made a significant contribution to the results of the CMS collaboration, which were awarded the 2013 European Physical Society Prize in High Energy and Particle Physics (ATLAS and CMS collaborations) and the 2025 Breakthrough Prize in Fundamental Physics (ATLAS, CMS, and LHC-b collaborations). The results obtained have also been recognized with three JINR Prizes and six LPP and VBLHEP JINR Prizes. JINR staff have successfully defended

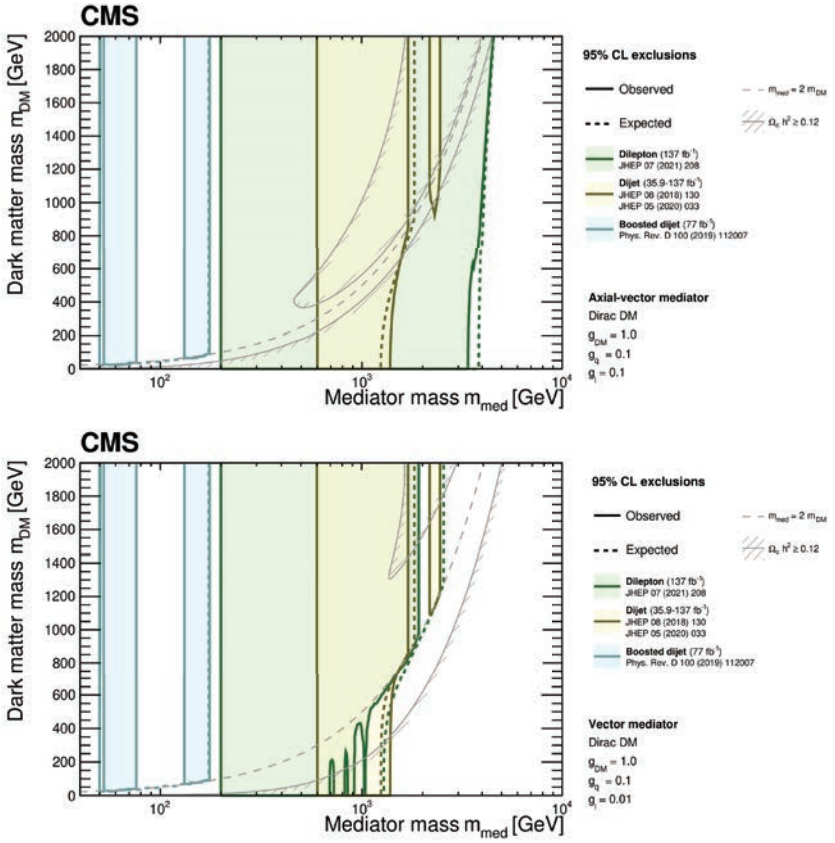


Fig. 34. Experimental constraints on the masses of candidate dark matter particles in scenarios with axial-vector (top) and vector mediators (bottom) between the Standard Model particles and a fermion dark matter

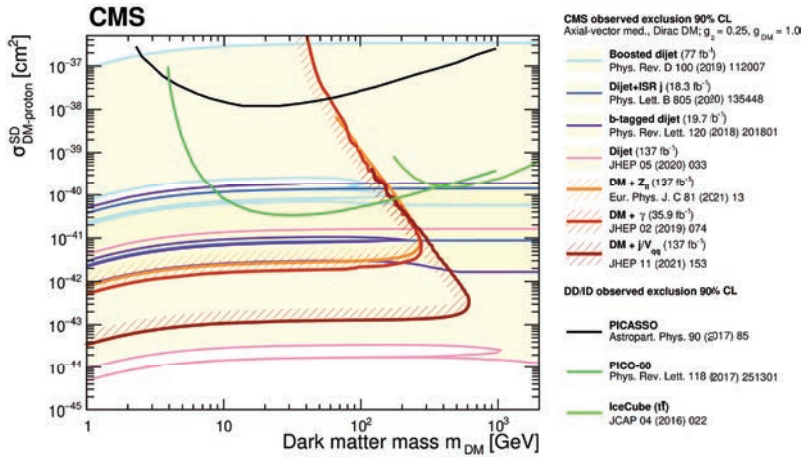


Fig. 35. Experimental constraints on the spin-independent and spin-dependent dark matter-nucleon scattering cross section

four doctoral and eight candidate dissertations and published a number of papers based on the results of research at the CMS facility[46].

THE ALICE EXPERIMENT

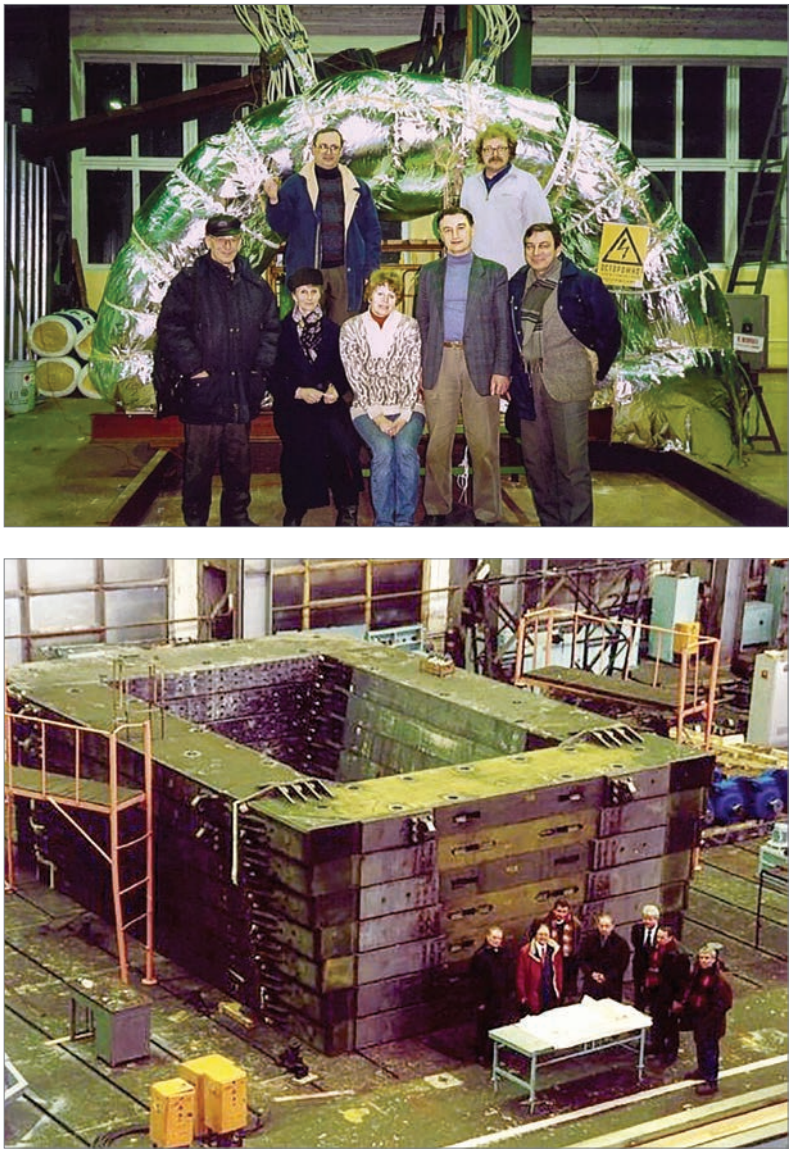
The main contribution of the JINR group to construct of the ALICE detector consisted in developing the technical design of a large dipole magnet for the forward muon spectrometer, developing and manufacturing a prototype winding for a large dipole magnet, developing a working draft for the magnetic circuit of a large dipole magnet and supervising its manufacture at the plant, as well as manufacturing drift chambers for the transition radiation detector and participating in the processing and analysis of experimental data.

In the framework of hydrodynamic models, the compressed strongly interacting system resulting from an $A–A$ collision undergoes longitudinal and transverse expansion, which determines the space–time dimensions of the radiation source of the observed particles. The opportunity of measuring these dimensions through femtoscopic Bose–Einstein correlations for pairs of identical particles was suggested more than 60 years ago and then studied in detail in the 1970s by the Dubna theorists G. I. Kopylov and M. I. Podgoretsky. The JINR group took an active part in these studies in the ALICE experiment at the LHC accelerator, mainly for pairs of charged kaons produced in collisions of particles and nuclei. A three-dimensional analysis of correlations was performed for such pairs, making it possible to study the three components of the radius of the particle emission source — in fact, the spatial shape of the source. Figure 36 shows the dependences of the three components of the radii on the average transverse mass of the particle pair $m_T = (m^2 + k_T^2)^{1/2}$ (m is the particle mass, k_T is the transverse momentum of the pair) for central Pb–Pb interactions at an energy of 2.76 TeV. The coordinate axes are directed: “long” — along the beam, “out” — along the transverse momentum of the pair, “side” — perpendicular to the latter in the transverse plane. The dependence of the ratio $R_{\text{out}}/R_{\text{side}}$ on $\langle m_T \rangle$ is also shown.

It is evident from Fig. 36 that the radii for kaons are noticeably larger than for pions, the m_T values being the same, and the ratios $R_{\text{out}}/R_{\text{side}}$ are close to unity. The lines in the figure represent the results of the prediction of the hydrokinetic model (HKM)[47], in which the dynamics of nuclei interaction includes an initial stage before thermal equilibrium, a prethermalized stage with a transition to an equilibrium quark-gluon plasma, and a stage of particle rescattering in the final state. The

[46] *Chatrchyan S. et al.* The CMS Experiment at the CERN LHC // JINST. 2008. V. 3. S08004;
Chatrchyan S. et al. Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC // Phys. Lett. B. 2012. V. 716. P. 30–61;
Chatrchyan S. et al. A New Boson at a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider // Science. 2012. V. 338, No. 6114. P. 1569–1575;
Chatrchyan S. et al. Evidence for the Direct Decay of the 125 GeV Higgs Boson to Fermions // Nature Phys. 2014. V. 10. P. 557–560;
Tumasyan A. et al. A Portrait of the Higgs Boson by the CMS Experiment Ten Years after the Discovery // Nature. 2022. V. 607. P. 60–68;
Hayrapetyan A. et al. CMS Physics Results from the First Decade of LHC Data // Phys. Rep. 2025. V. 1115. P. 1–772.

[47] *Shapoval V. et al.* // Nucl. Phys. A. 2014. V. 929. P. 1.



Prototype of a large dipole magnet (top) and fabricating the magnet at a plant (bottom)

importance of taking the latter into account is evident from the figure, where good agreement with experiment is achieved in the model taking such rescattering into account (w rescatt.) compared to the version without it (w/o rescatt.). The results obtained have been published[48].

The JINR group also actively participated in the study of ultraperipheral collisions (UPCs) of Pb–Pb with large (greater than the sum of the radii of the nu-

[48] *Acharya S. et al. (ALICE Collab.)* // Phys. Rev. C. 2017. V. 96. 064613.

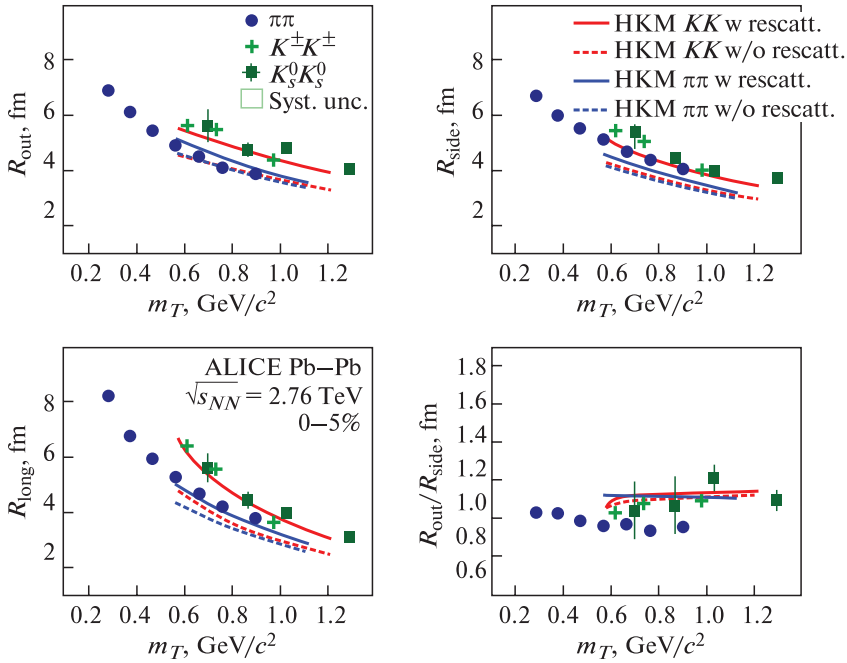


Fig. 36. Dependences of the three components of the particle source radii on the average transverse mass of a pair of particles m_T

clei) impact parameters of the collisions. In such processes, the photoproduction of vector mesons is possible, when a photon from the field of one nucleus fluctuates into a bound quark–antiquark pair (vector meson), which is elastically scattered on the other nucleus.

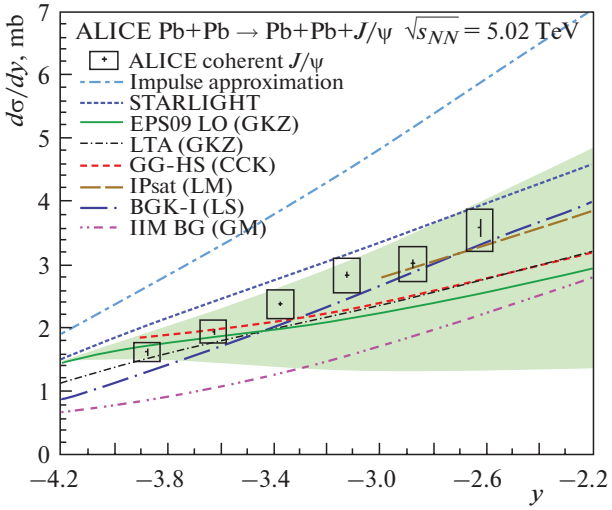


Fig. 37. Cross section of coherent photoproduction of J/ψ in Pb–Pb UPC at the energy of 5.02 TeV depending on the particle velocity

Figure 37 shows the cross section for coherent (scattering on the nucleus as a whole) J/ψ photoproduction in ultraperipheral interactions of lead nuclei at an energy of 5.02 TeV as a function of rapidity. Theoretically, this cross section is related to the function of parton distribution in nuclei and is proportional to the square of the gluon density, which allows for studies of gluon screening in the UPC. The lines in Fig. 37 are the results of predictions of various models. It is evident that the models that take gluon screening into account agree relatively well with the experimental data. The results have been published[49].

LHC DAMPER

The damping system for transverse coherent beam oscillations at the Large Hadron Collider was made within the framework of the joint CERN–JINR project "LHC Damper" [50]. V. P. Sarantsev, the founder of the JINR Department of New Acceleration Methods, and his long-time colleague I. N. Ivanov initiated the proposal for JINR's participation in this project in early 1991. I. A. Savin, who at that time headed the JINR Laboratory of Particle Physics and had a long-standing partnership with CERN, informed C. Rubbia (CERN) of the JINR proposal. D. Boussard (CERN), who at that time headed the CERN Accelerator RF Systems Department, visited Dubna in the summer of 1991 and discussed this initiative with JINR specialists. I. N. Ivanov and V. M. Zhabitsky specified the JINR proposal during their visits to CERN in 1991, taking into account the use of computer technologies in processing digital signals in the negative feedback circuits of the damper and JINR's experience in similar work at IHEP (Protvino) within the framework of the Accelerating-Storage Complex project. CERN specialists accepted the proposal. The project was approved in 1994 within the framework of the CERN–Russia–JINR agreements. Work began to develop unique damper devices under the leadership of T. Linnecar (CERN) and I. N. Ivanov, including 20 electrostatic deflectors designed for operation under ultra-high vacuum conditions and 20 powerful broadband amplifiers. The design, manufacture and commissioning of the damper equipment was completed under the supervision of W. Höfle (CERN) and V. M. Zhabitsky.

The LHC Damper system is used primarily to dampen residual oscillations of charged particle bunches after injection into the LHC. Figure 38 illustrates the damping quality of residual transverse oscillations of a 450-GeV proton bunch.

The damper ensures the stability of high-intensity beams of accelerated particles in the collider with energies from 450 GeV to 7 TeV. The number of bunches can reach 2800. The total kinetic energy of all particles in the beam is approximately 360 MJ. Therefore, even minor beam losses can lead to catastrophic consequences. To avoid particle losses, the coherent displacement of each bunch from its equilibrium state is measured at each revolution in the collider's orbit with a

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[49] *Acharya S. et al. (ALICE Collab.)* // Phys. Lett. B. 2019. V. 798. P. 134926.

[50] *Zhabitsky V. M., Höfle W.* LHC Transverse Feedback System: First Results of Commissioning // JINR News. 2009. No. 2. P. 11–14;

Höfle W. Progress in Transverse Feedbacks and Related Diagnostics for Hadron Machines // Proc. 4th Intern. Part. Accel. Conf. IPAC-2013, 12–17 May 2013, Shanghai, China. JACoW Publ., 2013. P. 3990–3994.

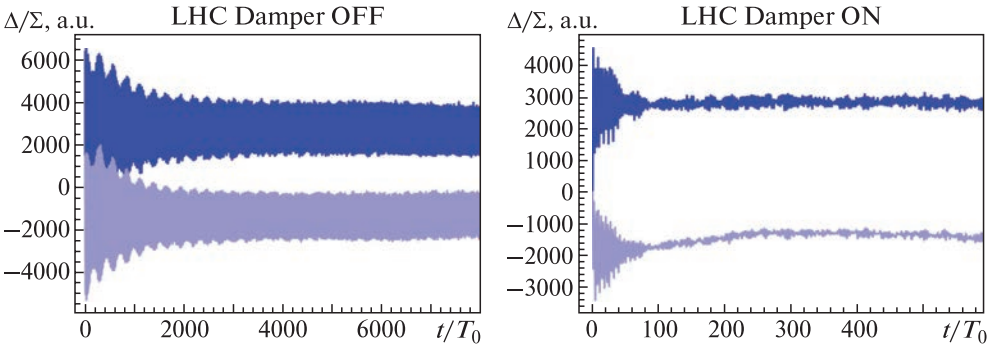


Fig. 38. Example of the LHC Damper system operation

perimeter of approximately 27 km. After one revolution, a corrective high-voltage pulse is generated on the deflector plates, which is synchronized with the moment of measurement of the bunch displacement with approximately 10^{11} protons and with a duration of up to 2.5 ns, following with a periodicity of at least 25 ns. The high-voltage pulse is matched in magnitude to the measured displacement of the bunch (amplitude value up to 11 kV). As a result, the emerging transverse coherent oscillations fade at a rate of approximately 40 revolutions in case of random deviations of the beam, the phase density of the bunch remains unchanged, and the required collider luminosity is achieved for colliding bunches.

The damper is also used to excite transverse particle oscillations during betatron frequency measurements and to remove particles from the accelerator chamber that are incident on the kicker magnet front, which extracts the beam from the accelerator's vacuum chamber. The damper has been successfully used in a mode with positive feedback switching to the negative one when carrying out studies initiating transverse particle oscillations, where a guaranteed rapid return of the beam to its original state with minimal oscillations is required.

In May 2010, a unique vibration damping system, made jointly by CERN and JINR specialists, was debugged on the LHC proton beam and still efficiently performs its functions at the collider during acceleration of protons and lead nuclei. E. V. Gorbachev, V. M. Zhabitsky, N. I. Lebedev, A. A. Makarov, N. V. Pilyar, S. V. Rabtsun (JINR) and W. Höfle, R. Louwerse, E. Montesinos, D. Valuch (CERN) were awarded the JINR First Prize for scientific and methodological work in 2010 to produce and launch powerful damper devices.

Specialists from few countries were willing to take the enormous risk associated with implementing the unique technologies required for fundamentally new systems for the LHC. Damper units were manufactured at Russian enterprises and JINR, including the research and production divisions organized by V. P. Sarantsev, not only in full compliance with the design specifications but also exceeding them. Russian materials were successfully used in the process.

An important result of the scientific and methodological work obtained during the adjustment and start-up of the damper should be noted. It was found that a small shift in the frequency of betatron oscillations occurs when damping transverse coherent oscillations with a noticeable amplitude. It was proposed to use a

resonant damper tuning mode in order to maintain resonant damping of relativistic particles in the collider. In this case, the maximum rate of coherent oscillations damping is ensured in the mode when the coherent frequency of transverse oscillations coincides with the natural betatron frequency. In April 2012, this mode was successfully tested. As a result, the adjustment time of the damping system when changing the collider operating modes was significantly reduced, since the specifications of the adjusted damper coincided with high accuracy with the calculated and theoretical predictions[51].

The particle oscillation damping system at the LHC has been operating reliably and efficiently since May 2010. The design potential allows for the use of new operating modes in accordance with the needs of physicists as the beam intensity and luminosity of LHC increase[52].

OTHER ACCELERATOR EXPERIMENTS

THE COMPASS EXPERIMENT

The COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) experiment is a continuation of a series of experiments at CERN studying the spin structure of the nucleon, such as EMC, NMC, and SMC, using unique polarized muon beams. Approved in 1997, it began data collection in 2002. A long-lived experiment, COMPASS completed its data collection only in 2021.

JINR's contribution to the construction of the COMPASS facility cannot be overestimated. The JINR team in the COMPASS experiment included employees of two laboratories — VBLHEP and DLNP.

The VBLHEP group ensured the development and long-term operation of the hadron calorimeter of the large-angle spectrometer. Yu. F. Kiselev was one of the key figures to build and maintain the unique cryogenic polarized target, and V. A. Anosov served as the project's Chief Engineer for 20 years.

The DLNP group also made a significant contribution to the development and maintenance of operation of the experimental facility. A muon identification system was developed for the large-angle spectrometer under the leadership of G. D. Alekseev. A wide-aperture electromagnetic "shashlik"-type calorimeter was made under the supervision of Z. V. Krumstein in collaboration with the VBLHEP group for the run to measure generalized parton distributions in deep inelastic Compton scattering.

The main results of measuring quark and gluon contributions to the nucleon spin, on the polarization of lambda hyperons, hyperon yields in the deep inelastic scattering reaction, and on measuring the polarizability of a charged pion were obtained with the decisive contribution of the VBLHEP group. Their contribution

[51] *Zhabitsky V. M.* Beam Dynamics in Synchrotrons with Digital Wideband Transverse Feedback // Phys. Part. Nucl. Lett. 2014. V. 45. P. 472–507.

[52] *Höfle W.* Status and Prospects in Fast Beam-Based Feedbacks // Proc. 13th Intern. Part. Accel. Conf. IPAC-2022, 12–17 June 2022, Bangkok, Thailand. JACoW Publ., 2022. P. 3112–3117.

to the development and implementation of a program for studying the polarized Drell–Yan process should be separately noted. Based on the results of this work, four candidate dissertations and one doctoral dissertation were defended by the VBLHEP staff. Twice, in 2007 and 2015, the results of the JINR group's work were recognized with JINR Prizes.

The precision measurement of charged pion polarizability in the charged pion bremsstrahlung in the Coulomb field of a nuclear target in the COMPASS experiment, proposed and carried out by the DLNP group led by A. G. Olshevsky, was a continuation of the pioneering work on measuring pion polarizability performed by DLNP staff at the SIGMA facility (Protvino). This work was awarded the JINR First Prize for 2014 (A. V. Guskov, Z. V. Krumstein, A. G. Olshevsky, and I. A. Savin (VBLHEP)). DLNP staff members carried out the first search for the photoproduction of exotic charmonia and obtained an indication of the existence of a new state. Young staff members also actively participated in studies of dimuon pair production in pion-nucleus interactions, including the Drell–Yan process and the single and pair production of J/ψ mesons. The DLNP researcher B. Parsamyan served as co-head of the COMPASS collaboration from 2021 to 2025. The results obtained during this time were included in three candidate dissertations and one doctoral dissertation.

The research at the COMPASS facility has not been exhausted yet. It continues on the upgraded experimental facility as part of the new AMBER project, in which

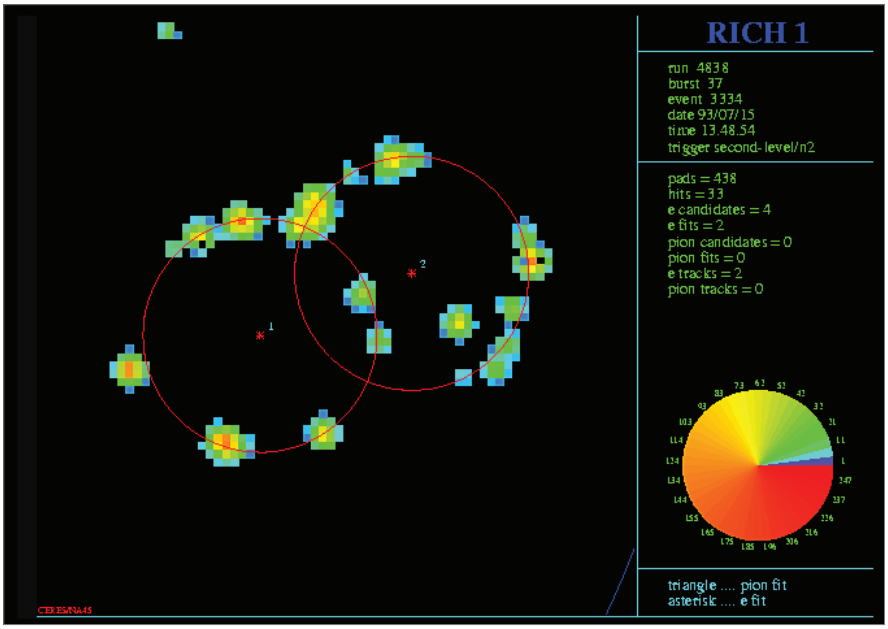


COMPASS experimental facility

the DLNP JINR group, led by A. V. Guskov, plays a leading role, proposing to study the parton structure of kaons and pions in the reaction of direct photon production. The results and experience gained in the COMPASS experiment are being actively used to prepare for the SPD experiment at the NICA collider.

THE NA45/CERES EXPERIMENT

In 1990, the JINR team headed by Yu. A. Panebrattsev began participating in the NA45/CERES experiment at CERN aimed at detecting direct electron–positron pairs formed during the first "hot stage" of nucleus–nucleus collisions. To mitigate the effect of hadron contamination, cutting-edge experimental techniques and technologies were employed to reconstruct Cherenkov radiation rings and interaction vertices using the Ring Image Cherenkov (RICH) detectors and silicon drift chambers. These methods were developed with the active participation of the Laboratory of Information Technologies, supervised by G. A. Ososkov.

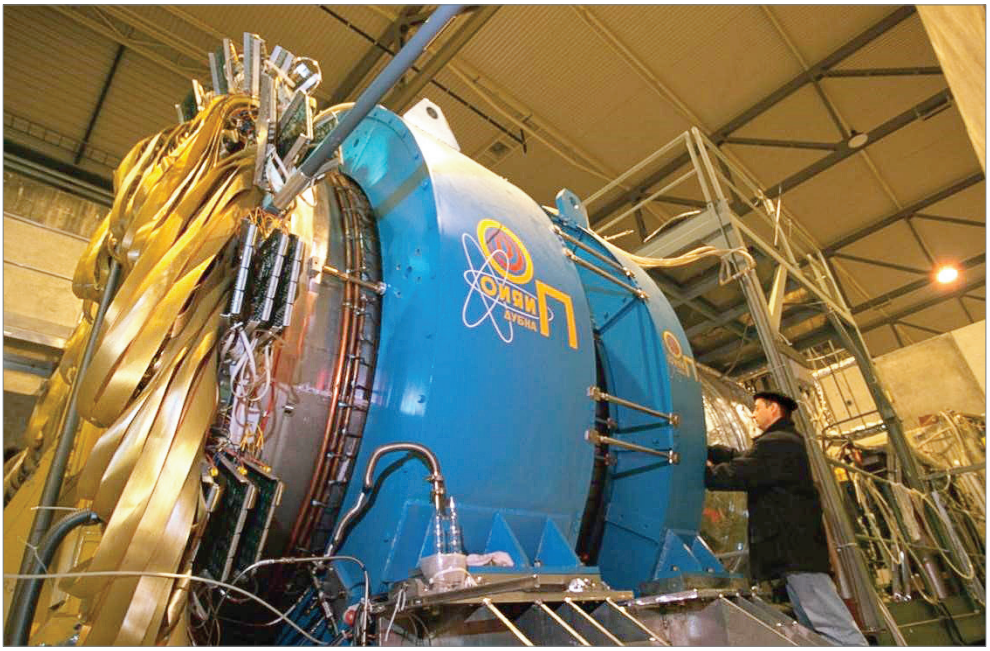


Cherenkov radiation rings in the RICH detector

The data processing methods first implemented in the NA45/CERES experiment were later applied at the STAR and HADES experiments (G. Agakishiev). The JINR team developed a first-level trigger system with event multiplicity selection (V. Yurevich) and a solenoid magnet was constructed at the JINR Experimental Workshop (led by V. Danilov).

The enhancement of electron–positron pairs in Pb + Au interactions at the energy of 158 GeV/nucleon was discovered in the NA45/CERES experiment[53] over

[53] *CERES Collab.* e^+e^--Pair Production in Pb–Au Collisions at 158 GeV per Nucleon // Eur. Phys. J. C. 2005. V. 41. P. 475–513.



The magnet produced at the JINR Experimental Workshop

the reference of neutral meson decay amounts to a factor of 2.31 ± 0.19 (stat.) ± 0.55 (syst.) ± 0.69 (decays) for semi-central collisions (28% σ/σ_{geo}), when yields were integrated over invariant mass $m > 200$ MeV/c^2.

THE NA48, NA48/1, NA48/2, NA62 EXPERIMENTS

Since the late 1990s, a group of JINR staff members led by V. D. Kekelidze has been actively involved in the preparation and execution of a series of experiments (NA48, NA48/1, NA48/2) at the SPS accelerator at CERN to search for direct CP parity violation and study rare kaon decays. The JINR group made a decisive contribution to construct the facility's basic detector, the liquid krypton (LKr) electromagnetic calorimeter to achieve the required experimental characteristics and made an important contribution to the development of a system for monitoring and modeling experimental data[54]. By 2004, a record number of decays of neutral and charged kaons had been registered.

The main result of the NA48 experiment is the measured value of direct CP violation in neutral kaon decays[55]: $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \cdot 10^{-4}$. Thus, the existence of direct CP violation was experimentally proven for the first time. Along with the result of the KTeV experiment (FNAL, USA) published later, this measurement is

[54] *Fanti V. et al.* The Beam and Detector for the NA48 Neutral Kaon CP Violations Experiment at CERN // Nucl. Instr. Meth. A. 2007. V. 574. P. 433–471.

[55] *Batley J. R. et al.* A Precision Measurement of Direct CP Violation in the Decay of Neutral Kaons into Two Pions // Phys. Lett. B. 2002. V. 544. P. 97–112.



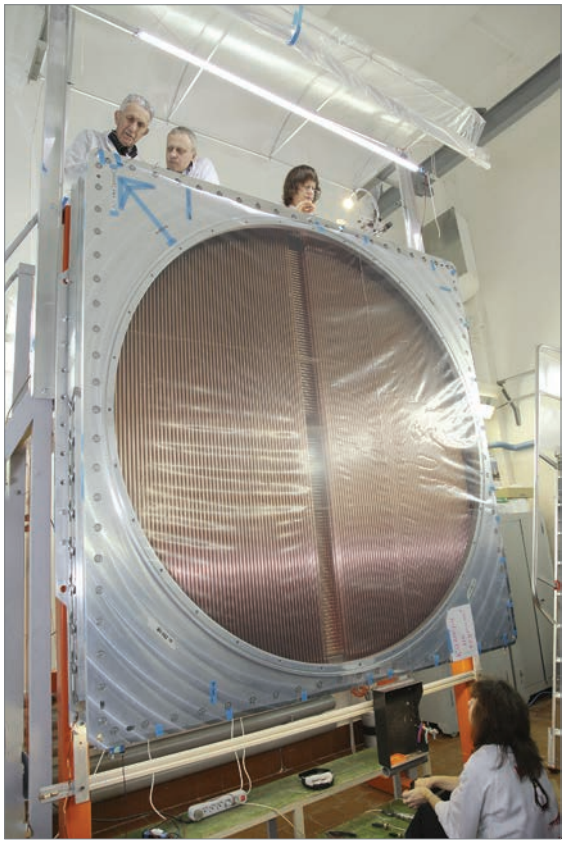

Left: V. D. Kekelidze and INFN work coordinator R. Fabrizio (Italy) at the cryostat of the LKr calorimeter manufactured at the Khrunichev State Research and Production Space Center (Moscow). 1994. Right: working meeting of the NA48 international collaboration. Dubna, 1997

the most accurate to date. The data analysis was carried out in parallel by several groups, including the group of D. T. Madigozhin (JINR).

A number of striking results were obtained in charged kaon decays in the subsequent NA48/2 experiment. The search for direct CP violation in $K^{\pm} \to 3\pi$ decays led to the most precise measurements of the relative difference in the slopes of the Dalitz plots. In $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays, this asymmetry was $(-1.5 \pm 2.1) \cdot 10^{-4}$, and in $K^{+} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays, it was $(1.8 \pm 1.8) \cdot 10^{-4}$, which is consistent with the predictions made on the basis of the Standard Model (SM). The leaders of this physical analysis were E. A. Gudzovsky and S. Balev (JINR). A new physical phenomenon was registered during the study of the $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decay: a spike in the mass spectrum of a pair of neutral pions. Calculations, quickly performed by the renowned theorist N. Cabibbo, led to an explanation of the observed phenomenon by rescattering and charge exchange in the final state of pions from the $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay. A detailed analysis of this phenomenon, carried out with the decisive participation of the group of D. T. Madigozhin (JINR), made it possible to obtain the most accurate measurement of the difference between the pion–pion scattering lengths in isospin states $I = 0$ and $I = 2$. The contribution of electromagnetic effects was calculated by S. R. Gevorkyan, A. V. Tarasov, and O. O. Voskresenskaya (JINR). Taking into account the results of the measurement of the K_{e4} decay form factors, performed in the same experiment, it was possible for the first time to simultaneously measure with high accuracy two pion–pion scattering lengths — the key parameters of the Weinberg chiral perturbation theory (ChPT). This effective theory describes strong interactions at low energies and is intensively used in the modeling of all hadron decays. A number of rare decays were investigated under

the leading role of E. A. Gudzovsky and E. Marinova (JINR). They measured with the highest accuracy the probability of the $K^{\pm} \to \pi^{\pm}e^{+}e^{-}(\gamma)$ decay, equal to $(3.11 \pm 0.12) \cdot 10^{-7}$, and estimated the slope of its form factor $\delta = 2.32 \pm 0.18$; for the decay $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$, the decay probability $(9.62 \pm 0.25) \cdot 10^{-8}$ and the form factor slope $\delta = 3.11 \pm 0.57$ were measured. The decay probability $K^{\pm} \to \pi^{\pm}\gamma\gamma$ was also measured: $(0.910 \pm 0.075) \cdot 10^{-6}$. S. N. Shkarovsky and D. T. Madigozhin most accurately measured the form factors of the semileptonic decays of charged kaons $K^{\pm} \to \pi^{0}e^{\pm}\nu_{e}$ and $K^{\pm} \to \pi^{0}\mu^{\pm}\nu_{\mu}$. With the decisive contribution of M. H. Misheva (JINR), the rare decay $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ was observed for the first time and its probability was measured: $(4.24 \pm 0.14) \cdot 10^{-6}$. The JINR group (A. M. Korotkova and D. T. Madigozhin) was the first to register another rare decay $K^{\pm} \to \pi^{0}\pi^{0}\mu^{\pm}\nu$ and measured its probability: $(3.45 \pm 0.16) \cdot 10^{-6}$. The results are consistent with the calculations of the ChPT[56].

The NA62 experiment was a continuation and development of the NA48/2 experiment in the study of rare decays of charged kaons. Its main objective was to measure the probability of the ultra-rare $K^{+} \to \pi^{+}\nu\nu$ decay using statistics of about



Module of the NA62 spectrometer chamber produced at JINR

[56] *Batley J. R. et al.* First Observation and Study of the $K^{\pm} \to \pi^{0}\pi^{0}\mu^{\pm}\nu$ Decay // JHEP. 2024. V. 03. P. 137.

100 events, which would allow for a highly reliable verification of the validity of the SM. JINR's participation in this experiment was organized by V. D. Kekelidze and Yu. K. Potrebenikov. To achieve this goal, it was necessary to develop a number of new technologies for detector systems capable of operating at high charged particle beam intensities while ensuring minimal background. As a result of many years of development of a unique technology to fabricate thin-walled drift straw tubes operating in vacuum, the NA62 charged particle spectrometer was made by the group of S. A. Movchan (JINR) in collaboration with CERN by 2014. More than ten years of operation of this spectrometer have proven its record-breaking reliability. This technology was further developed in T. L. Enik's group for use in a number of other JINR experiments, including NICA.

The JINR team is involved in the NA62 data taking runs, the development and maintenance of the control system for the entire experiment, and the development of data analysis software. Simultaneously with data taking, the NA62 experiment is carrying out physical analysis of the data. For example, in 2023, the results of the most precise measurement of the probability of radiative decays of $K^+ \to \pi^0 e^+ \nu\gamma$ for three kinematic regions were published. The analysis was performed by two groups, including a team from JINR led by D. T. Madigozhin. Based on the analysis of NA62 data recorded in 2016–2022, an intermediate result was published for the observation of 51 candidates for the $K^+ \to \pi^+ \nu\nu$ decay against the background of 18^{+3}_{-2} events[57]. This is the first observation of the rarest particle decay ever observed, proven with a statistical significance of 5σ. Its measured probability was $\mathrm{BR}(K^+ \to \pi^+ \nu\nu) = (13.0^{+3.3}_{-3.0}) \cdot 10^{-11}$. The obtained result already constrains the parameter regions for a number of theories that go beyond the SM. The NA62 experiment continues data taking, accumulating statistics to improve the accuracy of measuring the probability of the $K^+ \to \pi^+ \nu\nu$ decay and collecting rich experimental material for the analysis of other rare kaon decays with record measurement accuracy.

THE NA64 EXPERIMENT

The proposal for an experiment to search for light dark matter and study "new" physics of the "dark" sector at CERN's SPS accelerator was developed in collaboration between the INR RAS, IHEP (KI), and JINR. In 2015, on the recommendation of the SPSC committee, a two-week test run was performed, which demonstrated its potential, and in March 2016, the CERN Research Board approved a new experiment — NA64 — to search for dark matter using the electron beam of the SPS accelerator.

The concept of the NA64 facility is based on the use of a fully hermetic detector to search for missing-energy events associated with the production of dark matter particles and other "new" physics via scattering of high-energy electrons, positrons, hadrons, and muons on the nuclei of an active target. NA64 participants were the first to propose the use of electron and positron tagging using synchrotron radiation and successfully implemented this experimental technique.

[57] *Cortina Gil E. et al.* Observation of the $K^+ \to \pi^+ \nu\nu$ Decay and Measurement of Its Branching Ratio // JHEP. 2025. V. 02. P. 191.



The main part of the NA64 facility on the H4 beam of the SPS accelerator

The NA64 experimental program currently includes three main directions that can be efficiently explored at CERN accelerators in the mass range below the electroweak scale ($\ll$ 100 GeV). These are related to the search for dark matter and "new" physics using the electron/positron beams of the H4 channel, the muon beam M2, and the hadron beams of PS and SPS[58].

The JINR group played a significant role in developing the scientific program and making the magnetic spectrometer of the facility, whose basic tracking detector is thin-walled drift chambers built using straw tube technology. All chambers were designed and manufactured at JINR. Electromagnetic and hadron calorimeters, as well as synchrotron radiation detectors, were developed and manufactured jointly with INR and IHEP. The JINR group accounts for approximately 25% of the collaboration; the leader and technical coordinator of NA64 are also JINR employees. Group members are involved in both theoretical support of the experiment and all stages of its implementation, including modeling and data analysis.

[58] *Andreev Yu. M. et al.* Search for a Light Z' in the $L_\mu - L_\tau$ Scenario with the NA64-e Experiment at CERN // Phys. Rev. D. 2022. V. 106(3). 032015;

Andreev Yu. M. et al. Search for Light Dark Matter with NA64 at CERN // Phys. Rev. Lett. 2023. V. 131. P. 161801;

Andreev Yu. M. et al. First Results in the Search for Dark Sectors at NA64 with the CERN SPS High Energy Muon Beam // Phys. Rev. Lett. 2024. V. 132(21). P. 211803.



Straw chambers before installation on the M2 muon beam of the SPS accelerator

NA64 currently gets the world's most stringent constraints on the parameters of light dark matter, while leaving a significant amount of variable space for further research to either detect the existence of dark matter or close the main models most motivated by it.

THE NA49 AND NA61/SHINE EXPERIMENTS

The NA49 experiment was carried out at SPS for a long time and was aimed at studying the region of extreme energy densities, where the transition of hadronic matter to a new state, quark-gluon plasma, could occur. A group of physicists from JINR took an active part in this experiment. The main components of the NA49 detector were a magnetic spectrometer and four large time projection chambers (TPC) for tracking and identifying particles, which measured the ionization losses of particles dE/dx in the TPC gas. Arrays of ToF scintillators complemented the particle identification; the 900-channel ToF detector was one of the key detectors (Fig. 39). The highly complex work on its production was carried out entirely at the Laboratory of High Energies in 1998, based on its production and technical potential. The detector was manufactured in a very short time — within 1.5–2.0 years, assembled and launched at CERN by the beginning of the experiment. Together with dE/dx measurements in large TPCs, the high-resolution ToF detector (60–70 ps) provided excellent particle identification.

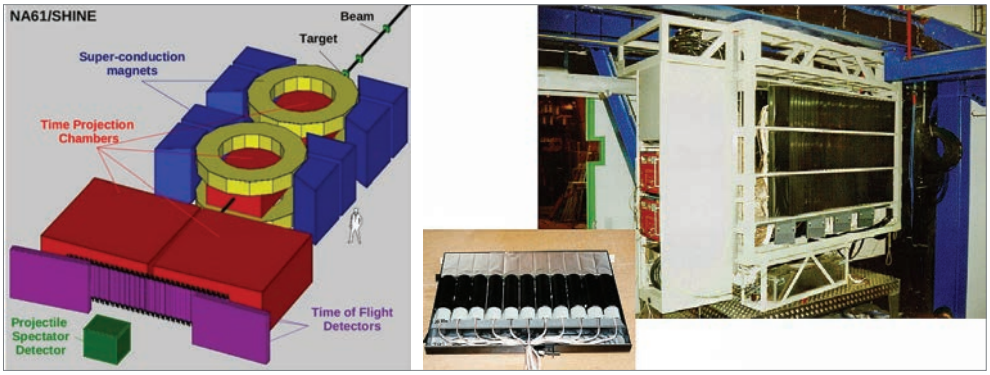


Fig. 39. NA61/SHINE facility scheme and ToF detector

On the eve of CERN's 50th anniversary, the successful participation of the JINR laboratory in the NA49 experiment was noted in a letter from Carl Schwarz, publisher of Nuclear and High Energy Physics Elsevier, to the head of the JINR group, A. I. Malakhov. Among the 50 most cited papers written by CERN-affiliated scientists and published in Elsevier, there were two NA49 papers with authors from JINR.

The main goal of the heavy-ion program at CERN's SPS is to search for deconfinement states in strongly interacting matter at the early stage of nucleus–nucleus collisions at the energy density of about 1 GeV/fm^3. Under these conditions, QCD predicts a phase transition between hadronic matter and quark-gluon plasma. The energy dependence of inclusive observables, such as the K/π particle yield ratio, the total pion yield, and the slopes of the K- and π-meson transverse momentum spectra, were predicted within the SMES (Statistical Model of Early Stage) thermodynamic approach as a consequence of the transition of nuclear strongly interacting matter to a deconfinement phase state. The predicted signatures of the onset of deconfinement at SPS energies, namely a clearly defined maximum in the K^+/π^+ ratio in Pb + Pb central collisions around 30A GeV ($\sqrt{s_{NN}}$ = 8 GeV), as well as a characteristic plateau in the slope parameter of the K^+-meson spectra in the SPS energy range, were reliably confirmed by the results of the NA49 experiment (Fig. 40). The ToF analysis of the transverse spectra of K^- and π mesons provided by the JINR group was a significant contribution to these studies[59].

Another direction of data analysis in the JINR group was the study of the dependence of p and $\overline{p}$ production on the energy and centrality of interactions, the ratio of $\overline{p}/p$ and $\overline{\Lambda}/\overline{p}$ yields, as well as the production of light d, $\overline{d}$, t and ^{3}He nuclei in Pb + Pb collisions with the beam energy from 20 to 158 A GeV. The main observations in these studies substantiate the modern concept of the phenomenological theory of relativistic heavy-ion collisions, which includes a strong

[59] *Alt C. et al. (NA49 Collab.)* // Phys. Rev. C. 2008. V. 77. 024903.

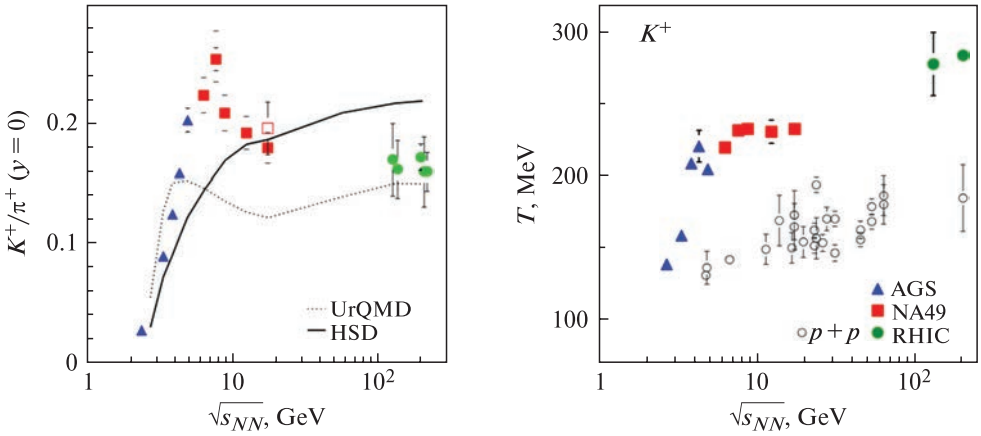


Fig. 40. Energy dependence of the K^+/π^+ ratio and the slope parameter of the K^+ spectra in the collision of Pb + Pb nuclei

collective expansion of the high energy density source created at the early stage of the interaction.

During the first ten years after the CERN press release about the discovery of quark-gluon plasma in 2000, the NA49 results were widely cited, and the subsequent stage was carried out within the framework of the NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) project[60]. The NA61/SHINE research program, dedicated to strong interactions, is based on two-dimensional scanning of beams of light, intermediate, and heavy nuclei ($p + p$, p + Pb, Be + Be, Ar + Sc, Xe + La, Pb + Pb) with energies in the range $13A$–$158A$ GeV and includes a search for the critical point on the phase diagram of nuclear matter and a study of the properties of the system at the beginning of deconfinement. The physics program was also extended by measurements of the production of charm D^0 and anti-D^0 mesons, so-called "open charm" particles, in $A + A$ collisions, which became one of the main goals after 2021.

The NA6l/SHINE collaboration is also implementing a program of measurements of a wide range of particle production for the neutrino oscillation experiments performed by J-PARC and FNAL to more accurately determine the initial neutrino flux from the target. These measurements require reliable particle identification, which is one of the advantages of the detector.

Between 2019 and 2022, the NA6l/SHINE collaboration carried out extensive upgrades to the facility. Engineers and physicists at VBLHEP manufactured a new high-resolution (~ 50 ps) time-of-flight system based on mRPC detectors, chambers made of multigap resistive plates, which was crucial to identify charged particles in the central region of reaction rates. The Laboratory team was responsible for the design, construction, and operation of the ToF detector, which contains 1728 time-of-flight data recording channels collected in two left-right beam-symmetric detector channels. The first half of the detector was assembled, commis-

[60] *Antoniou N. et al. (NA61/SHINE Collab.).* CERN-SPSC-2006-034. 2006.

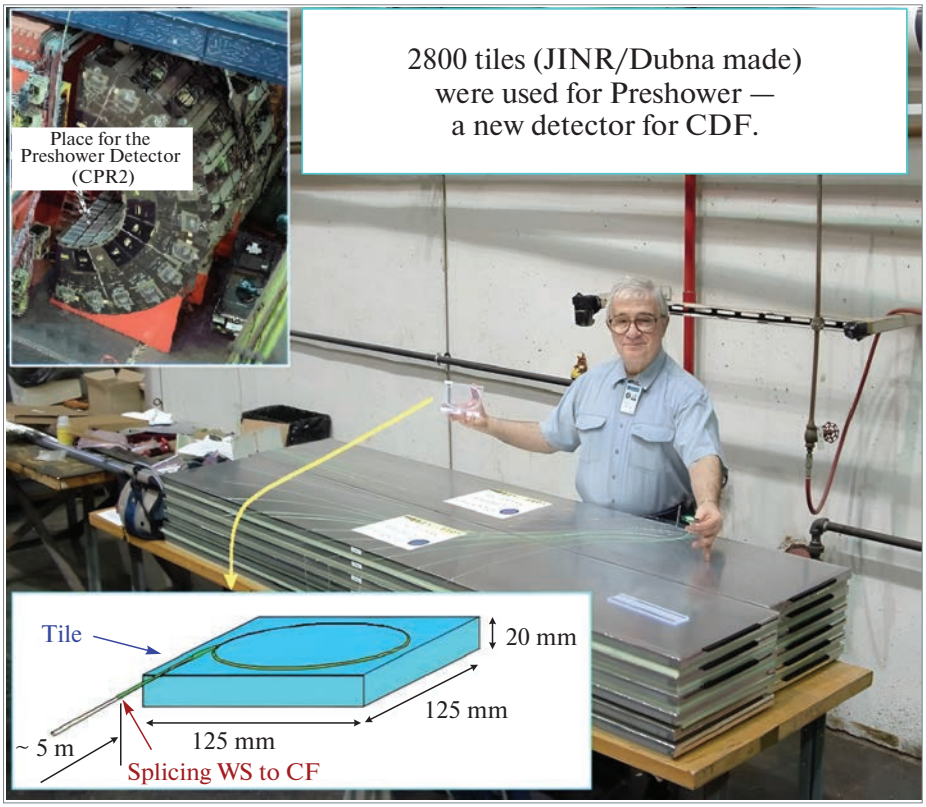
sioned, and demonstrated reliable operation in runs of the SPS accelerator at CERN during 2023–2024. The second part of the ToF detector is currently being installed and put into operation.

Based on the processing and analysis of the results obtained in the NA49 and NA61/SHINE experiments, VBLHEP physicists successfully defended two doctoral and three candidate dissertations.

THE CDF PROJECT

In October 2011, the era of the FNAL Tevatron (Batavia, USA) came to an end. The JINR physicists made an outstanding contribution to the CDF experiment at the Tevatron. In collaboration with scientists from INFN (Pisa, Italy) and the Institute for Single Crystals of the National Academy of Sciences of Ukraine (Kharkov), they developed unique, large-scale, next-generation scintillation detectors for the CDF muon trigger, electronics, and a method to generate a Level II trigger for silicon vertex detector signals. The JINR scientists measured the *t*-quark mass in single-lepton and two-lepton decay modes with high precision.

Yu. A. Budagov, A. N. Sissakian, D. Bellettini, V. G. Kadyshevsky, and B. V. Grinev laid the foundation for these achievements. Success was achieved thanks to



Yu. A. Budagov demonstrating the module of the CDF detector. Insets: top — arrangement of the modules on the CDF; bottom — scintillation tile

the coordinated work of the INFN–JINR team: V. V. Glagolev, A. M. Artikov, A. Yu. Semenov, G. Chlachidze, I. A. Suslov, D. Chokheli, G. Velev, D. Pauletta, F. V. Prokoshin, O. E. Pukhov, A. V. Simonenko, and I. E. Chirikov-Zorin.

A group of JINR scientists made a decisive contribution to the development of scintillation counters for the CDF muon trigger, a silicon vertex detector (SVD) trigger for selecting secondary vertex events, and the electromagnetic calorimeter preshower (CPR2). The group participated in the upgrade and operation of the scintillation counter system and made a parameter monitoring system to provide uninterrupted operation during Run II.

The collaboration of JINR and the Institute for Single Crystals (Kharkov), which included scientists from JINR, Ukraine, the USA, Italy, Greece, Uzbekistan, Slovakia, Georgia, and Russia, developed unique new detectors at JINR based on the UPS 923 plastic scintillator. The novelty of this development consisted in collecting light by means of a flat tape made from a fiber-optic wavelength shifter.

A fundamentally important constant of modern theory, the top-quark mass determined at CDF, was included in the prestigious International Tables of Elementary Particle Properties. The contributions of JINR physicists have been repeatedly recognized in the Fermilab Today Daily among the top achievements of FNAL. In the field of *t*-quark physics, JINR staff members actively participated in measuring the *t*-quark mass in the lepton-jet and dilepton decay channels



Yu. A. Budagov, O. E. Pukhov, G. Chlachidze, V. V. Glagolev, A. M. Artikov, and D. Chokheli. The JINR counter is ready for installation in the CDF muon complex. 2000



V. V. Glagolev at the JINR stand at FNAL determines the parameters of scintillation counters that arrived from Dubna

of the tt-pair. The group successfully studied the properties of the t-quark: the charge of t-quark was measured in collaboration with colleagues from Bratislava, and the measurements allowed one to reject the hypothesis of the existence of an exotic t-quark with a 99% confidence level. Also, members of the JINR group took an active part in the search for the Higgs boson at the Tevatron; in particular, they analyzed the $H \to \gamma\gamma$ decay channel, which was included in the full combined analysis, which made it possible to narrow the search area for the Higgs boson mass to 120–140 GeV/c^2.

By means of the subsystems constructed, upgraded, and maintained by the JINR team, remarkable research in the field of B-physics was carried out: B_S^0–$\bar{B}_S^0$ oscillations were discovered, and baryons Ω_b^-, Σ_b, Σ_b^* and Ξ_b^- were observed.

The staff of the Department of Multiple Hadronic Processes defended two doctoral and four candidate dissertations based on their work at CDF. In 2006, a group of department staff members was awarded the JINR First Prize for their work “Development and Construction of a Scintillation Muon Detector for the CDFII Facility for Heavy Quark Physics Experiments at the FNAL Tevatron”. The European Physical Society (EPS) announced the awarding of the 2019 High Energy and Particle Physics Prize to the CDF and D0 collaborations for the discovery of the t-quark and the detailed measurement of its properties. This prize recognizes outstanding contributions to high energy physics.

THE D0 PROJECT

In 1992, an agreement was signed on JINR's participation in the joint D0 experiment with the Fermi National Accelerator Laboratory (FNAL).

The DLNP JINR staff developed, manufactured, and tested about 7 000 mini drift tubes (MDTs) with lengths from 1 to 6 m and assembled the FAMUS muon system for the D0 facility.

Specialists from DLNP JINR (Dubna), IHEP (Protvino), and PNPI (Gatchina) represented Russia in the project.



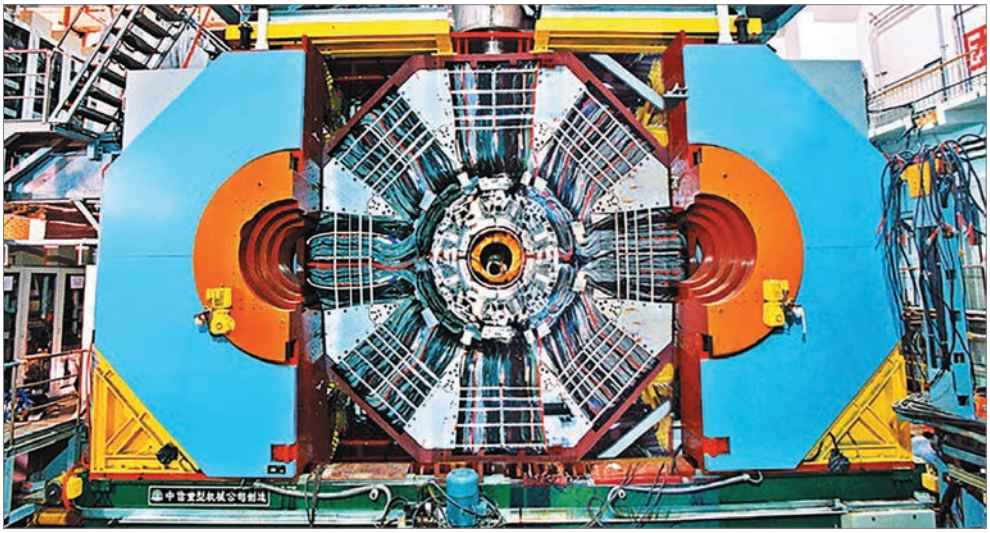
The joint Russian–American team which participated in the assembly, testing, and launch of the D0 detector muon system

THE BES III EXPERIMENT

The primary objective of the BES III experiment at the BEPC II electron–positron collider (IHEP of CAS, Beijing) is to conduct precise measurements in the region of tau-lepton pair production and charmonium resonances. This experiment, along with the Daya Bay experiment, is the first joint project of the JINR and Chinese scientists in the field of elementary particle physics after 1965.

In 2005, a group of DLNP employees under the leadership of G. A. Shelkov was formed to participate in this experiment. This group made a significant contribution to the preparation of the BES III physics research program, became one of the main developers of the experiment's software, and helped design and deploy the BES III distributed computing system.

Participation in the analysis of BES III data allowed expanding the range of scientific tasks solved by the DzhelepovLaboratory of Nuclear Problems by including



BES III facility

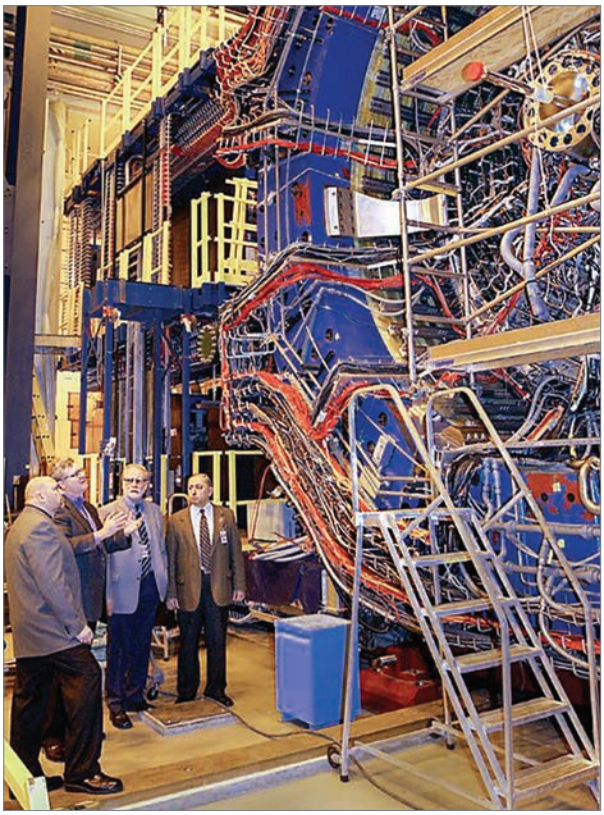
light hadron spectroscopy, the study of charmed meson decays, and the formation of charmonium states in electron–positron annihilation.

THE STAR EXPERIMENT

The decision on JINR's participation in the STAR (Solenoidal Tracker At RHIC) experiment at RHIC (Relativistic Heavy Ion Collider) in Brookhaven (USA) was made in 1993, when the LHE group (led by Yu. A. Panebrattsev) and the LPP group (led by I. A. Savin) became participants of the STAR Collaboration. The goal of the research was to experimentally establish the patterns of the transition of quarks and gluons into protons and neutrons, the nature of nuclear forces, and the phase diagram of nuclear matter. It was planned to obtain beams of polarized protons with the energy up to 510 GeV at the RHIC collider. Participation in these experiments made it possible to expand JINR's research program in studying the spin structure of the proton. Traditions in the field of spin physics were established and continue to exist at JINR. Therefore, JINR's main contribution to the STAR project is its participation to develop detectors for studying polarization phenomena — the central and end-cap electromagnetic calorimeters[61].

In 2000, the first experiment was carried out at the STAR facility with beams of gold nuclei with the energy $\sqrt{s_{NN}} = 200$ GeV. The RHIC collider and the STAR facility were continuously improved over the years. The most important result of this work is the implementation of a unique experimental research program using a wide range of beams of nuclei (up to uranium), including polarized beams, the

[61] *STAR Collab.* STAR Detector Overview // Nucl. Instr. Meth. 2003. V. 499. P. 624;
STAR Collab. The STAR Barrel Electromagnetic Calorimeter // Ibid. P. 725;
STAR Collab. The STAR Endcap Electromagnetic Calorimeter // Ibid. P. 740.





Visit of the JINR Director V. G. Kadyshevsky and JINR Vice-Director A. N. Sissakian to the STAR experiment. Discussion of new results with the Spokesman of the STAR experiment T. Hallman

energy from several GeV to $\sqrt{s_{NN}}$ = 200 GeV and particle probes with light (u, d, s) and heavy (c, b) quarks, photons, leptons, lepton pairs, jets, light nuclei, antinuclei, hypernuclei, and antihypernuclei.

The STAR experiment has achieved world-class physics results for the first time.

— A new state of strongly interacting nuclear matter, an "ideal liquid", was discovered in collisions of gold nuclei at the energy of 200 GeV, and its properties were studied in the processes involving the production of light and heavy quarks and jets (elliptical flow, nuclear modification factor, $\Delta\eta-\Delta\varphi$ correlations, quark NCQ scaling).
— The energy scanning program was completed in the energy range of 3–200 GeV to study the phase diagram of nuclear matter in the temperature range T_{ch} = 60–160 MeV and baryon densities μ_B = 25–720 MeV).
— The interaction of antiprotons was studied and the charge symmetry of matter and antimatter was established using the method of femtoscopic correlations [62].

[62] *STAR Collab.* // Nature. 2015. V. 527. P. 345.

— CPT symmetry was verified in the processes with hypertritium and antihypertritium production[63] .
— The effect of rotation of nuclear matter was discovered and the global polarization of hyperons was measured in nucleus–nucleus collisions[64].
— Symmetry of the production of matter (p, d, ^{3}He, ^{4}He) and antimatter ($\overline{p}$, $\overline{d}$, $^3\overline{\text{He}}$, $^4\overline{\text{He}}$) was determined[65] in collisions of gold nuclei at the energy of 200 GeV.
— A positive integral contribution of gluons to the proton spin was found in collisions of longitudinally polarized protons at the energy of 510 GeV with the production of jets.
— The asymmetry of spin-dependent sea anti-u and anti-d quark distributions in the proton was discovered in the processes with the production of W and Z bosons.

One of the research areas of the JINR group is the use of experimental data from the STAR facility to search for new symmetries and scaling regularities in the interactions of hadrons and high-energy nuclei[66]. The method of correlation femtoscopy was developed in the works of R. Lednický and V. L. Lyuboshits and was successfully applied in the STAR experiments to study ΛΛ correlations in collisions of gold nuclei[67]. The use of this method turned STAR into a unique "factory" to study hyperon–hyperon interactions, which are important to describe various baryon–baryon interactions and investigate the equation of state of the matter formed in neutron stars.

The BES-II energy scanning program successfully investigated the "transition" energy region from hadronic to quark degrees of freedom. It was found that the scaling of the number of constituent quarks (NCQ) observed at high energies in Au + Au collisions in the central rapidity region is violated at low energy around 3 GeV (Fig. 41).

The magnitude of the elliptical flux turns out to be negative for all hadrons (π, K, p), and the rapidity slope of the direct flux is positive for most particles. This result is explained by the influence of the repulsive medium field of spectator nucleons, which increases with decreasing the collision energy[68].

The Hot QCD Physics experimental program is currently underway. It is planned to study the microstructure of the QGP in gold–gold collisions at the energy of 200 GeV to detail the QCD phase diagram and determine the properties of the QGP on small scales. Statistics will be collected in the new kinematic range and with the increased luminosity of the RHIC collider on Au–Au and p–Au interactions at the collider energy of 200 GeV and in experiments with polarized protons at the energy of 510 GeV, comparable in volume to what was collected in all previous

[63] *STAR Collab.* // Nature Phys. 2020. V. 16. P. 409.
[64] *STAR Collab.* // Nature. 2017. V. 548. P. 62.
[65] *STAR Collab.* // Nature. 2011. V. 473. P. 353.
[66] *Zborovsky I., Tokarev M.* New Properties of Z-Scaling: Flavor Independence and Saturation at Low Z // Intern. J. Mod. Phys. A. 2009. V. 24. P. 1417.
[67] *Adamczyk L. et al. (STAR Collab.).* ΛΛ Correlation Function in Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV // Phys. Rev. Lett. 2015. V. 114. 022301.
[68] *STAR Collab.* // Phys. Lett. B. 2022. V. 827. P. 77137003.

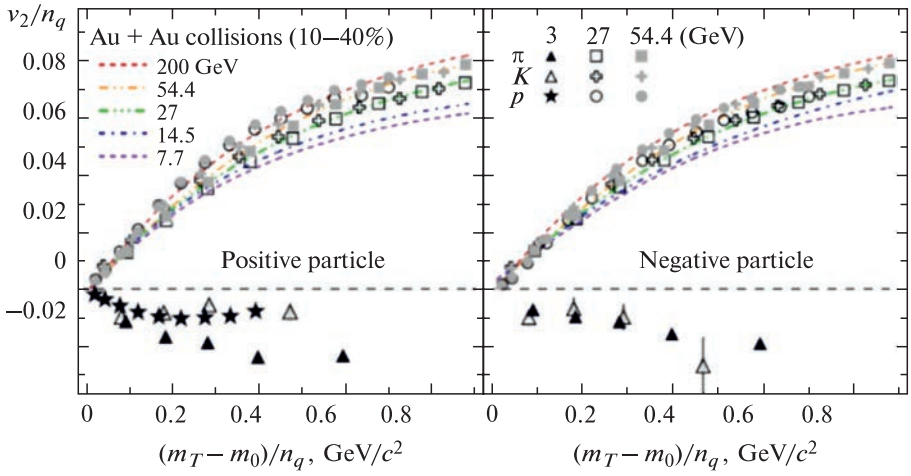


Fig. 41. NCQ scaling violation at energy $\sqrt{s_{NN}}$ = 3 GeV in Au + Au collisions

years. The obtained data set will undoubtedly be used to prepare the experimental program for the future electron–nucleus collider, for the development of theoretical models, and in other projects.

THE CBM EXPERIMENT

JINR's participation in the CBM (Compressed Baryonic Matter) experiment was approved in 2010. The CBM project is dedicated to study relativistic nuclear collisions of gold ions in the energy range up to 11 *A* GeV at the FAIR (Facility for Antiproton and Ion Research) accelerator complex, which is under construction in Darmstadt (Germany). It is planned to thoroughly investigate the energy range of 4–11 *A* GeV, where the highest baryon density for nuclear collisions is expected.

The CBM facility is a magnetic spectrometer equipped with the most modern detectors. Two modes of operation are planned: "electron + hadron" and "muon". Employees of VBLHEP, DLNP, BLTP, and MLIT JINR participated in the project implementation and made a decisive contribution to prepare the technical project for the superconducting dipole magnet[69]. They actively participated in the preparation of the technical projects for the muon system[70] and the annular Cherenkov detector[71]. JINR specialists participated in the construction of the muon chambers of the CBM detector and the silicon tracking system based on strip silicon detectors, in the development of algorithms, the creation of databases, the elaboration of the

[69] *CBM Collab.* Technical Design Report for the CBM Superconducting Dipole Magnet. GSI-2015-02000. 2013.

[70] *CBM Collab.* Technical Design Report for the CBM Muon Chambers. GSI-2015-02580. 2015.

[71] *CBM Collab.* Technical Design Report for the CBM Ring Imaging Cherenkov Detector. GSI-2014-00528. 2013.

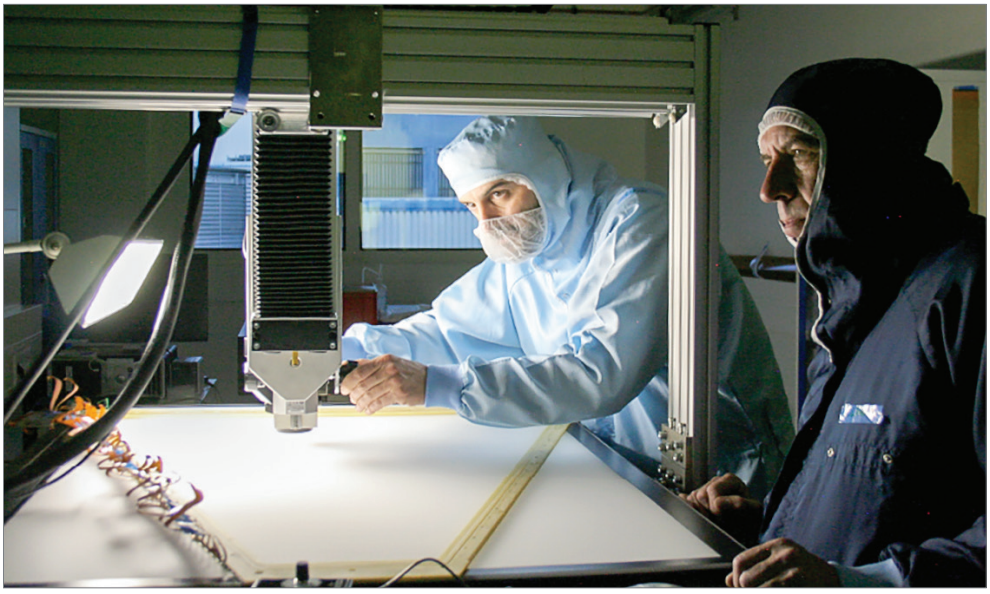
physics program, and the modeling of the setup parameters and physical processes. Dozens of joint papers were published in NIM and other journals.

Although JINR's participation in this project was officially terminated in May 2023, the experience gained in the CBM experiment is already being successfully used to implement the MPD, SPD and BM@N projects at NICA.

THE HADES EXPERIMENT

The HADES (High Acceptance Di-Electron Spectrometer) experiment was officially launched at GSI (Darmstadt, Germany) in 1994. The JINR group was among the main members of the collaboration and made key contributions to make the spectrometer's tracking system, develop software, online control and processing algorithms, and the analysis of the obtained experimental data. The HADES spectrometer[72] belongs to the second generation of di-electron detectors and is designed to detect electron–positron pairs in heavy-ion collisions. HADES can also detect and identify hadrons, which makes it possible to study strangeness and multiple pion production.

The main experimental goal of HADES was to study the properties of dense nuclear matter created in heavy-ion collisions and the properties of hadrons in the medium (masses, decay widths). The matter formed in these collisions differs from that studied at SPS, RHIC, or LHC, i.e., it consists primarily of baryons (nucleons and their excited states — baryon resonances) and light mesons. The matter can be compressed by three times more than usual density of nuclear matter to approximately 10–12 fm/s.



Reconstruction of one of the MDC-2 sectors by the JINR employees at GSI

[72] *Agakishiev G. et al.* // Eur. Phys. J. A. 2009. V. 41. P. 243.

Di-electron pairs formed from hadron decays in the medium and rare strange hadrons (kaons, hyperons) are the main probes measured in the experiment. Since conclusions about the influence of the medium depend heavily on understanding the properties of hadrons in vacuum and the mechanism of their production in nucleon–nucleon collisions, an additional program is being implemented focused on the production of e^+e^- pairs, kaons, and hyperons (Σ, Λ) in elementary collisions.

The JINR group manufactured the second plane of the multiwire drift chambers (MDC-2)[73], developed the readout electronics based on the ASD-8 microcircuit, and maintained the MDC and the readout electronics in working order before and while data taking, also participating in the upgrading of the tracking system. JINR employees played a key role in the development of an algorithm to search for charged particle tracks based on the solution of G. Schubert's problem for four straight lines, in the precision adjustment of the HADES detectors, in the analysis of Cherenkov radiation rings in RICH for particle identification based on the Hough transform, and participated in taking and analysis of the data obtained in *pp*, *np*, πA, *pA*, and *AA* collisions at the GSI energies.

JINR's participation in HADES was terminated at the initiative of the German side in March 2022.

[73] *Bokemeyer H. et al.* // Nucl. Instr. Meth. A. 2002. V. 477. P. 397; *Carabatos C. et al.* // Nucl. Instr. Meth. A. 1998. V. 412. P. 38.

PHYSICS OF NEUTRINO AND RARE PROCESSES

The Dzhelepov Laboratory of Nuclear Problems (DLNP), and accordingly JINR, currently has the most powerful Neutrino Program in the world. The range and spectrum of phenomena and energies being studied is extremely broad: from very low energies, at which neutrinos can be coherently scattered by atoms and nuclei (the νGeN, Ricochet, and SATURNE experiments), to energies orders of magnitude higher than the highest human-generated ones at the Large Hadron Collider (Baikal-GVD). In each of the ranges under study, neutrinos carry unique information inaccessible to other methods and, as is now clear, are the key to new physics beyond the Standard Model.

It is important to emphasize that, in addition to its extensive scope, the laboratory conducts experiments in which it is essentially the lead or co-lead organization (experiments at the Kalinin Nuclear Power Plant, on Lake Baikal, and new experiments at the Baksan Neutrino Observatory) and participates in cutting-edge international projects (of particular note are the JUNO reactor experiment, which will shape the understanding of neutrino properties in the coming years, "large" accelerator experiments such as T2K and NOvA, and smaller-scale experiments that could change physics, such as COMET). In any case, the criterion for participation is science on the front lines of current knowledge and a contribution that is significant even for collaborations consisting of hundreds of scientists.

How did the Laboratory of Nuclear Problems become the leading center for the study of neutrinos, or more precisely, the physics of weak interactions? First, it's important to emphasize the fundamental historical background: it is linked to the name of Bruno Pontecorvo, whose classic works essentially foresaw the development of neutrino physics decades in advance. The next factor was the comprehensive development of a wide variety of approaches to experimental physics at both the Institute and the laboratory. The unique detectors and expertise possessed by Dubna scientists proved to be in high demand. The history of the Neutrino Program at JINR, in which the Laboratory of Nuclear Problems played a leading role, was shaped primarily by outstanding persons. It is worth noting the role of Tsvetan Vylov, who served as LNP Director from 1988 to 1992, and as JINR Vice Director from 1992 to 2005.

At that time, the laboratory already had extensive experience related to methods that had been developed and used for decades to study nuclei and the properties of radioactive isotopes and particles, most of which were in one way or another associated with the LNP phasotron. A key milestone in the history of the laboratory, leading to changes that shaped its current scientific direction, was the idea, generated by Tsvetan Vylov in the mid-1980s, of using classical spectrometric techniques to study the neutrino sector in non-accelerator experiments. The laboratory's refocusing on the search for and study of rare processes required the creation of a new spectrometric school, mastering the latest techniques, and borrowing the best experimental practices from international partners. Later, given the importance of neutrino research in modern physics, participation in accelerator experiments also began. DLNP Directors N. A. Russakovich, A. G. Olshevsky, and V. A. Bednyakov (in chronological order) played a significant role in this. The most important recent development is the implementation of an ambitious global project in neutrino physics — the construction of the gigaton volume neutrino telescope on Lake Baikal. The close cooperation of DLNP JINR with INR RAS, organized with the support of V. A. Matveev and G. V. Trubnikov, plays a significant role in the implementation of this project. Here it is necessary to mention V. B. Brudanin: it is largely thanks to his efforts in cooperation with G. V. Domogatsky (INR RAS), spokesperson of the collaboration, and with the support from DLNP and JINR directorates that a unique neutrino detector is currently being actively developed. It has already begun to explore the mysteries of the Universe. It must be said that the creation of Baikal-GVD required difficult decisions, including those related to the allocation of significant funds from the JINR budget. Without the principled position of JINR Directors V. A. Matveev and G. V. Trubnikov, who recognized the potential of this scientific field, the breakthrough development of the experiment would have been impossible.

A striking example of the use of classical spectrometric methods in modern experiments is the search for the neutrinoless mode of double beta decay. It is appropriate to quote a letter dated July 28, 1988, from LNP Director Ts. Vylov to Academician S. T. Belyaev (in connection with the development of a nuclear physics research program in the USSR):

"Currently, there are several problems in neutrino physics that can be solved using precision nuclear spectroscopy methods <…>.

DOUBLE BETA DECAY

Interest in the study of neutrinoless double beta decay is associated with the search for possible nonconservation of lepton charge and the existence of right-handed currents,

as well as with identification of the nature and mass of (anti)neutrinos.

The detection of two-neutrino double beta decay is interesting, but has no fundamental physical significance. However, measuring the $2\beta2\nu$ decay probability is the best way to test the accuracy of calculation of matrix elements, which play a fundamental role in interpreting data on neutrinoless double beta decay.

Due to the peculiarities of double beta decay, the observation of such a rare process requires a very thin source and a spatial detection instrument capable of measuring the electron energy and total energy spectra. Separation of the 0ν and 2ν channels requires high energy resolution (better than 1%) and measurement of the electron angular distribution. This limits the source thickness and therefore imposes the requirements for the linear dimensions of the source and detector for observing such a rare process ($\lambda \approx 10^{-29}$ s^{-1}). At this point, natural and cosmic backgrounds intervene. Consequently, the success of the solution will depend on the optimal choice of the effect/background ratio.

Clearly, at this stage, the most important issue is the direct observation of the double beta decay (DBD) process. Rejecting a detailed study of the elementary process allows somewhat simplified experimental conditions, namely:

a) high energy resolution with high efficiency is required;

b) a rough observation of the spatial picture is necessary, since the mechanisms of $2\beta2\nu$ decay allow two extreme cases: the electron escape in one direction ($1 - \cos\theta$) and the electron escape in different directions ($1 + \cos\theta$);

c) the system must be capable of suppressing various background sources: operation in underground conditions, selection of particularly pure construction materials, coordinate registration, separation of signals from various radiation sources, etc.

It is not difficult to understand that the most stringent condition (a) requires the use of semiconductor detectors — the only currently available device with high resolution and efficiency. Based on these requirements, we have proposed an experiment to search for DBD using a telescope with HPGe detectors. Similar projects (though currently based on Si(Li) detectors) have already been proposed and are being implemented in other laboratories around the world. It can be expected that the development of promising experiments searching for $2\beta0\nu$ decay will follow the path of improving this approach — for example, by introducing coordinate registration.

In conclusion, I would like to add the following. Large focus is being made in the USSR on studying neutrino properties. Unfortunately, the experimental level of the results reported at international conferences is very low. It seems to me that if the

efforts of various competing groups within the USSR could be concentrated, based on their well-known advantages over other countries (the availability of ^{76}Ge, success in detecting beta particles using HPGe detectors, the level of low-energy electron spectroscopy techniques, the availability of low-background laboratories with methods for selecting pure materials, etc.), and if the staff and resources of JINR Member States could be attracted, it would be possible to obtain results in neutrino physics quite quickly and at a high scientific level.

It is amazing how the essence of modern, cutting-edge double beta decay experiments was precisely defined almost 40 years ago. Today, of course, these processes are studied using the most advanced methods: cryogenic detectors, large liquefied noble gas detectors, tracking calorimeter detectors, specially designed semiconductor detectors, and special shielding to reduce background levels to a few counts per ton of matter per year. Such background levels seemed fantastic and unattainable 40 years ago.

In fact, the entire modern JINR Neutrino Program is like this: fantastic in its methods and in the knowledge scientists want to gain.

NEUTRINO ASTROPHYSICS

THE BAIKAL-GVD PROJECT

The JINR Laboratory of Nuclear Problems has been involved in the development of neutrino telescopes on Lake Baikal since 1991. These facilities consist of a system of photodetectors distributed throughout the water at a depth that excludes the influence of sunlight. The main objectives of these detectors are to search for sources and study fluxes of high-energy neutrinos of astrophysical origin, indirectly search for dark matter particles, search for exotic particles such as magnetic monopoles, and study astrophysical manifestations of other extensions of the Standard Model of elementary particles.



The central suspension of the NT-200 detector with control modules and a gas calibration laser. The entire facility 43 m in diameter is lowered using a cable to which the suspension is attached



The Baikal project at JINR was launched by (left to right) K. V. Konishchev, I. A. Belolaptikov, B. A. Shaybonov, and E. N. Pliskovsky

During that period in the early 1990s, the NT-200 deep-underwater neutrino telescope project was being developed under the leadership of the High Energy Neutrino Astrophysics Laboratory (HENAL) of INR RAS. Its configuration was determined, the hardware and design of the telescope, as well as the software for operation and data processing, were actively developed, with the DLNP staff playing a key role. As a result, the world's first deep-underwater neutrino telescope NT-200 consisting of eight strings of 24 optical modules each was deployed between 1993 and 1998, and the first neutrino events were recorded.

A Baikal group of young HENAL specialists, the core of which included I. A. Belolaptikov, K. V. Konishchev, E. N. Pliskovsky, and B. A. Shaybonov, was formed in the Department of Nuclear Spectroscopy and Radiochemistry at DLNP JINR under the leadership of Department Head V. B. Brudanin. The group conducted research and developed software packages for telescope modeling and control, as well as data processing, and also participated in expeditions on Lake Baikal.

Scientific research focused on searching for high-energy astrophysical neutrinos, magnetic monopoles, "dark matter" particles, localized sources and diffuse neutrino fluxes. The research established upper limits for detecting the sought-after particles and confirmed the results of simulations of astrophysical process, which led to the conclusion that the effective volume of the telescope must be increased from 0.01 to 1 km^3.

By 2004, the process of increasing the effective volume of the telescope to 0.02 km^3 was completed with the installation of three external strings, and the telescope was renamed NT-200+. During this period, research was conducted into transition from using Russian-made main telescope components to foreign-made components. This development phase culminated in the release, in 2010, of the

first version of the Scientific and Technical Project for the NT-1000 telescope, with an effective volume of up to 1 km^3.

The period from 2011 to 2014 was devoted to the search for a new component base, the development of a new type of optical module, the technical design of the telescope's supporting structures, and testing of the new components on laboratory benches and as part of the NT-200+ telescope. An international assessment and refinement of the Scientific and Technical Project for the Baikal Deep-Underwater Neutrino Telescope was also conducted with renaming NT-1000 to Baikal-GVD and culminated in signing a Protocol between INR RAS and JINR on joint research to combine efforts and reduce the timeframe for achieving scientific and technical results in the creation of the Baikal Deep-Underwater Neutrino Telescope (Baikal-GVD) with an effective volume of a cubic kilometer. From this point on, JINR has been committed to full participation in the implementation and financing of the project. This created prospects for implementing the research, development, and experience results accumulated over three decades, especially since both INR RAS and JINR retained the core of specialists who had led to these results.

The Baikal-GVD telescope project was reviewed by the interdepartmental working group on priorities for the development of ground-based astronomical infrastructure projects in the Russian Federation for the period 2016–2025. A group of 12 leading experts and heads in astronomy and astrophysics established at the initiative of the Administration of the President of the Russian Federation met in 2015 and deemed it important to support the creation and commissioning of the Baikal-GVD neutrino telescope as a modern project in the field of high-energy neutrino astronomy. They assigned the highest priority to the project and recommended immediate funding.

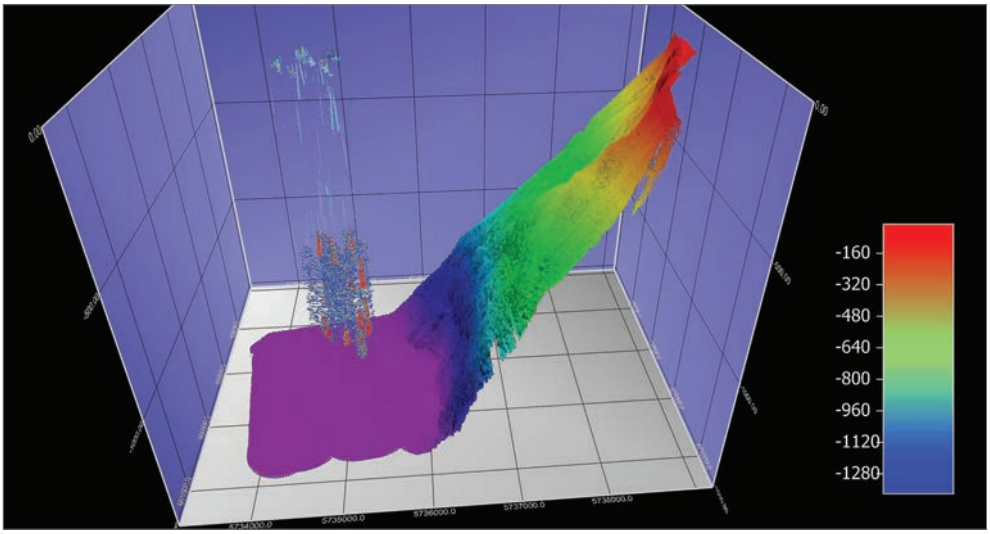
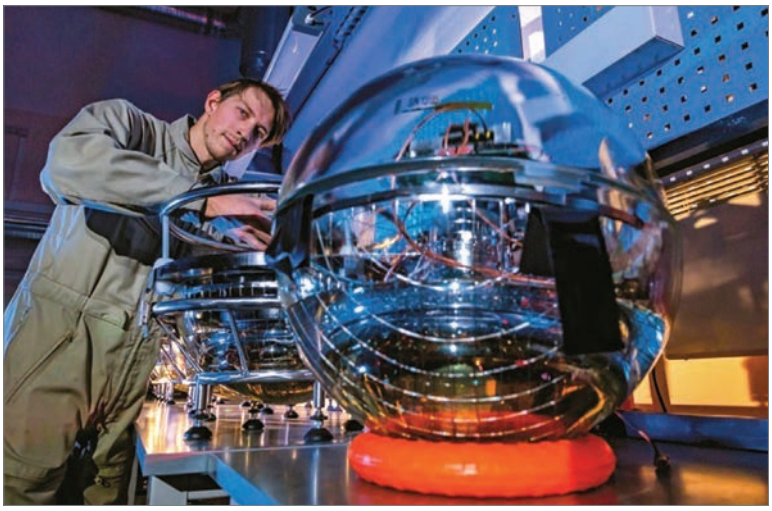


Fig. 1. The Baikal-GVD neutrino telescope, as seen by the INRTU multibeam echosounder in July 2020



Assembly of the Baikal-GVD optical module. D. A. Orlov

Back in 2015, the first Dubna cluster of the Baikal-GVD telescope was installed, which had an effective volume of 0.05 km^3 for recording showers (cascades) and carried 288 optical modules with photomultipliers.

This unique event was noted in the prestigious European physics journal "CERN Courier", and in Dubna, a special memorable award was given to JINR



Installation of the detector. Left to right: Zh.-A. Dzhilkibaev, D. Ye. Zvezdov, T. V. Elzhov, and V. Shatunov



V. A. Matveev is awarded with the Dubna city administration's special award for the commissioning of the Dubna cluster

Director V. A. Matveev. He has been involved in the Baikal project for almost 40 years, since his being director at INR RAS.

A significant amount of infrastructure and technology development work both at Lake Baikal and at the main institutes was done with the direct participation of JINR. A work area for assembling, calibrating, and testing optical modules was established at DLNP. As a result, working and living conditions for specialists, ice operations technologies, and the ability to assemble, accumulate, and deliver cargo to the telescope installation site were significantly improved, enabling the installation of up to two clusters per year as early as 2019.

At this stage, the BARS data processing system was developed and is now being successfully implemented through joint efforts. Automated data processing procedures are being finalized. Algorithms for selecting and reconstructing muon and neutrino event trajectories have been developed, and procedures for reconstructing cascade events and their display systems have been improved. Data analysis since 2016 has identified six candidate events for detecting astrophysical neutrinos in the energy range from hundreds of TeV to 1 PeV, which is consistent with model calculations and the results of IceCube event detection[1]. Thus, the telescope has begun to supply data for the development of research in high-energy neutrino astrophysics and astronomy.

On March 13, 2021, at the ice camp on Lake Baikal in the place where the neutrino telescope is deployed under the ice, Minister of Science and Higher Education of Russia V. N. Falkov and JINR Director G. V. Trubnikov signed a Memorandum of Understanding between the Ministry of Science and Higher Education of Russia and JINR on the development of the Baikal deep-underwater neutrino telescope. At the same time, with the participation of INR RAS Director M. V. Libanov, the Baikal-GVD deep-unerwater neutrino telescope comprising eight clusters (2304 optical modules) was officially commissioned. The effective

[1] *Allakhverdyan V. A. et al.* Neutrino Telescope in Lake Baikal: Present and Nearest Future // PoS ICRC2021. 2021. V. 002; doi: 10.22323/1.395.0002.



Minister V. N. Falkov and JINR Director G. V. Trubnikov are signing a Memorandum of Understanding between the Ministry of Science and Higher Education of Russia and JINR

detector volume for recording high-energy neutrino events (over 100 TeV) reached ~ 0.4 km^3.

In 2022, during the analysis of data obtained during the operation of the detector in the 2018–2021 configurations, 11 under-horizon cascade events with energies exceeding 15 TeV initiated by neutrinos of astrophysical origin were identified. This confirmed, at a 3σ confidence level, the results of the first observation of a flux of high-energy astrophysical neutrinos at the Antarctic IceCube detector[2].

In 2023, during an analysis of the data obtained during operation of the detector in the 2018–2022 configurations, correlations of cascade events with energies exceeding 100 TeV with bright radio blazars were investigated. Although no statistically significant effects were detected in the current dataset, the analysis points to a number of possible associations with both extragalactic and galactic sources. In particular, an analysis of the observed triplet of neutrino candidates in the galactic plane was performed, its potential connection with certain galactic sources was investigated, and the coincidence of the arrival directions of the cascade events with several bright blazars was examined.

The increased statistics of the data accumulated from 2018 to 2023 enhanced the significance of the astrophysical neutrino flux observation. The reliability of the flux observation was now greater than 5σ. On the basis of these data, it was also concluded that the flux of galactic neutrinos with energies above 200 TeV was much

[2] *Allakhverdyan V. A. et al. (Baikal-GVD Collab.).* Diffuse Neutrino Flux Measurements with the Baikal-GVD Neutrino Telescope. e-Print:2211.09447 [astro-ph.HE]; Phys. Rev. D. 2023. V. 107. P. 042005.

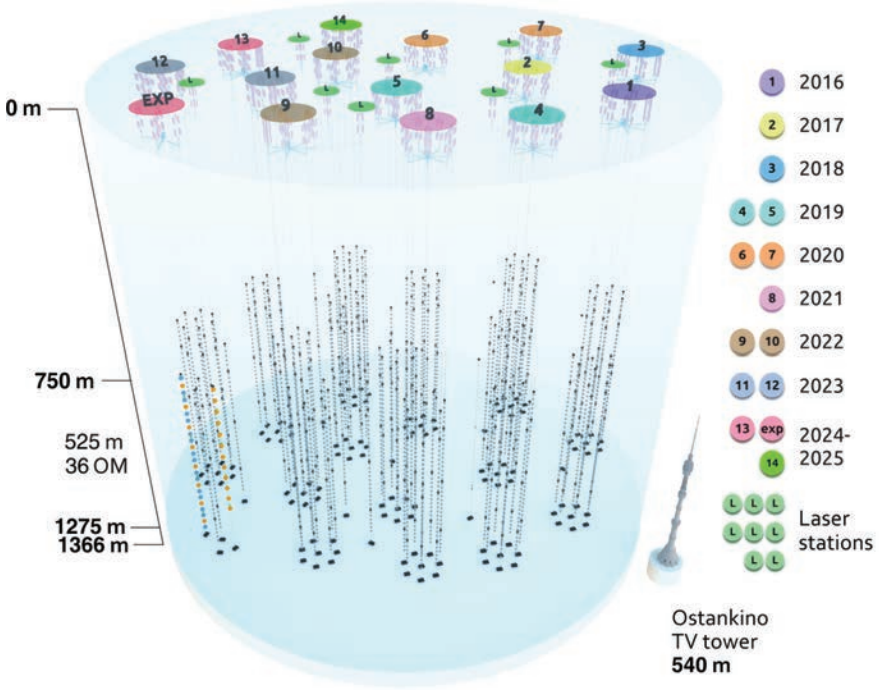


Fig. 2. The Baikal-GVD neutrino telescope after deployment, 2025. The detector's effective volume is more than 0.6 km^3 for cascade events from neutrinos in the energy range of 100 TeV–10 PeV

higher than predicted by current models. This Baikal-GVD result[3] is confirmed by an analysis of publicly available data from the IceCube neutrino telescope with energies above 200 TeV. The combined results of the two experiments highlight the urgency of developing new concepts of the origin and propagation of cosmic rays in our Galaxy and require more precise experimental measurements.

In October 2013, a memorandum of cooperation was signed between the IceCube, Antares, KM3NeT, and Baikal-GVD collaborations to create a network of neutrino telescopes (GNN) as the first stage of the Global Neutrino Observatory (GNO). The Baikal-GVD collaboration was also included in the list of 11 Russian megascience projects under the KREMLIN + program for collaboration with European research organizations and their involvement in research at Russian facilities. The DLNP JINR staff are included in and working under the international scientific program for the rapid exchange of data and events in space at facilities operating on various physical principles.

The project is currently being implemented based on plans for its development until 2030, primarily by the Institute for Nuclear Research of the Russian Academy of Sciences (Moscow) within the framework of a government order and the Joint

[3] *Allakhverdyan V. A. et al. (Baikal-GVD Collab.).* Probing the Galactic Neutrino Flux at Neutrino Energies above 200 TeV with the Baikal Gigaton Volume Detector. arXiv:2411.05608 [astroph. HE]. 2024.



The Baikal-GVD collaboration meeting. Dubna, June 2025

Institute for Nuclear Research (Dubna) acting on the basis of a decision of the Committee of Plenipotentiaries and the JINR Topical Plan.

In 2025, 14 clusters of the Baikal-GVD telescope operated in the data acquisition mode. They contain 4284 optical modules together with the intercluster strings and several strings on the experimental cluster based on a fiber-optic DAQ. The facility remains the largest neutrino telescope in the Northern Hemisphere.

THE TAIGA EXPERIMENT

Since 1993, DLNP has been studying ultrahigh-energy cosmic rays by recording extensive air showers. The TAIGA project, which is being implemented at the Tunka Astrophysical Complex located 50 km from Lake Baikal, studies gamma radiation and charged cosmic rays in the energy range of 10^{13}–10^{18} eV by recording Cherenkov radiation from extensive air showers.

There is a wide variety of tasks. These include studying the high-energy edge of the spectrum of the brightest galactic and extragalactic gamma-ray sources, searching for galactic pevatrons, applying a new hybrid approach to studying the mass composition of cosmic showers in the 10^{14}–10^{17} eV range, and studying the anisotropy of cosmic showers in the 100–3000 TeV energy range.

It was planned to use small experimental Cherenkov telescopes to study the energy range above 50 TeV using cameras with a 15° field of view. With these telescopes in operation, the percentage of events shared with the TAIGA-HiSCORE facility will increase up to a factor of 10, and the high efficiency of their separation from gamma quanta will be maintained.

In 2020, the 1-km^2 TAIGA prototype was commissioned. The distribution of extensive air showers from gamma quanta was obtained after 40 hours of observa-



Left to right: JINR Director G. V. Trubnikov, A. N. Borodin, ISTP SB RAS Director G. A. Zherebtsov, and D. V. Naumov with the fifth gamma-ray telescope (ACT-5) of the TAIGA facility being prepared for dispatch to the testing ground

tions of a gamma source in the Crab Nebula. The distribution is constructed for events when the telescope is pointed both at the source (ON distribution) and at a background region without the source (OFF distribution). The significance of the source signal was determined from the excess of events at small angles. The



Alignment of the fourth Cherenkov telescope in preparaion for the observational data collection season

resulting excess of events for the ON distribution indicated the detection of gamma rays[4,5] from the Crab Nebula with a significance of 6.3σ.

At the end of November 2023, employees of RIAP ISU, MSU, and JINR installed a lens telescope with a matrix of silicon photomultipliers.

In 2024, preparatory work was completed to upgrade and expand the detectors to an area of approximately 100 km^2. Telescopes with a composite mirror diameter of about 10 m are planned for the project, which will require the manufacture of lightweight composite mirrors. Their production will enable a transition from the traditional process of manufacturing monolithic glass mirrors to a faster and more efficient production of larger quantities of mirrors for Cherenkov telescopes.

Sector No. 4 of Astrophysical Research at the DLNP Department of Particle Physics, in collaboration with the Digital Production Center of Dubna State University, proposed a technology and manufactured a prototype lightweight composite mirror for the TAIGA Cherenkov telescopes. The mirror's parameters were measured, the technology was refined, and a proposal was prepared for the TAIGA collaboration to organize production of a batch of mirrors.

Since 2015, JINR has manufactured five Cherenkov telescopes with a composite mirror and a wide-angle lens Cherenkov telescope. All the telescopes have been shipped to Buryatia and installed at a testing site near the village of Tory. Three mirror Cherenkov telescopes (ACT-1, ACT-2, and ACT-3) and the wide-angle lens telescope are fully operational and are collecting data. The ACT-4 telescope was launched in 2025, and ACT-5 will be launched in late 2026.

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[4] *Budnev N. et al. (TAIGA Collab.)*. TAIGA — An Advanced Hybrid Detector Complex for Astroparticle Physics and High Energy Gamma-Ray Astronomy in the Tunka Valley // JINST. 2020. V. 15, No. 9. C09031.

[5] *Kuzmichev L. et al. (TAIGA Collab.)*. Cherenkov EAS Arrays in the Tunka Astrophysical Center: From Tunka-133 to the TAIGA Gamma and Cosmic Ray Hybrid Detector // Nucl. Instr. Meth. A. 2020. V. 952. P. 161830.

EXPERIMENTS AT THE KALININ NPP

THE νGeN EXPERIMENT

The νGeN experimental facility was created by scientists at DNLP JINR to study the fundamental properties of neutrinos. The search for coherent elastic neutrino scattering, the neutrino magnetic moment, and other rare processes — manifestations of new physics beyond the Standard Model — is being conducted at the Kalinin Nuclear Power Plant in Udomlya.



The νGeN detector during assembly at the Kalinin NPP

The νGeN spectrometer is installed in close proximity to the reactor core (~11 m), allowing it to operate with a massive neutrino flux: more than $4.4 \cdot 10^{13}$ cm$^{-2} \cdot$ s^{-1}. At the same time, the surrounding materials of the reactor, comparable to ~50 m of water equivalent, provide good shielding from background cosmic radiation.

The signals are recorded by a specially designed low-threshold germanium detector. Passive and active shielding systems were installed around it to protect it from external radiation. Data analysis has not yet revealed any signs of the expected signal from coherent neutrino scattering, but it has allowed a new limit on the number



The νGeN collaboration. Dubna, 2021

of elastic coherent neutrino scattering events to be set, depending on the quenching value[6].

The νGeN facility sensitivity to coherent elastic scattering of reactor antineutrinos is among the best in the world. The background level achieved in the experiment is the lowest among similar experiments with germanium detectors, and the neutrino flux is among the best. All this allows high sensitivity in searching for rare processes, in particular measuring the magnetic moment of neutrinos in reactors.

THE DANSS EXPERIMENT

Since 2009, the JINR Dzhelepov Laboratory of Nuclear Problems has been implementing the DANSS (Detector of AntiNeutrino based on Solid Scintillator) project — a compact new-generation neutrino detector for precision measurement of the flux of reactor antineutrinos and the search for new physics, including testing the hypothesis of the existence of sterile neutrinos.

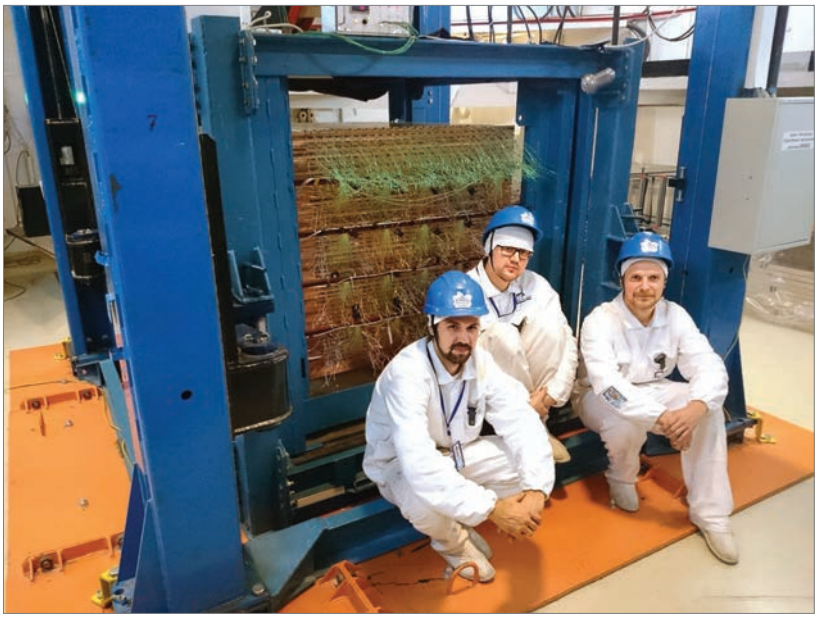
The history of the DANSS project dates back to the early 2000s, when a team from DLNP JINR, together with colleagues from ITEP, conducted the Gemma experiment at the Kalinin Nuclear Power Plant, dedicated to searching for the neutrino magnetic moment. It was then that the need arose to determine the change in the antineutrino flux from a nuclear power reactor – this parameter is critical for interpreting the results and reducing systematic errors. The initiators of the creation of a new type of compact detector were V. B. Brudanin, V. G. Egorov (JINR), and A. V. Starostin (ITEP), who proposed the idea of using segmented plastic scintillator technology with the possibility of installation directly under the reactor core.

The DANSS prototype (DANSSino), representing 1/50th the size of the future detector, was assembled in Dubna in 2011, and the first measurements at the Kalinin NPP began in 2012. This was possible due to years of preparation, accumulated experience in spectrometry and low-background measurements, and close collaboration with the Kalinin NPP and Rosenergoatom. Despite its small size, the prototype detector demonstrated sensitivity to changes in reactor power, giving the green light for a full-scale version of the detector.

DANSS is a modular detector with a volume of approximately 1 m^3 consisting of more than 2500 gadolinium-coated scintillation counters for efficient neutron capture[7]. Optical signals from each 1-m-long detector are collected using wavelength shifting optical fibers, which are then coupled to standard and silicon photomultiplier tubes. A high degree of segmentation and a multichannel readout system ensure event topology reconstruction and efficient signal separation from inverse beta decay and background interactions, making the facility one of the best in its class in terms of event selection and a signal-to-background ratio of up to 1/50. The pioneering mobile system is a key feature of DANSS, allowing the detector to be moved on a platform within a range of distances from ~10.9 to ~12.9 m from the reactor core without interrupting operation. This makes it possible to measure

[6] *Belov V. et al. (νGeN Collab.)*. New Constraints on Coherent Elastic Neutrino–Nucleus Scattering by the νGeN Experiment // Chin. Phys. C. 2025. V. 49. 053004.

[7] *Alekseev I. et al. (DANSS Collab.)*. DANSS: Detector of the Reactor Antineutrino Based on Solid Scintillator // JINST. 2016. V. 11, No. 11. P. 11011; arXiv:1606.02896 [physics.ins-det].



Assembling the DANSS detector. Left to right: E. A. Shevchik, I. V. Zhitnikov, and A. S. Kuznetsov



The DANSS collaboration. 2012

the antineutrino flux at different distances and minimize systematic errors, which are often a key obstacle when searching for signs of antineutrino oscillations into sterile states.

Since its launch, the DANSS facility has recorded the highest antineutrino flux among similar experiments: over 5000 inverse beta decay events per day with a record-low background level. A vast array of experimental data has been accumulat-



V. G. Egorov at the assembled DANSS detector



The DANSS collaboration. 2025

ed, covering six reactor campaigns. The experimental results[8] proved to be key to the analysis of the so-called "reactor anomaly" and have become one of the most significant contributions to the search for sterile neutrinos with a mass of approximately 1 eV. The measurement of reactor power with an accuracy of 1.5% is among the project's clearly practical achievements, being also the first for experiments of this type.

[8] *Alekseev I. G. et al.* The DANSS Experiment: Recent Results and Perspective // Bull. Lebedev Phys. Inst. 2024. V. 51. P. 8–15.

The DLNP JINR team is currently actively working on a large-scale upgrade of the facility — the DANSS-2 project, which aims to further improve measurement accuracy and reduce the influence of background effects. The DANSS results have been published in leading scientific journals, and two candidate dissertations have been defended based on them, with another defense planned for the near future. The project team includes V. V. Belov, I. V. Zhitnikov, S. V. Kazartsev, A. D. Bystryakov, A. S. Kuznetsov, D. V. Medvedev, E. A. Shevchik, M. V. Shirchenko, and other laboratory staff. The DANSS experiment would certainly not have been possible without the assistance of the ITEP and LPI researchers: M. V. Danilov, I. G. Alekseev, A. S. Kobyakin, I. V. Machikhilyan, D. N. Svirida, N. A. Skrobova, and many other colleagues who made significant contributions to the development of the project.

The DANSS experiment is one of the most successful neutrino projects carried out at JINR, which makes a significant contribution to fundamental research into the nature of neutrinos and the search for new physics beyond the Standard Model.

EXPERIMENTS AT OTHER SCIENTIFIC CENTERS

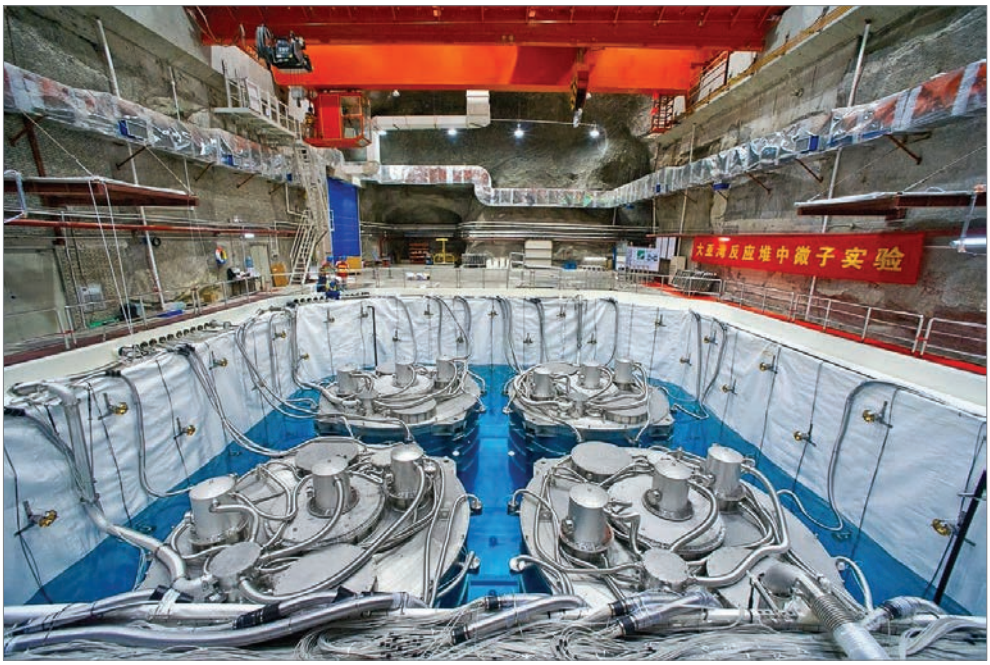
THE DAYA BAY EXPERIMENT

The primary goal of the Daya Bay experiment is to determine one of the last remaining unknown fundamental parameters of the Standard Model — the lepton mixing angle θ_{13}. The measurement method is based on comparing electron antineutrino fluxes at distances of approximately 2 km and in close proximity to their sources — nuclear reactors at nuclear power plants (NPPs). The experiment utilized eight identical antineutrino detectors located at distances ranging from 400 m to 2 km from the Daya Bay, Ling Ao, and Ling Ao II NPPs in southeastern China.

The angle θ_{13} determines the contribution of the electron flavor to the third mass state of the neutrino. For 10 years of operation, the experiment has accumulated over 5 million antineutrino interactions, allowing the measurement of the antineutrino flux and energy spectrum with record precision at various distances from the nuclear power plant. The identical design of the antineutrino detectors and regular calibration campaigns have significantly reduced systematic uncertainties when comparing spectra at different distances.

Planning for the Daya Bay experiment began in 2003, and the first collaboration meeting was held in 2005. Site preparation and construction began in 2009. Data has been collected since December 2011, when only a portion of the detectors were operational. By February 2012, sufficient data had been collected to enable a key discovery: the Daya Bay experiment reliably established a non-zero value for the angle θ_{13}, with a significance level of five standard deviations[9]. Ten years later, the parameter θ_{13}, initially the least studied, became known with the highest

[9] *Gonchar M. (Daya Bay Collab.)*. Precise $\sin^2 2\theta_{13}$ Measurement by the Daya Bay Reactor Neutrino Experiment // DAE Symp. on Nuclear Physics, Dec. 3–7, 2012, New Delhi; Daya Bay document 8103.



The "remote" experimental site of the Daya Bay experiment. Four antineutrino detectors in the pool during filling with water. 2011

accuracy among lepton mixing angles: the error of $\sin^2 2\theta_{13}$ was only 2.6%. Furthermore, another fundamental quantity — the absolute value of the difference of squares of the neutrino masses $|\Delta m^2_{32}|$ — was measured[10] with an accuracy of 2.4%, the highest among reactor neutrino experiments.

The data collection continued until 2022. The full data set and the statistical analysis software package were published in 2025.

In addition to precision measurements of oscillation parameters, the Daya Bay experiment also made significant contributions to neutrino physics: measuring the flux of reactor electron antineutrinos with the lowest error; determining the time dependence of the energy spectrum of reactor antineutrinos; measuring the energy spectrum of antineutrinos from the fission of the ^{235}U and ^{239}Pu isotopes; experimentally obtaining the first-ever limit on the size of the neutrino wave function; and obtaining the best possible limits[11] on the parameters of light sterile neutrinos with masses up to 0.5 eV.

The JINR team participated in all stages of the experiment, beginning with its preparation. Specifically, JINR was responsible for the production of one and a half metric tons of fluorescent dopant (PPO) for the liquid scintillator, the devel-

[10] *An F. P. et al. (Daya Bay Collab.).* Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay // Phys. Rev. Lett. 2023. V. 130. P. 161802; arXiv:2211.14988 [hep-ex].

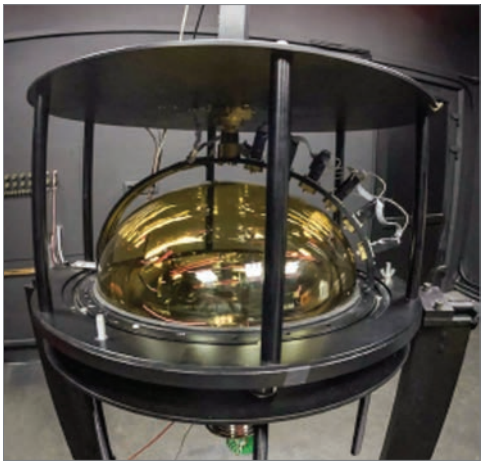
[11] *An F. P. et al.* Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay // Phys. Rev. Lett. 2017. V. 118. P. 251801.

opment of a muon veto system design based on a plastic scintillator, the selection of antineutrino interaction events, and the analysis of experimental data, including the main oscillation analysis of the experiment.

THE JUNO EXPERIMENT

JUNO (Jiangmen Underground Neutrino Observatory) is one of the world's largest neutrino experiments located in southern China. Its primary goal is to expand the study of the lepton sector of the Standard Model initiated at Daya Bay and achieve unprecedented precision comparable to that achieved in the quark sector of the Standard Model. Key goals include determination of neutrino mass hierarchy and precise measurement of the parameters Δm^2_{31}, Δm^2_{21}, and $\sin^2 2\theta_{12}$ with a relative uncertainty of less than 0.5%.

JUNO is the only experiment in the world capable of achieving this level of precision. The results from JUNO and Daya Bay will form the basis for future studies of CP violation in the leptonic sector.



A scanning station for large photomultiplier tubes of the JUNO central detector

The central detector of the experiment is a sphere with a radius of 17 m filled with 20 000 t of liquid scintillator. More than 18 000 photomultiplier tubes located on the surface of the sphere record the emitted light. Eight nuclear reactors located approximately 53 km from the detector serve as the antineutrino source.

An energy nonlinearity of less than 1% and a deposited energy resolution $\sigma = 3\%$ at 1 MeV are required to achieve sensitivity to the mass hierarchy.

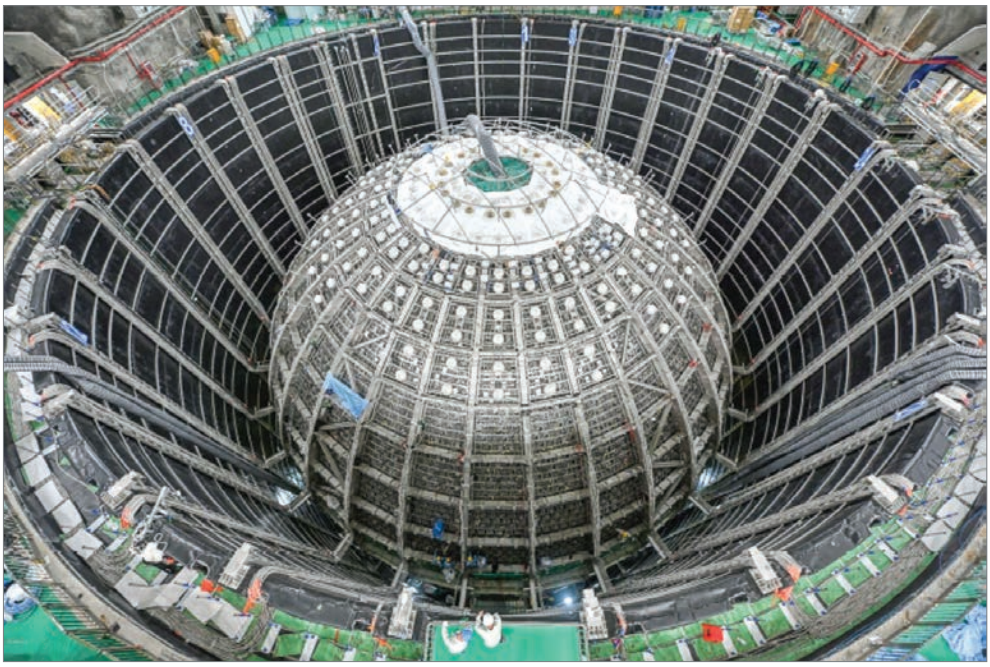
The near TAO (Taishan Antineutrino Observatory) detector provides a reference spectrum with a resolution $\sigma = 2\%$ and a statistical error of ~1%.

The first proposals for the experiment were received in 2008, and the first meeting of the collaboration took place in 2014. The main detector was constructed between 2022 and 2024, with physics data collection beginning in 2025.

The JUNO experiment program goes far beyond measuring reactor neutrino parameters; it includes measuring solar and geoneutrinos, atmospheric neutrinos, searching for neutrinos from supernovae (flares and diffuse background), and searching for sterile neutrinos, proton decay, invisible neutron decay channels, and dark matter particles.

Facility modification is planned after completion of the main physics program to conduct an experiment on neutrinoless double beta decay.

JINR is involved in all key areas of the experiment. The DLNP staff participate in the development and production of power modules for the JUNO PMTs and



Assembling the central detector of the JUNO experiment

the TAO silicon PMTs, the creation of scanning stations for PMT calibration, the development of the mechanics of the muon veto system, the assembly of the JUNO and TAO facilities, the development of the data acquisition system and reconstruction algorithms, the energy response analysis and event selection, and the physical analysis of reactor and atmospheric neutrinos.

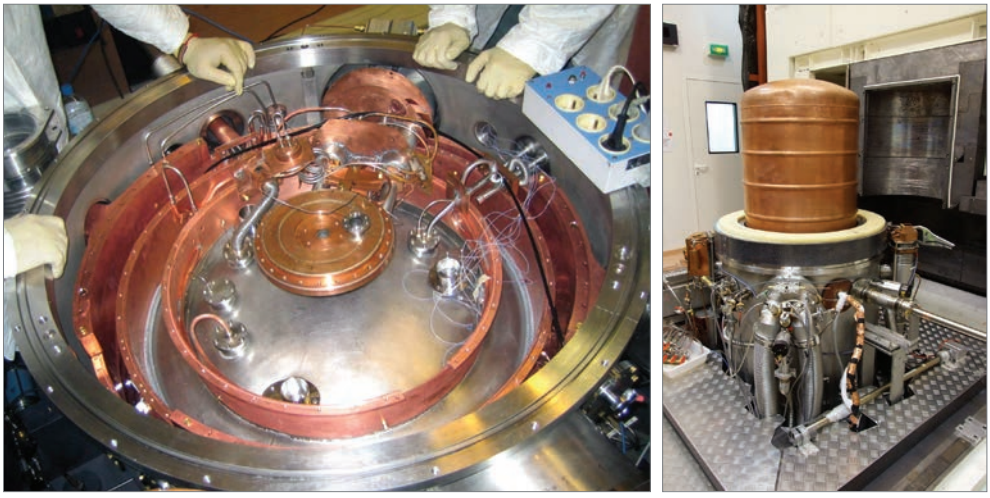
THE EDELWEISS, RICOCHET AND CUPID-Mo EXPERIMENTS

Since 2005, the JINR Dzhelepov Laboratory of Nuclear Problems has been participating in experiments to search for and study rare events using bolometer detectors operating at millikelvin temperatures. The main advantage of using such detectors is the ability to achieve a near-zero energy threshold using powerful methods for separating background events. This line of research at DLNP JINR began with the participation in the EDELWEISS experiment, although the development of the technology of bolometer detectors operating at millikelvin temperatures (mK bolometers) had been initiated in the laboratory by B. S. Neganov, V. N. Trofimov, and others much earlier. The main goal of the EDELWEISS experiment was the direct search for dark matter particles by their scattering on germanium nuclei. The initiative to apply the extensive spectrometric experience accumulated at DLNP JINR to the direct search for dark matter arose from Ts. Vylov and V. B. Brudanin. E. A. Yakushev was made responsible for conducting these studies.

At that time (early 21st century), the DLNP JINR researchers were already actively involved in low-background experiments (NEMO-3 and TGV) conducted

at the LSM (Laboratoire Souterrain de Modane) underground laboratory in the French Alps, in a tunnel connecting France and Italy. Considering all the circumstances, and especially the prospects of the research method, E. A. Yakushev and the team formed for this research joined colleagues from France and Germany to create a new, unique facility, EDELWEISS, at LSM.

The participation of the DLNP JINR team in this experiment led to the development of cutting-edge spectrometric methods and their application to studying one of the most crucial problems in modern physics — determining the nature of dark matter. With extensive experience in traditional spectroscopy, low-background measurements, and detector operation, the JINR team was responsible for



The EDELWEISS cryostat. Left: during assembly; right: assembled; foreground: a low-background neutron detector developed at DLNP JINR



The EDELWEISS experiment. D. V. Ponomarev, S. V. Rozov, and E. A. Yakushev install the detectors. 2016



The EDELWEISS experiment in the LSM underground laboratory. The photo was taken after disassembling the NEMO-3 facility (one of its modules is in the foreground) and before SuperNEMO assembly. Top right: the clean room housing the cryostat surrounded by a protective system. Top left: the control room. Bottom left: the cryostat's technical section

such important aspects of the experiment as neutron background monitoring, radon elimination and control, calibration with radioactive sources, low-background measurements of materials, and the development of new low-threshold detectors. The team participated in all stages of the assembly and operation of the facility, its multiple upgrades, data analysis, and simulations. Two decades of research and three phases of the experiment yielded a set of results that significantly constrained the parameters of hypothetical dark matter particles. These included the traditional search for weakly interacting massive particles (WIMPs), the low-mass region (below 10 GeV/c^2), and the search for axions and axion-like particles. It is generally recognized that the results of EDELWEISS research over the past decades have been important for the development of the techniques for direct search for dark matter particles and have been significant for world science[12].

The EDELWEISS experiment was completed in 2023. During its final phase, detectors were created that had unique properties for detecting low-energy events with a threshold of a few electronvolts. Therefore, the logical continuation of this experiment was the Ricochet experiment aimed at precisely studying the coherent scattering of reactor neutrinos in search of new physics[13]. It is expected that in such

[12] *Armengaud E. et al.* Search for Sub-GeV Dark Matter via the Migdal Effect with an EDELWEISS Germanium Detector with NbSi Transition-Edge Sensors // Phys. Rev. D. 2022. V. 106. 062004.

[13] *Augier C. et al. (Ricochet Collab.).* Fast Neutron Background Characterization of the Future Ricochet Experiment at the ILL Research Nuclear Reactor // Eur. Phys. J. C. 2023. V. 83. 20; https://arxiv.org/pdf/2208.01760.pdf.

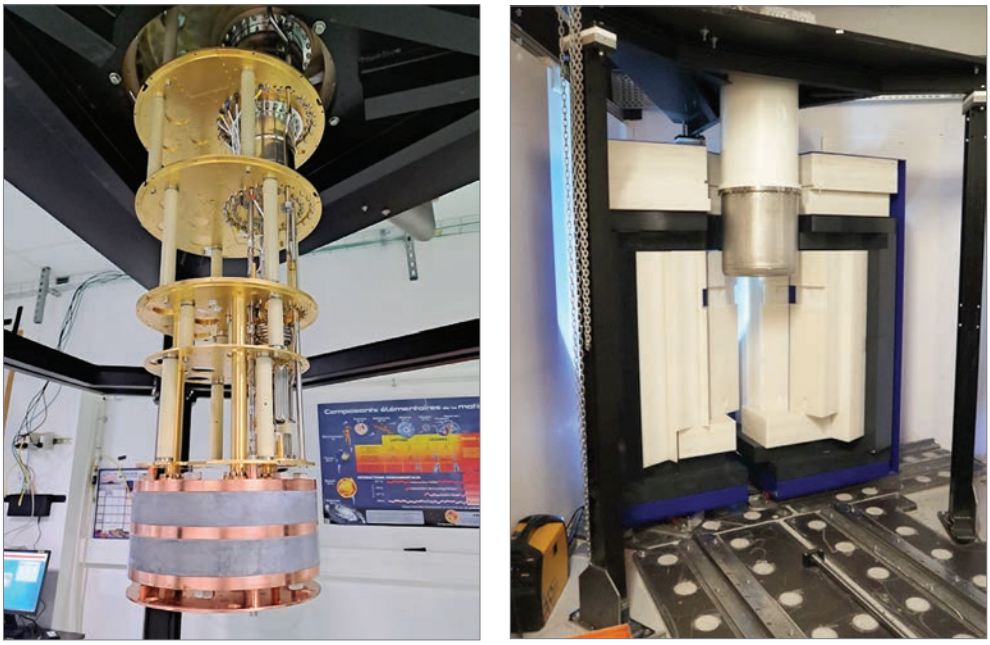


The Ricochet collaboration meeting. Grenoble, 2024

scattering the influence of new physics beyond the Standard Model will lead to spectral distortions in the nuclear recoil energy range below 100 eV. Currently, only bolometer detectors, such as those developed within EDELWEISS, are capable of precisely studying this energy range. The Ricochet facility, consisting of a dilution cryostat, germanium bolometers, and passive and active shielding, was assembled at the Institut Laue–Langevin (ILL, Grenoble, France) research reactor, and data collection began in 2025. JINR's contribution to this facility is decisive: from the cryogenic system with a low-background cryostat and active muon shielding to auxiliary detectors and new methods for assessing background conditions. Ricochet is aimed at studying the fundamental properties of neutrinos. The results obtained are expected to be of great significance for modern particle physics, nuclear physics, and astrophysics.

From 2019 until the end of EDELWEISS operation, bolometer measurements using the EDELWEISS infrastructure (cryostat, electronics, low-background materials) were extended to the CUPID-Mo experiment. This experiment searched for neutrinoless double beta decay of the ^{100}Mo isotope using 20 Li_2MoO_4 scintillator crystals while simultaneously measuring the phonon signal. The experiment achieved zero background for the neutrinoless beta decay search region by effectively separating events from alpha, beta, and gamma particles. Using data accumulated in the EDELWEISS cryostat, the CUPID-Mo experiment performed precision measurements of ^{100}Mo double beta decay and established a new best limit on its neutrinoless decay mode.

Five candidate dissertations and one doctoral dissertation were defended based on research on this topic. The following JINR scientists participated in the work at various stages: V. B. Brudanin, D. V. Filosofov, Yu. B. Gurov, D. V. Karaivanov, S. V. Kazartsev, T. Khusainov, J. Khushvaktov, A. V. Lubashevskiy, N. A. Mir-



The Ricochet cryostat. Left: during testing in Lyon. Right: inside the shielding at the ILL

zaev, D. V. Ponomarev, A. V. Rakhimov, I. E. Rozova, S. V. Rozov, A. V. Salamatin, S. S. Semikh, K. V. Shakhov, E. A. Shevchik, N. Temerbulatova, E. A. Yakushev, and others.

THE NEMO AND SuperNEMO EXPERIMENTS

The Neutrino Ettore Majorana Observatory, where the NEMO experiment began in 1989, is located in the underground laboratory (LSM) in the Fréjus road tunnel in France. Three detectors were used in the experiment: NEMO-1, NEMO-2, and NEMO-3. The prototype detectors, NEMO-1 and NEMO-2, were used until 1997. The experimental facility for the NEMO-3 project was developed and built beginning in 1994; data were collected from 2003 to 2011.

The NEMO-2 and NEMO-3 detectors made it possible to measure double neutrino decay and establish limits for neutrinoless double beta decay for a number of elements, such as ^{100}Mo and ^{82}Se. Scientists from DLNP JINR participated in the first-generation NEMO-2 and NEMO-3 experiments[14].

The NEMO project continues, the work on the development of an improved SuperNEMO detector at LSM is currently underway, and a next-generation detector is being developed. The DLNP JINR team plays a key role in this project,

[14] *Gomez H. on behalf of NEMO-3 and SuperNEMO Collab.* Latest Results of NEMO-3 Experiment and Present Status of SuperNEMO // Nucl. Part. Phys. Proc. 2016. V. 273–275. P. 1765–1770.



Assembling the NEMO-3 calorimeter. Left to right: L. Margaron, E. A. Yakushev, and O. I. Kochetov

specifically, by contributing to the development of the passive shielding, veto system, calorimeter, software development, data processing, and radiochemical purification methods.

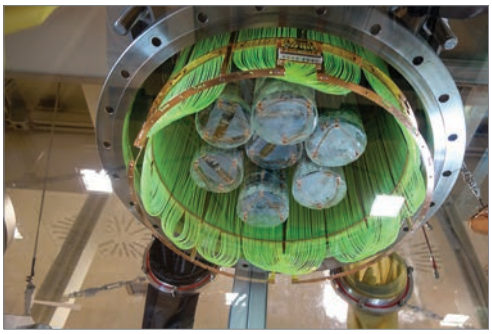
THE GERDA, MAJORANA AND LEGEND EXPERIMENTS

In the early 2000s, the international collaborations GERDA and Majorana were formed with the participation of the JINR Laboratory of Nuclear Problems. Their goal was to search for neutrinoless double beta decay ($0\nu\beta\beta$) of the ^{76}Ge isotope. The discovery of this process, which violates the conservation of lepton number, would be a direct indication of the Majorana nature of the neutrino (the identity of neutrinos and antineutrinos) and would clearly indicate the existence of physics beyond the Standard Model.

Both experimental facilities were housed in underground laboratories designed to minimize cosmic background: the Majorana Demonstrator at the Sanford Underground Research Facility (SURF, USA) and the GERDA facility at the Laboratori Nazionali del Gran Sasso (LNGS, Italy). Both experiments utilized germanium detectors enriched with ^{76}Ge isotope, with a total active mass of dozens of kilograms. The average mass of each detector was less than 1 kg.

The Majorana project utilizes a classic approach — germanium detectors mounted in ultrapure copper cryostats. GERDA, however, successfully utilized for the first time an innovative technique — open detectors immersed directly in liquid argon. This configuration simultaneously provided cooling to operating temperature and served as effective passive and active shielding from external radiation, due to the scintillation properties of argon. Thanks to this and to the selection of useful events based on pulse shape, the GERDA experiment achieved record-low



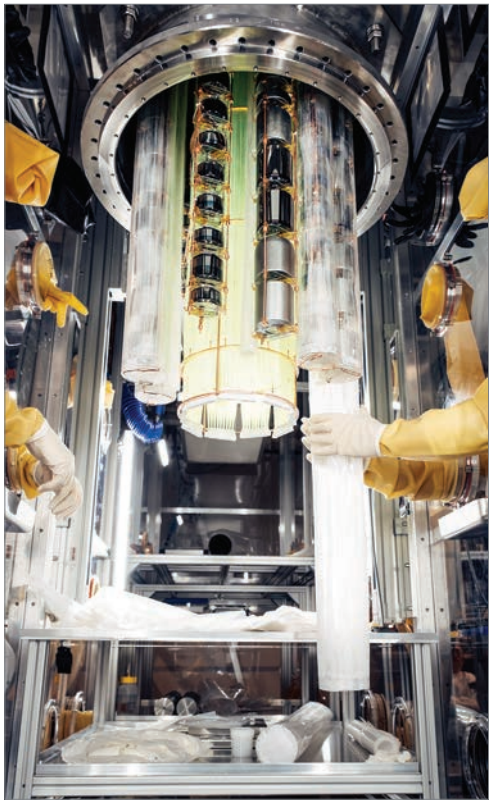


The GERDA experiment. Left: the final assembly of the detector array carried out by K. N. Gusev, the head of the GERDA (LEGEND) project at JINR and technical coordinator of the experiment. Right: the assembled GERDA detector array with its nylon covers and the assembled argon veto system before being immersed in liquid argon

background levels and set a world-leading half-life limit[15]: $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ y (90% CL) with an unprecedented sensitivity of $1.8 \cdot 10^{26}$ y. A clear success of Majorana is its best energy resolution of any experiment searching for $0\nu\beta\beta$ decay. Data collection in both projects is currently complete.

The combined efforts of the GERDA and Majorana collaborations, along with the involvement of new participants, have launched the next phase — the large-scale LEGEND experiment, which is being implemented at LNGS. The final stage of the project plans to increase the mass of the ^{76}Ge isotope to 1 t. Like GERDA, LEGEND utilizes a configuration with open germanium detectors immersed in liquid argon and a scintillation detection system. A significant improvement is the widespread use of a new type of detectors — inverted coaxial detectors — with a mass of up to 4 kg, which maintains highly effective background suppression based on waveform analysis.

The DLNP JINR researchers, extensively experienced in low-back-



The LEGEND experiment. Final assembly of the facility — the process of putting the nylon covers on the detector strings

[15] *Agostini M. et al. (GERDA Collab.).* Final Results of GERDA on the Search for Neutrinoless Double-β Decay // Phys. Rev. Lett. 2020. V. 125. P. 252502.



Winners of the 2020 JINR First Prize

ground double-beta decay research (NEMO-3 and TGV experiments), actively participated in all stages of the germanium projects. The JINR physicists analyzed experimental data and worked with open germanium detectors: from demonstrating their performance in a cryogenic environment to the final installation and dismantling within GERDA. During the early stages of the experiment, the DLNP specialists developed and implemented a plastic muon veto system. They made a significant contribution to the development and testing of argon scintillation registration principles and the creation of the first active argon veto system, successfully implemented in 2015. In 2018, in collaboration with the University of Munich, an improved version of this system with increased light collection efficiency was implemented. Special attention was paid to suppressing the background of the ^{42}Ar isotope. The DLNP staff developed specialized nylon covers with a wavelength-shifting coating, which significantly reduced the contribution of this component to the overall background.

A team of authors consisting of K. N. Gusev, M. V. Fomina, A. A. Klimenko, A. V. Lubashevskiy, N. S. Rumyantseva, E. A. Shevchik, M. V. Shirchenko, A. A. Smolnikov, I. V. Zhitnikov, and D. R. Zinatulina were awarded the 2020 JINR First Prize in the category of experimental research papers for their work "Background-free search for the neutrinoless double beta decay of ^{76}Ge in the GERDA experiment".

In 2022, as part of the LEGEND experiment, with the decisive participation of the DLNP staff, an array of 101 germanium detectors and a new argon veto sys-

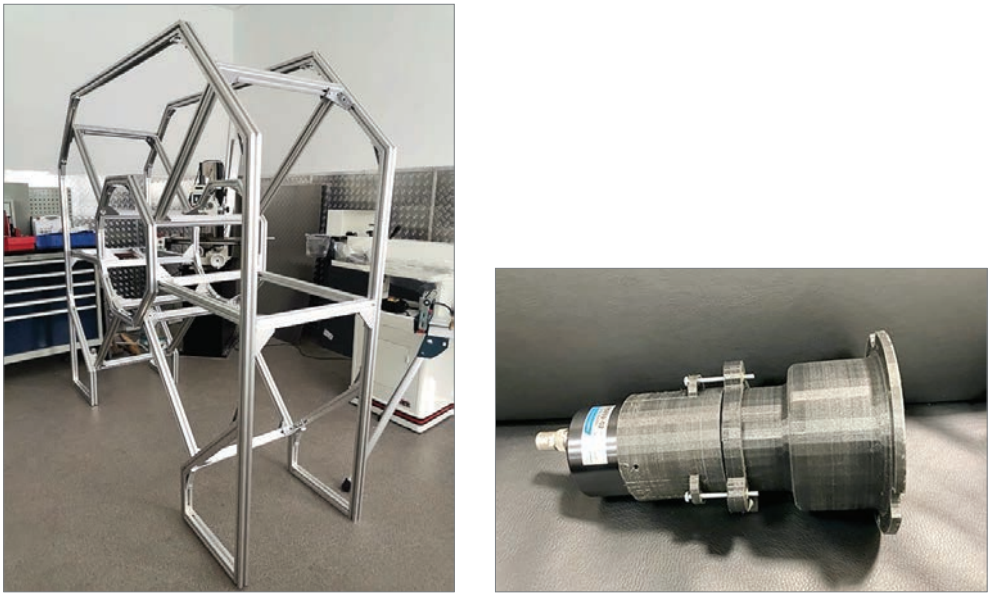
tem, developed and manufactured by a joint team from DLNP and the University of Munich, was assembled. The total mass of the enriched ^{76}Ge isotope exceeded 100 kg for the first time. The DLNP scientists and engineers continue to actively participate in the LEGEND project, which in its final phase has the highest potential for detecting neutrinoless double beta decay among all existing and planned experiments.

The results of GERDA, Majorana, and LEGEND have been presented at numerous conferences and meetings, and multiple papers have been published in peer-reviewed journals, including "Nature" and "Science". Several candidate and doctoral dissertations based on the experimental data are currently being prepared for defense. The following JINR scientists participated in the projects at various stages: V. B. Brudanin, V. G. Egorov, M. V. Fomina, K. N. Gusev, A. A. Klimenko, A. V. Lubashevskiy, N. S. Rumyantseva, E. A. Shevchik, M. V. Shirchenko, A. A. Smolnikov, S. I. Vasiliev, E. A. Yakushev, I. V. Zhitnikov, D. R. Zinatulina, and others.

THE MONUMENT EXPERIMENT

The MONUMENT project is aimed at experimentally measuring muon capture on several daughter nuclei (relative to neutrinoless 2β decay candidates). These measurements are important for verifying the accuracy of theoretical calculations of nuclear matrix elements.

A team of scientists from DLNP JINR, together with their European colleagues, submitted a proposal to perform ordinary muon capture measurements on several isotopes at the Paul Scherrer Institute (PSI) meson factory in Switzerland.



The detector mounting base (left) and the muon trigger with a target (right), developed and built at JINR by participants of the MONUMENT project



Left to right, sitting: S. V. Kazartsev, V. V. Belov, E. A. Shevchik; standing: M. F. Fomina, I. V. Zhitnikov, M. V. Shirchenko, N. S. Rumyantseva, K. N. Gusev, and D. R. Zinatulina

The proposal was reviewed and approved by the PSI Program Committee, and beam time was allocated for the study from 2021 to 2023.

The project continues and expands the previous muon capture measurement program proposed by and implemented under the leadership of JINR staff from 1998 to 2006. The DNLP JINR team, in turn, has extensive experience in precision nuclear spectroscopy and implementation of experiments studying not only rare processes but also those related to muon capture.

Today, the MONUMENT collaboration consists of 27 participants from 11 institutes. JINR plays a leading role in the experiment. The experimental infrastructure at the accelerator complex is provided by the partners. The members of the collaboration on the JINR side include outstanding skilled engineers and specialists: V. V. Belov, M. V. Fomina, K. N. Gusev, S. V. Kazartsev, N. S. Rumyantseva, E. A. Shevchik, M. V. Shirchenko, Yu. A. Shitov, I. V. Zhitnikov, and D. R. Zinatulina (head of the project).

From 2021 to 2023, ordinary muon capture measurements were carried out with isotopically enriched ^{136}Ba, ^{76}Se, ^{100}Mo, and ^{48}Ti targets at the PSI meson factory in Switzerland. The detector mounting base and the muon trigger system with the target were designed and built at JINR. Analysis of the data obtained in 2021–2023 with solid ^{136}Ba, ^{76}Se and ^{48}Ti targets is currently ongoing. The next stage of measurements is planned for autumn 2026 with isotopically enriched ^{12}C and ^{13}C targets.

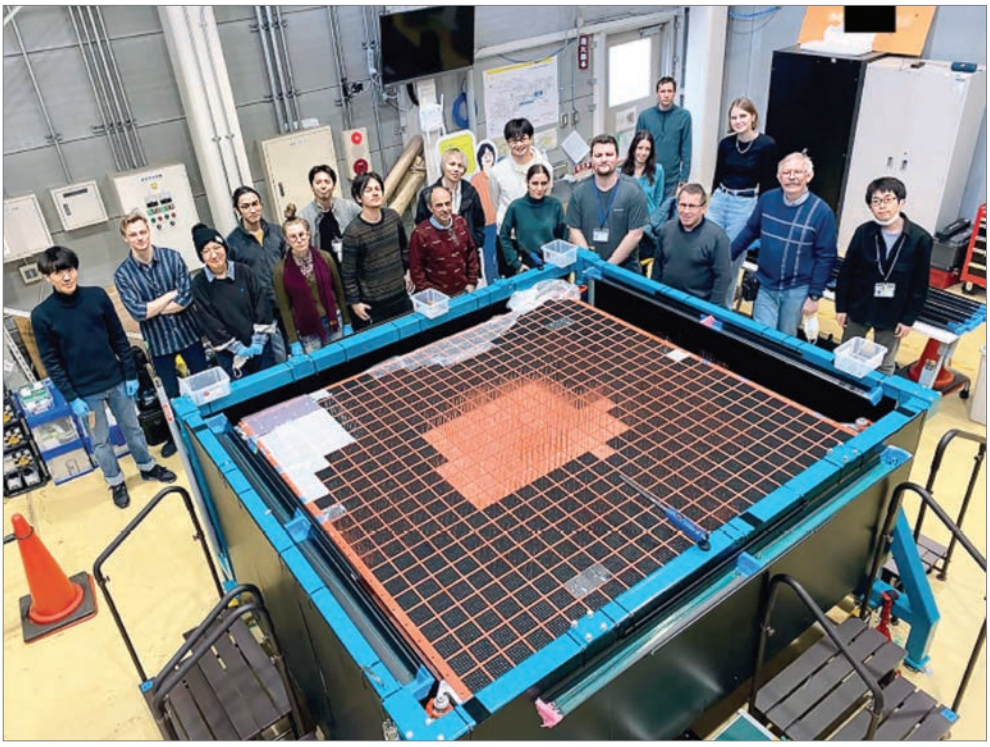
THE NOvA AND T2K EXPERIMENTS

The objectives of the NOvA and T2K experiments are to measure neutrino oscillation parameters, and, primarily, the still-unknown phase of violation of CP parity and the neutrino mass ordering. This information is in high demand: in particular, the mass ordering plays a significant role in modeling neutrino fluxes in supernova explosions. It is also important for assessing the prospects of a whole class of neutrino physics experiments searching for neutrinoless double beta decay. It is an input parameter for experiments on direct measurement of neutrino masses and search for relic neutrinos. The phase of CP violation in the lepton sector is associated in a number of models with a crucial phenomenon — the emergence of matter–antimatter asymmetry in the Universe.

JINR has been participating in the NOvA experiment since 2014. During this time, staff from the DLNP Department of Elementary Particle Physics made significant and diverse contributions. Their methodological research was used to refine a number of systematic uncertainties and improve detector modeling. The members of the group are developing several physical analyses related to the study of atmospheric muon fluxes, the search for magnetic monopoles and neutrinos from supernova explosions, and the detection of atmospheric neutrinos. For many years, JINR physicists have played a key role in the primary physical analysis of the NOvA experiment — the study of oscillations of three flavor neutrinos. This expertise has also found application in the active participation in the first joint



B. Miller (FNAL), A. Sheshukov, and O. Petrova (DLNP JINR) in front of the NOvA far detector



Participants in the final assembly stage of SuperFGD at J-PARC in spring 2023

analysis of the NOvA and T2K experiments aimed at measuring neutrino oscillation parameters.

The NOvA experiment is based at the Fermi National Accelerator Laboratory (FNAL, USA). The first detector of the experiment is located at a short distance (1 km) from the target to measure the initial composition of the particle beam. The beam then travels a distance of 809 km, and its flavor composition is recorded in the far detector. Both detectors are track calorimeters assembled from PVC cell planes filled with liquid scintillator. The near detector measures $3.9 \times 3.9 \times 15.9$ m, while the far detector measures $15.5 \times 15.5 \times 59.6$ m. The cross section of the individual cells that make up the planes in the near and far detectors is the same: 6×4 cm, and the length of the cells is equal to the transverse dimensions of the detectors.

A special feature of the NOvA experiment is the almost complete identity (except for the sizes) of the near and far detectors, which, during extrapolation, allows reduction in some of the systematic uncertainties, thus reducing their influence on the results.

JINR has been participating in the T2K experiment since 2020. Physicists from the DLNP Department of Multiple Hadronic Processes and Department for Research and Innovation conduct methodological research, model neutrino fluxes using measurements made in the SHINE experiment (CERN), and have already contributed to the assembly of a new target for the near detector of the experiment.

The T2K experiment is conducted at the J-PARC (Japan Proton Accelerator Research Complex). The particle flux under study is recorded in two detector complexes located at a distance of 295 km from each other. The T2K near detector complex is located 280 m from the target and consists of the INGRID on-axis detector and the ND280 off-axis detector. The T2K far detector is the Super-Kamiokande facility.

THE BOREXINO EXPERIMENT

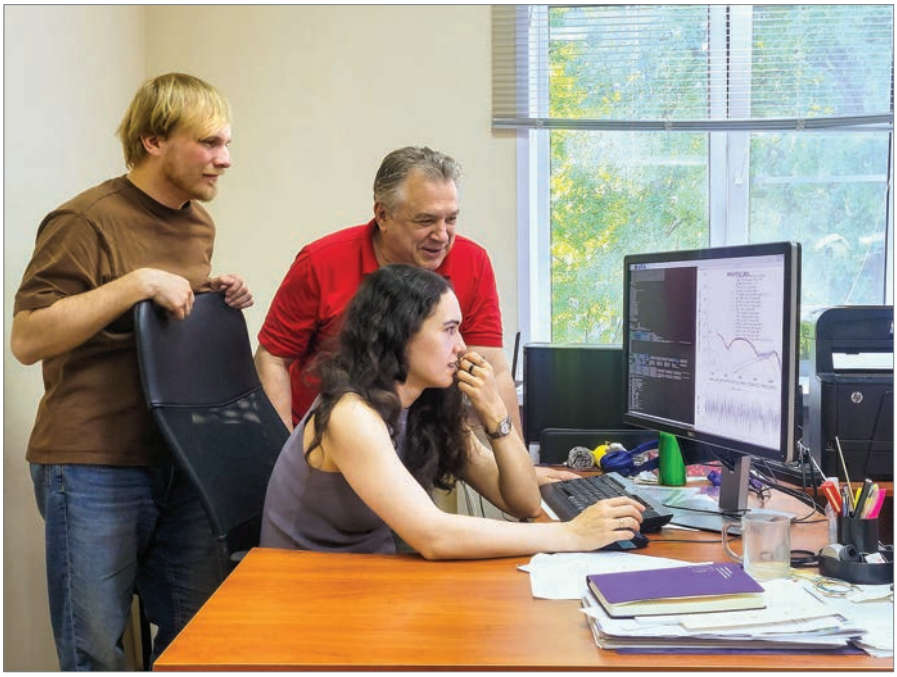
The idea of a large-volume liquid scintillation detector for recording low-energy solar neutrinos in real time was presented by an international group of physicists back in 1990. Dubna scientists joined the project in 1991 and participated both in the creation of the detector and in the analysis of its data.

Data collection at the Borexino detector began in May 2007 and continued until October 2021; the accumulated data are still being processed. After the shutdown of the detector, results of the observation of neutrinos from the carbon–nitrogen cycle were published.

The DLNP JINR team participated in processing Borexino data to obtain the key result on solar beryllium neutrinos. The analytical apparatus developed during the analysis of data from the prototype detector was successfully adapted for analyzing Borexino data. A precise analytical description of the spectra at low energies enabled direct measurement of the *pp*-neutrino flux, which was one of Borexino's most striking results. It should be emphasized that the idea for this measurement came from the Dubna scientists.



The Borexino collaboration at Gran Sasso against the background of the open CTF structure installed as an art object. 2018



The Borexino team discussing new results. Left to right: M. B. Gromov, O. Yu. Smirnov, and A. V. Vishneva. 2025

In addition to the primary analysis, the DLNP team searched for rare processes. This work yielded the strongest constraints on the effective magnetic moment of solar neutrinos, the violation of the electric charge conservation law, the violation of the Pauli exclusion principle in nuclei, and the antineutrino contamination in the solar neutrino flux.

The first reliable observation of a flux of geoneutrinos, or neutrinos produced by the decay of naturally occurring radioactive isotopes in the Earth, is among the most important results obtained with the group's participation. The measurement of geoneutrino fluxes confirmed the accuracy of general ideas about the internal structure of the Earth[16].

Four candidate dissertations and one doctoral dissertation were defended based on research conducted at Borexino. The group was awarded the 2013 DLNP JINR First Prize in experimental physics for the paper "Geoneutrino flux measurement at the Borexino detector", the 2014 JINR First Prize for the paper "Real-time measurements of solar neutrinos from the *pp* reaction at Borexino", the 2018 JINR First Prize for the series of three papers "Study of the *pp*-chain solar neutrino properties with the Borexino detector", and the 2019 DLNP JINR First Prize for the series of papers "Neutrino geophysics".

[16] *Smirnov O.* Experimental Aspects of Geoneutrino Detection: Status and Perspectives // Prog. Part. Nucl. Phys. 2019. V. 109. P. 103712.

THE OPERA EXPERIMENT

In 2001, JINR joined the international OPERA collaboration, which was developing a detector to search for oscillations of muon neutrinos into tau neutrinos using the CNGS neutrino beam directed from CERN to the Gran Sasso underground laboratory in Italy. Participation in this project was a continuation of the research conducted by DLNP JINR scientists as part of the MINOS and NOMAD experiments, and, earlier, the Neutrino Detector at IHEP (Protvino).

Within the OPERA project, the DLNP JINR team actively participated in the development of the Target Tracker (TT), the main electron detector. This included manufacturing scintillation strips, assembling modules and calibrating them in France, and assembling the detector in Gran Sasso. The total TT area was 6200 m^2, and the data acquisition system included 62 488 PMT channels. After the detector was commissioned, a software package for processing TT data was developed at the DLNP JINR to search for event peaks in the OPERA detector. The DLNP JINR team was responsible for analyzing the TT data and searching for neutrino event peaks almost throughout the experiment. Furthermore, an automatic scanning sta-



The OPERA detector in the Gran Sasso underground laboratory

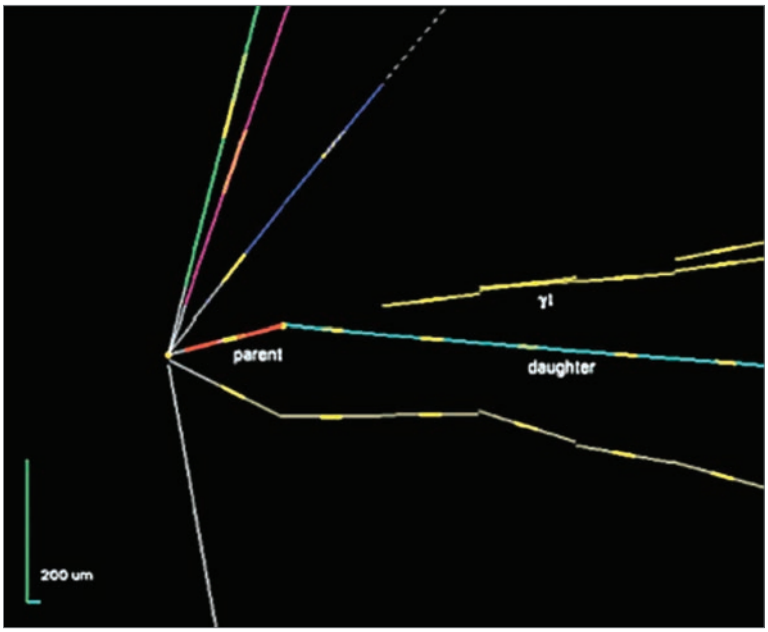


Fig. 3. The first recorded tau-neutrino interaction in the OPERA detector

tion developed at DLNP JINR was used to analyze neutrino events in a nuclear emulsion.

The main data were collected from 2008 to 2012, and their analysis continued for several more years. A total of approximately 20 000 neutrino events were registered by the detector. Ten events of tau-neutrino interactions were found among these events using specialized selection criteria and sophisticated analysis methods, including neural networks, with a confidence level exceeding 6σ. Thus, oscillations of muon neutrinos into tau neutrinos were discovered, and the main goal of the experiment was successfully achieved[17]. The experiment also yielded other important results: the charge asymmetry of cosmic muons was measured, and constraints on the existence of sterile neutrinos were established. In 2022, the team of experiment participants was awarded the JINR First Prize for a series of papers devoted to the study of neutrino oscillations.

Following the completion of the OPERA project, research on tau neutrinos, particularly the processes of their production at accelerators, was continued within the framework of new CERN projects: NA65 (since 2017) and FASER (since 2021). DLNP physicists are participating in these experiments, analyzing data from emulsion detectors used to register different types of neutrinos. In 2023, the FASER experiment detected for the first time neutrinos produced in proton beam collisions at the LHC, and estimated the interaction cross section in the energy range of 600 GeV to 2 TeV.

[17] *Agafonova N. et al. (OPERA Collab.).* Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment // Phys. Rev. Lett. 2015. V. 115, No. 12. P. 121802.

The Target Tracker detector was later disassembled and transported to China to record cosmic muons in the JUNO experiment; thus it was given a second life.

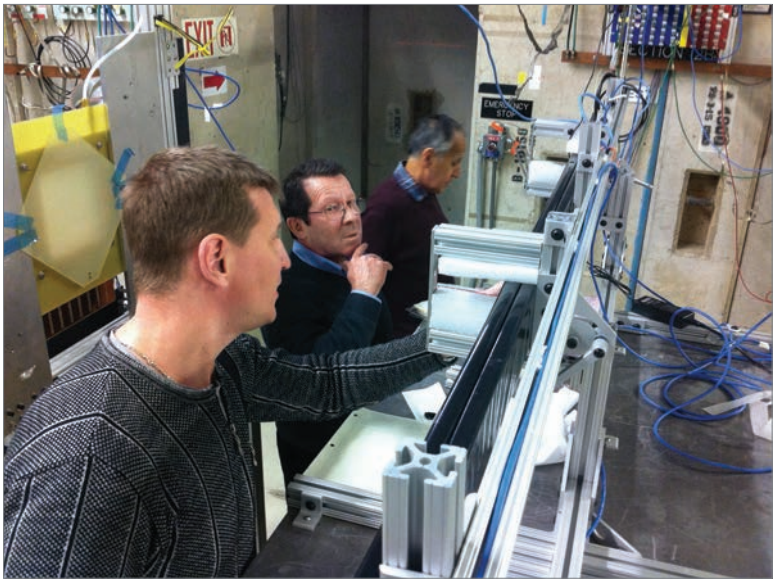
THE Mu2e EXPERIMENT

Processes with charged lepton flavor violation (cLFV) are strictly forbidden in the Standard Model with massless neutrinos. These processes include, in particular, the decays $\mu^+ \to e\gamma$, $\mu^+ \to 3e$, and the coherent conversion of a muon to an electron in the nuclear field $\mu^- + N \to e^- + N$. The discovery of neutrino oscillations showed that neutrinos have a nonzero mass, and this does not forbid processes with charged lepton flavor violation. However, such processes would occur at a level of $\sim\Delta m_\nu^4 / M_W^4 < 10^{-50}$, which is immeasurable under current conditions. However, some theories show the possibility of processes with charged lepton flavor violation beyond the Standard Model at levels of 10^{-15}–10^{-20}.

The Mu2e experiment at FNAL (Batavia, Illinois, USA) plans to search for the coherent conversion of a muon to an electron in the field of an aluminum nucleus: $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$, which violates the lepton charge conservation law. The emission of monoenergetic electrons with $E = 105$ MeV after muon capture into the orbit of an aluminum atom is a characteristic of such an event. The current experimental limit on the process of coherent conversion of a muon to an electron in the nuclear field was established by the SINDRUM II experiment to be $R_{\mu e} < 7 \cdot 10^{-13}$ (90% CL).



D. Chokheli (left) and Yu. N. Kharzheev at the University of Virginia (USA), assembling a prototype of the CRV system



A. V. Simonenko, Yu. I. Davydov, and A. M. Artikov (left to right), preparing a CRV system module for beam testing at FNAL (USA)

Researchers at the DLNP Department of Multiple Hadronic Processes have been actively involved in preparing the Mu2e experiment since 2009. One of the group's areas of work is the creation of an electromagnetic calorimeter in collaboration with colleagues from Italy (Frascati, Pisa) and the USA (Caltech, Pasadena). Staff members of the DLNP Department of Multiple Hadronic Processes, including N. V. Atanov, V. Yu. Baranov, Yu. A. Budagov, V. V. Glagolev, Yu. I. Davydov, and others, were actively involved in this project at various times.

Together with colleagues from Italy and the United States, LYSO, BaF_2, and CsI crystals were studied, which were considered candidates for use in the calorimeter. Prototype calorimeters based on LYSO crystals were tested in accelerator beams in Mainz and Frascati. Due to economic and technical constraints, CsI crystals were ultimately chosen. Studies of the CsI crystal-based calorimeter prototypes were conducted in the secondary electron beam in Frascati and in the direct beam of the LUE-75 linear electron accelerator at the Yerevan Physics Institute (Armenia). It is worth noting that the Yerevan colleagues succeeded in achieving a linear accelerator operating mode that provided a beam of several hundred electrons per second, an unconventional task. At all stages of this work, JINR's staff made significant contributions to bench studies of individual crystals, the development and testing of preamplifiers, and the creation and study of calorimeter prototypes. The results obtained during this work formed the basis for two candidate theses by staff members of the Department of Multiple Hadronic Processes.

The second focus area involves the development of the cosmic background veto system (Cosmic Ray Veto, CRV), jointly with colleagues from the University of Virginia and FNAL (USA). A. M. Artikov, D. Chokheli, Yu. N. Kharzheev, A. V. Simonenko, I. I. Vasiliev, and others made significant contributions to this area.



Participants in the CRV system prototype proton beam testing are satisfied with the research results. FNAL, 2016

Background suppression is the key objective of any experiment aimed at searching for forbidden processes or studying rare processes. To achieve the expected single-event sensitivity of Mu2e, the cosmic background must be suppressed to a level where no more than 0.25 cosmic muon event simulating the target electron is obtained during three years of data collection. This requirement is achievable using the CRV veto system, which has a cosmic ray detection efficiency of at least 99.99%. A strip of extruded polystyrene scintillator measuring 20×50 mm in cross section is the main component of the CRV module. Each strip has two so-called coextruded longitudinal holes within the scintillator body, each 2.6 mm in diameter. Each hole accommodates a wavelength-shifting (WLS) fiber with a diameter of 1.4 mm.

Participants in the Mu2e experiment from DLNP made a decisive contribution to the development of the CRV system, as well as the design of all stages of module assembly and testing for mass production. The DLNP researchers were the first to propose and experimentally demonstrate an increase in light collection from scintillators when detecting signals using wavelength-shifting fibers by injecting liquid optical filler into the holes. It was shown that filling the holes with liquid optical filler increases light collection from the detector by approximately 50%. A fundamental difference between this method and traditional two-component adhesive is the absence of a time limit on the hole filling. Research into the development of a method for increasing light collection from long scintillators by injecting liquid

optical filler into the holes was awarded the 2019 JINR Second Prize for methodology, research and technology papers.

Increasing light collection by filling the holes with liquid filler will compensate for the loss of scintillator light yield due to natural aging. It should be noted that achieving the required efficiency of 7-m-long Mu2e counters over the entire duration of the experiment is practically impossible without filling the holes with optical filler. The proposed technique can be used in any experiment with a similar counter design.

In 2025, FNAL completed the assembly of the entire Mu2e spectrometer in a building specially constructed for the experiment. Data will be collected in two stages. The facility is planned to operate for a year during the first stage (Run I). A two-year break is then planned for accelerator upgrades, after which the second data collection (Run II) will be conducted over a period of two to three years. It is expected that if the desired signal is absent in the Run I data, the Mu2e experiment will set a new limit on the process of coherent muon-to-electron conversion in a nuclear field of $R_{\mu e} < 6.2 \cdot 10^{-16}$ (90% CL), improving the existing limit by three orders of magnitude. As a result of data collection in Run II, in the absence of a muon-to-electron conversion signal, Mu2e will lower the limit by another order of magnitude.

Mu2e is planned to continue operation under the improvement of the FNAL accelerator complex. Proton Improvement Plan II (PIP-II) aims to create the world's most intense high-energy neutrino beam for DUNE. This plan will lay the foundation for the future high-intensity program capable of providing a beam of up to 100 kW for the Mu2e-II experiment. This will enable the detection of new physics events or, in their absence, at least further lowering of the limit on the process of coherent muon-to-electron conversion in the nuclear field $R_{\mu e}$ by an order of magnitude.

THE PEN, MEG AND MEG II EXPERIMENTS

The aim of the PEN project (PSI, Switzerland) was the precise study of the $\pi^+ \to e^+\nu$ decay.

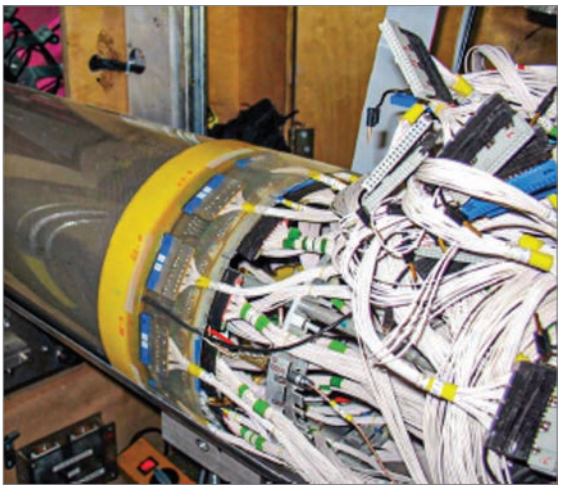
The central coordinate detectors of the PEN spectrometer are cylindrical multiwire proportional chambers developed and manufactured at DLNP.

The facility was also supplemented with a DLNP-made mini time projection chamber (mTPC), designed to determine hit points of charged particles on a target.

The charged particle detector in the MEG spectrometer consisted of 16 radially arranged drift chambers. The DLNP JINR staff participated in the manufacture of the drift chambers.

The uniqueness of the developed chambers lies in the minimum possible amount of matter in the working volume, combined with high efficiency and coordinate accuracy, which allowed for world-leading results in the search for the $\mu^+ \to e^+\gamma$ decay.

MEG II is an upgraded MEG facility. After replacing and improving the performance of several spectrometer components, it is expected to achieve a limit on the $\mu^+ \to e^+\gamma$ decay probability at a level of $(4–5) \cdot 10^{-14}$.



The block of cylindrical chambers at the moment of installation in the central part of the PEN spectrometer

The MEG II charged particle detector was radically modified by replacing 16 flat drift chambers with a hyperbolic multiwire chamber (CDCH). DLNP employees A. O. Kolesnikov, N. P. Kravchuk, and V. L. Malyshev participated in the construction and maintenance of the chamber. The combination of the results from the MEG runs prior to 2013 and the MEG II runs in 2021–2022 has already yielded a record-breaking result: $B(\mu^+ \to e^+\gamma) < 1.5 \cdot 10^{-13}$ (90% CL).

THE PIBETA EXPERIMENT

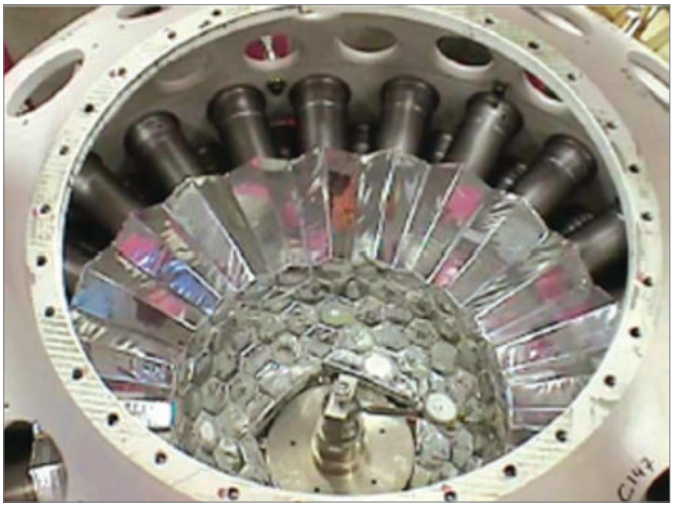
The PIBETA detector, developed by an international collaboration with the active participation of physicists from the DLNP Department of Intermediate-Energy Physics, is designed for the precision study of rare decays of pions and muons at rest. The design and properties of the detector's main components were chosen to maximize the efficiency and reliability of recording the rare processes under study.

The PIBETA detector is the first in the world to use 240 ultrapure CsI crystals with a total mass of 1.6 t to create a 4π calorimeter. These crystals have a short scintillation decay time and a small radiation length, which is critical for developing a compact device capable of operating with large particle fluxes (loads).

The detector also utilizes the world's first original thin-walled cylindrical multiwire proportional chambers developed and manufactured at DLNP. The chambers were accompanied by original anode and cathode electronics. All of this enabled the precise study of rare processes with a relative probability of ~10^{-8} at an absolute level with an accuracy of ~0.5%.

Using the PIBETA detector, statistics on pion beta decay and radiative decays of pions and muons were obtained in continuous multi-month data collection runs on the pion beam of the PSI meson factory (Switzerland) during 1999–2001.

As a result, a new value for the relative probability of pion beta decay was obtained: BR = $(1.038 \pm 0.004\ (\text{stat.}) \pm 0.006\ (\text{syst.})) \cdot 10^{-8}$ with an accuracy almost an



Assembling crystals for the PIBETA facility

order of magnitude greater than that previously known. This value is in full agreement with the Standard Model, in which, according to the PDG data, it should be BR = $(1.038–1.041)\cdot10^{-8}$ (90% CL). In turn, this confirms at a new level the validity of the hypothesis of vector current conservation in weak interactions.

New data on radiative decay have allowed the unambiguous estimation of the axial-vector form factor $F_A = 0.0115(4)$. The new F_A value was determined with an accuracy approximately 4 times better than previously and is consistent with calculations in the chiral Lagrangian model.

As a result of a preliminary analysis of data on the radiative decay of the pion, indications were obtained of the absence of a destructive anomaly in this decay inconsistent with the Standard Model of electroweak interactions.

NUCLEAR PHYSICS

The Flerov Laboratory of Nuclear Reactions (FLNR) was founded in 1957 by the distinguished Soviet physicist Georgy Nikolaevich Flerov. His scientific persistence in the search for new heavy and superheavy elements shaped the future direction of nuclear physics to a great extent. In 2012, his name was recorded as the name of element 114 of the Mendeleev's Periodic Table of Chemical Elements — flerovium (Fl), officially recognized by the International Union of Pure and Applied Chemistry (IUPAC).



Academician G. N. Flerov

In 1958, Yu. Ts. Oganessian joined the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. A close student of Academician G. N. Flerov, he contributed significantly to the further development of heavy-ion physics. The first ion beam was produced at the U-300 accelerator in September 1960 thanks to him. Yu. Ts. Oganessian authored fundamental works on the synthesis of new elements using heavy-ion beams. In the 1960–1970s, Oganessian's team carried out the first experiments on the synthesis of elements with $Z = 104–108$. Fusion reactions of neutron-rich actinide isotopes with accelerated calcium-48 ions were chosen to study very heavy nuclei at U-400 cyclotron. In 1999–2003, these reactions were the first to synthesize nuclei with $Z = 111–116$ and 118, whose decay properties demonstrate the existence of the "island of stability" in the region of superheavy elements. Academician Yu. Ts. Oganessian is the Scientific Leader of the Flerov Laboratory of Nuclear Reactions. In 2016, element 118 of the Periodic Table was officially named "oganesson". In 2012, construction of the Superheavy Element (SHE) Factory began. The facility is based on the new high-current DC-280 accelerator and is equipped with several modern, highly efficient setups for physics and chemistry research. The DC-280 cyclotron was commissioned in 2018, and first experiments at the SHE Factory were launched as early as 2020.



Academician Yu. Ts. Oganessian

Thanks to G. N. Flerov and Yu. Ts. Oganessian, the Flerov Laboratory of Nuclear Reactions became one of the world's leading nuclear physics centers. Today, FLNR is more than just a laboratory; it is the world's largest research center in the field of heavy-ion physics, implementing international projects, building unique accelerator complexes, and carrying out applied research.

DEVELOPMENT OF THE FLNR ACCELERATOR COMPLEX

Modern nuclear physics is impossible without a sophisticated experimental base. The FLNR accelerator complex is developing dynamically, and its evolution is directly linked to the fundamental task of exploring the boundaries of the material world — the limits of the existence of atomic nuclei and atoms. Particular attention is paid to the Laboratory's internal engineering culture. Much of what is used at the Laboratory — from accelerator systems to vacuum and radiation protection systems — is developed on-site, taking into account the unique experimental conditions. The Laboratory has its own design bureau, teams specializing in automation, cryogenics, electronics, vacuum and radiation engineering, and staff concentrated on target production.

The development of the FLNR accelerator base, which includes a number of modern accelerators, was driven by the high level of its engineering staff and the pursuit of record-breaking beam parameters. This section is devoted to the development of the FLNR accelerator complex in the 21st century.

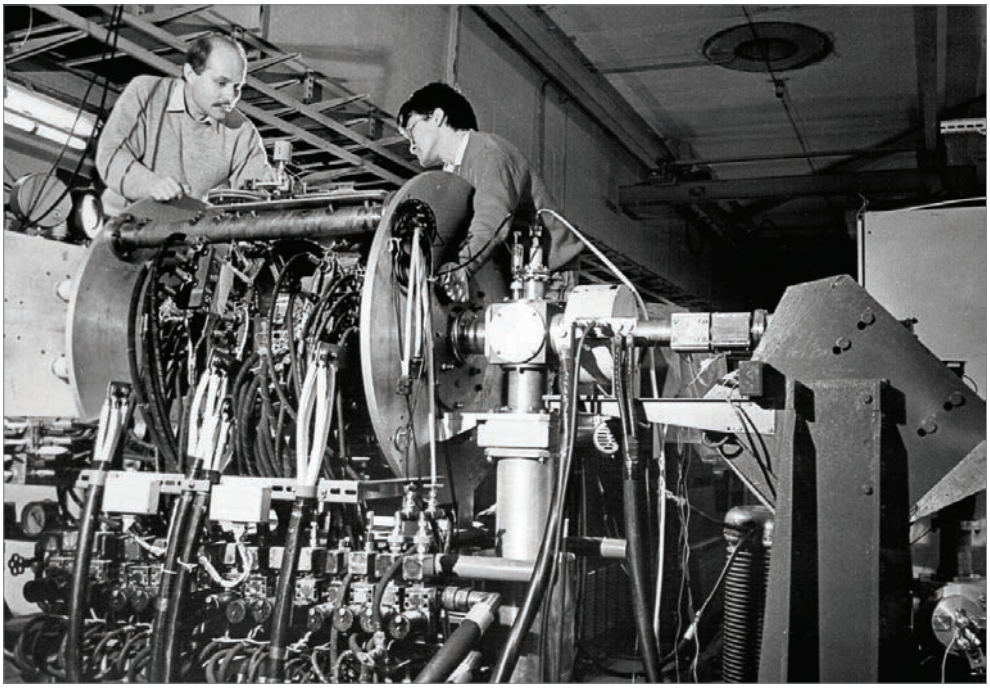
THE DRIBS-I PROJECT

At the beginning of the century, the DRIBs-I complex was completed and commissioned. It was designed to produce exotic radioactive nuclei in fragmentation reactions on a beryllium target of light-ion beams (^{7}Li, ^{11}Be, etc.) at the U-400M accelerator with energies of approximately 40 MeV/nucleon and intensities of several pμA. The project involved the development of a target and a hot catcher, and solving complex problems of nuclear diffusion and effusion into the ion source. A unique 2.45-GHz ion source, a high-vacuum ion guide between the cyclotrons, and a beam diagnostics system were created. The complex utilized equipment from two cyclotrons — the U-400M and U-400.

ION SOURCES

Ion sources play a crucial role in providing intense beams for nuclear physics experiments. At the beginning of the 21st century, there was an urgent need to increase the intensity of ^{48}Ca beams and reduce the consumption of this expensive isotope during the search for superheavy elements.

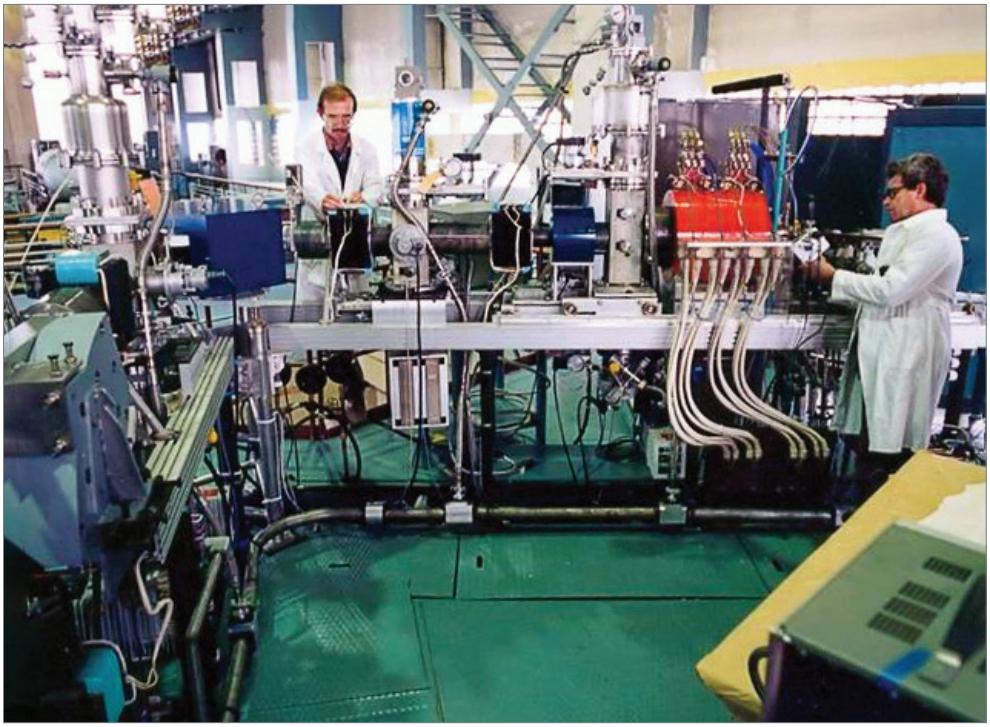
At the turn of the century, comprehensive experiments were performed using intense heavy-ion beams of the U-400 cyclotron to explore the opportunity to synthesize superheavy elements. For example, argon and manganese beam intensities routinely reached dozens of pμA using a Penning source. However, attempts to effectively accelerate ^{48}Ca ions from such a source were unsuccessful — intensities at the level of 0.1 pμA were only achieved with a huge isotope consumption of 10 mg/h, corresponding to a cost of approximately $1000 per hour. It was necessary to increase the intensity tenfold and reduce the isotope consumption tenfold. This could be achieved using a new generation of ion sources based on plasma ionization in a magnetic "bottle" with electrons resonantly accelerated in a microwave field — an electron cyclotron resonance (ECR) source.



The first ECR source at FLNR — DECRIS-I

Concurrently with the development of its own ECR source in the mid-1990s, the U-400 cyclotron was equipped with an ECR-4M source delivered from France and an axial beam injection system. Acceleration efficiency increased fourfold. Only after a simple improvement — installing thermal shields in the discharge chamber — the challenge of efficiently using the expensive isotope was resolved and a cruising mode became feasible for the synthesis of new elements (Fig. 1).

All cyclotrons and facilities using the ISOL scheme at FLNR were further equipped with ECR ion sources of various modifications, with operating frequencies from 2.45 GHz for synthesizing single-charged ions to 18 and 28 GHz for producing beams of multi-charged ions of heavy elements up to $^{238}U^{38+}$, including those with superconducting magnetic systems.



ECR-4M ion source and beam transport to the U-400 cyclotron. V. B. Kutner and S. L. Bogomolov. 1997

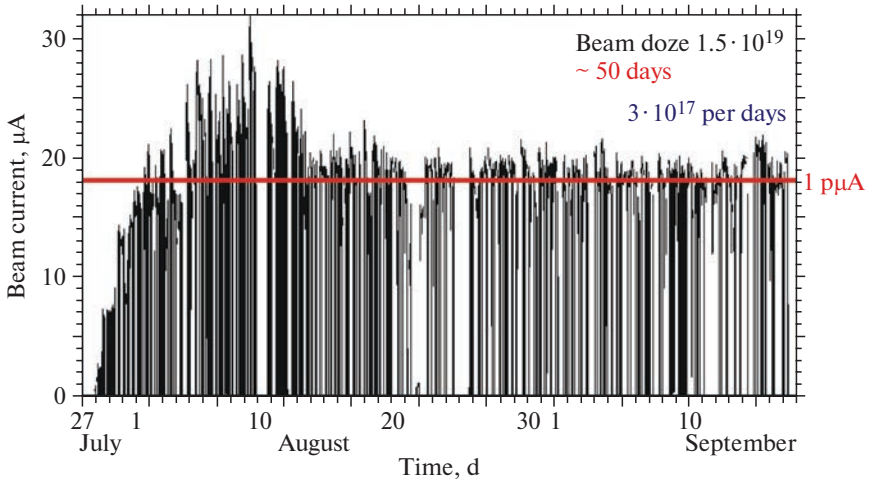
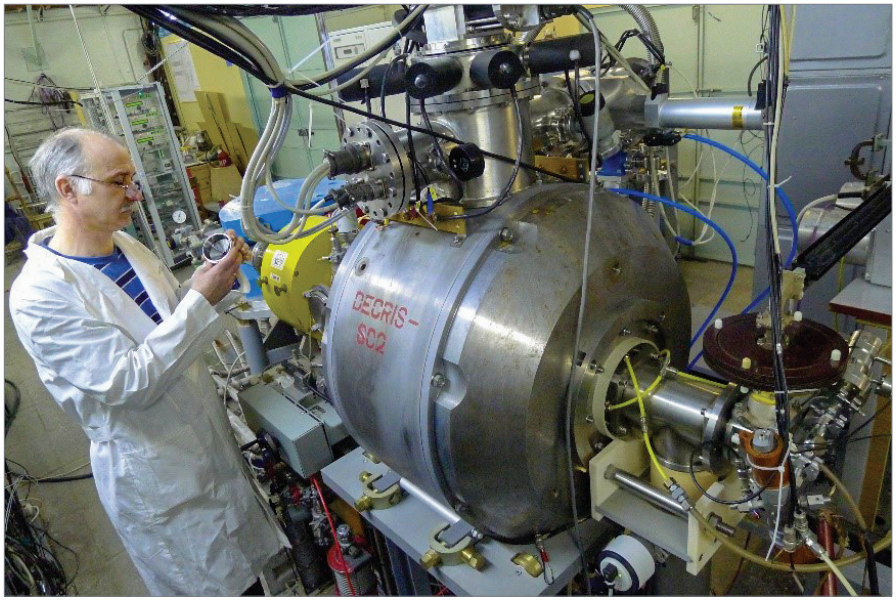


Fig. 1. Cruising mode of $^{48}Ca^{5+}$ acceleration at U-400. Isotope consumption is 0.5 mg/h. 2010

In total, more than ten ECR ion sources for accelerators and physics facilities have been developed at FLNR, 90% of which are intensively used at the Laboratory and in those of the JINR Member States.



All-permanent magnet DECRIS-PM ion source of the DC-280 cyclotron



Leading Engineer V. N. Loginov standing by the superconducting DECRIS-SC2 ion source of the U-400M cyclotron

FLNR CYCLOTRONS

Accelerators at FLNR are effectively used for a wide range of physics and chemistry experiments, including condensed matter physics and materials modification. The total accelerator beam time-on-target was maintained at 15 000 h annually thanks to the experimental program and the efforts of all services of the Laboratory's Chief Engineer.

U-400M Cyclotron

The U-400M accelerator was built in the unstable early 1990s using the magnet of the first cyclotron at FLNR, the U-300. The rearrangement of sections was needed by the end of the second decade of the 21st century, followed by replacement of the main copper coils, which weighed 110 t. In addition, it was decided to completely upgrade and rebuild the cyclotron's outdated systems — the entire vacuum system, control and monitoring system, radiation safety, interlocks and access control systems, beam diagnostics systems, and partially other systems. The magnetic field and beam extraction system were adjusted. The complex technology of dismantling and assembling the main coils without disassembling the magnet was solved within three years; the systems were developed and upgraded, and the U-400M cyclotron complex was back in operation in 2025 in a new technological quality — with beams of heavy ions from He to Bi with energies from 5 to 55 MeV/nucleon and intensities of up to 10 pμA.



Completion of the U-400M cyclotron upgrade. A group of participants

U-400R Cyclotron

The first beam at the U-400 cyclotron was produced back in 1978, and although the cyclotron's subsystems have been continually improved and upgraded over the years, the ability to vary the accelerated beam energy has remained unchanged — significant variation of the accelerated beam energy was possible only by changing its charge. The primary goal of the U-400 project was to produce a ^{48}Ca beam with the energy of 240–260 MeV and intensity of 1 pμA. This task was ultimately accom-

plished, enabling the synthesis of six new superheavy elements with $Z = 113–118$. Currently, experiments on the synthesis and study of the properties of superheavy elements are primarily performed at the new accelerator complex — Superheavy Element Factory — with the intense beams from the DC-280 cyclotron. Therefore, as early as 2000s, a project was developed to construct a new cyclotron, the U-400R, based on the U-400 cyclotron. The beams of the U-400R cyclotron would then be used for a wide range of experiments in nuclear physics, chemistry, condensed matter, and materials modification. For this purpose, the project provides for the production of accelerated ion beams ranging from ^{4}He to ^{238}U with a 25-fold maximum energy variation due to the magnetic field and ion charge from 0.8 to 27 MeV/nucleon[1]. Implementation of the project required the construction of a new experimental building.

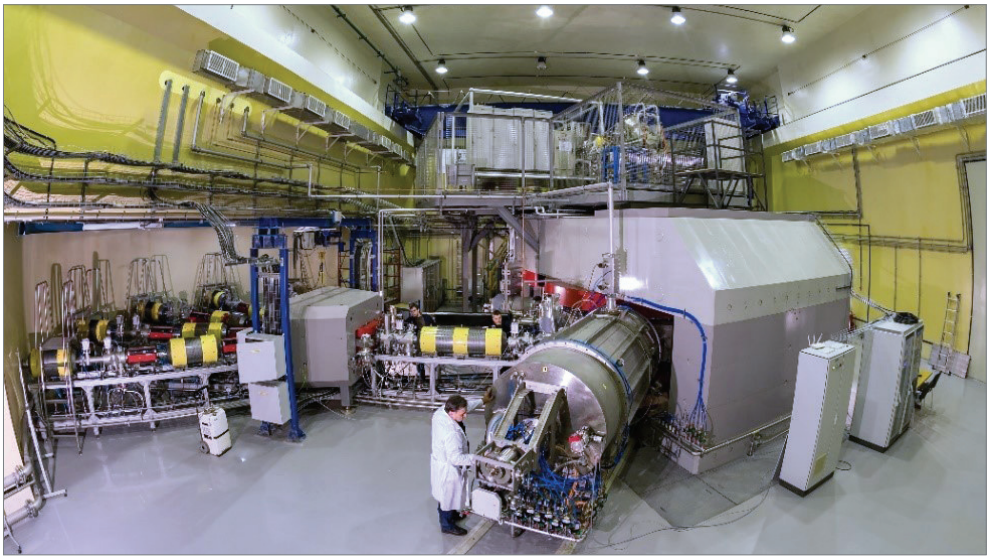


The U-400R experimental hall under construction

DC-280 Cyclotron

The need not only to synthesize superheavy elements but also to study their properties led to the formulation of requirements for the Laboratory's new accelerator, following the U-400. First and foremost, these included a tenfold — to 10 pμA — increase in the ion intensity of isotopes from ^{48}Ca, ^{50}Ti, ^{54}Cr, and up to ^{64}Ni not at the expense of increased material consumption but rather by enhancing the accelerator's efficiency. The energy ranged from 4 to 8 MeV/nucleon, with an energy spread not exceeding 0.5%. Taken together, this would have meant the construction of a unique heavy-ion cyclotron with an efficiency of beam transmission from the ion source to the target of approximately 50%. The solution to

[1] *Gulbekyan G., Gikal B., Kalagin I., Kazarinov N.* Development of FLNR JINR Heavy Ions Accelerator Complex in the Next 7 Years // Phys. Part. Nucl. Lett. 2010. V. 7, No. 7. P. 511–516.



DC-280 cyclotron with five channels of extracted beams



Adjusting the DC-280 cyclotron modes. FLNR Chief Engineer I. V. Kalagin is at the control panel

this problem was based on the entire experience of constructing and operating the Laboratory's cyclotrons. In order to manage the space charge of the injected beam, it was decided to increase the injection potential to 100 kV, reduce the cyclotron's magnetic field to around 1 T, and increase the acceleration rate to 500 kV/rev to efficiently extract the beam with the deflector. In 2018, the DC-280 cyclotron was commissioned and, after several years of operation and parallel optimization, it reached parameters close to the design ones.



FLNR Superheavy Element Factory

The DC-280 cyclotron is a key element of the Superheavy Element Factory complex, which also includes experimental facilities and engineering support systems.

DC-140 Cyclotron

The expansion of the scope of tasks in condensed matter physics and materials modification, in studies of the radiation resistance of semiconductor devices, and the irradiation of polymer materials for track-etched membranes with heavy-ion

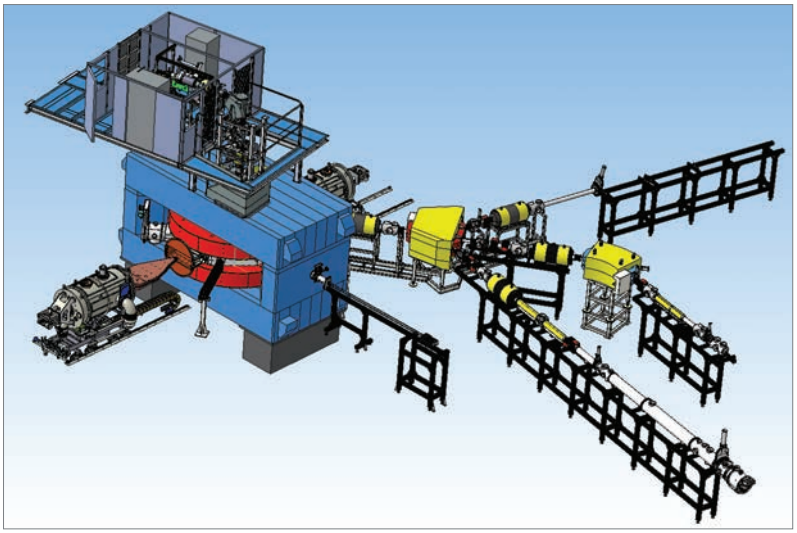


Fig. 2. Schematic view of the DC-140 cyclotron with an ion source and extracted beam channels





DC-140 cyclotron

beams logically led to the construction of the specialized DC-140 cyclotron complex (Fig. 2) for producing accelerated heavy-ion beams up to Bi with the fixed energies of 2.1 and 4.8 MeV/nucleon. Beam intensities on the targets are expected to be up to 0.2 pμA. The complex is designed to provide 6000 h of beam time per year. The project is scheduled for implementation in 2026.

FLNR ELECTROMAGNETIC SEPARATORS: SUPERHEAVY ELEMENTS

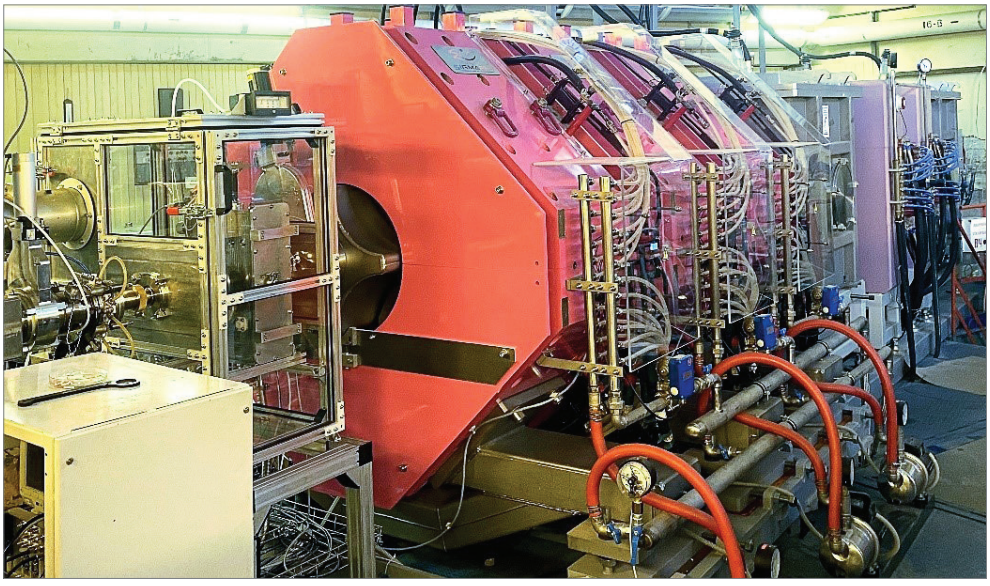
The first electromagnetic separators for studying heavy and superheavy isotopes using the U-400 cyclotron beams — the three-stage electrostatic separator VASSILISSA and the gas-filled separator DGFRS-1 — were constructed at FLNR in the late 1980s.

RECONSTRUCTION OF THE VASSILISSA SEPARATOR

The VASSILISSA separator has been successfully used for over 20 years to study the properties of nuclei synthesized in fusion reactions, as well as the mechanisms of these reactions. The separator provided for a large volume of research on the synthesis and survival regularities of highly excited compound nuclei in the $82 \leqslant Z \leqslant 94$ region in complete fusion reactions, as well as on the production and decay properties of more than 20 neutron-deficient isotopes.

The performance limitations of the electrostatic separator became clear during its operation. For example, when studying neutron-rich isotopes produced in asymmetric reactions, the transmission of evaporation residues was $< 2\%$. The maximal electric rigidity of the nuclear reaction products accessible for study with this separator did not exceed 2 MV, which greatly hampered the study of reaction products more symmetric than $^{208}Pb + {}^{48}Ca$.

In the 2010s, a decision was made to upgrade the existing VASSILISSA electrostatic separator into a velocity filter, ensuring more efficient separation of fusion



The reconstructed VASSILISSA separator — SHELS velocity filter

reaction products, independent of the charge state of the transported ions. The dispersive part of the new separator is a two-stage velocity filter with static spatially separated electric and magnetic fields. The first focusing triplet utilized quadrupole lenses with larger apertures.

The first tests of the new separator were carried out in May 2013 using a ^{22}Ne ion beam from the U-400 cyclotron. The primary beam's total energy suppression factor was $> 10^{16}$, enabling operation with beams of up to 10 pμA. The maximum electric rigidity of the studied products was 10 MV. Transmission was more than doubled for asymmetric reactions.

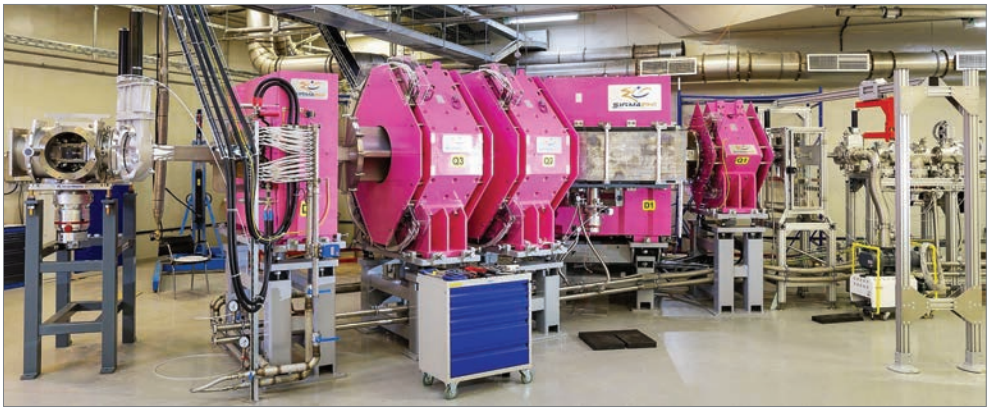
The main focus of research at the new separator is α-, β-, and γ-spectroscopy of nuclei in the separator's focal plane, the study of neutron emission in the spontaneous fission of heavy isotopes, and the properties of nuclear reactions. The SFiNx online neutron detector is used for these purposes alongside the GABRIELA system.

GAS-FILLED SEPARATORS

The production of ECR sources of multi-charged ions, as well as highly efficient, high-speed separators of nuclear reaction products, made it possible in the late 1990s and early 2000s to carry out full-scale experiments on the synthesis of superheavy elements with $Z = 113–118$ in ^{48}Ca-induced reactions.

Since 2020, research in the field of superheavy elements has continued at the Superheavy Element Factory, equipped with a high-current heavy-ion DC-280 cyclotron, capable of producing ion beams 10 times more intense than the existing U-400 cyclotron. The complex also includes new gas-filled separators: DGFRS-2 for experiments on synthesis and DGFRS-3 (GRAND), which has a similar design, for nuclear spectroscopy and experiments on the chemistry of superheavy elements.

Experience gained during the operation of the DGFRS-1 allowed to set the requirements for the new DGFRS-2 separator and optimize its ion-optical scheme. A vertically focusing quadrupole lens was added in front of the dipole magnet to in-



Gas-filled separator DGFRS-3 (GRAND) on channel No. 2 of the DC-280 cyclotron

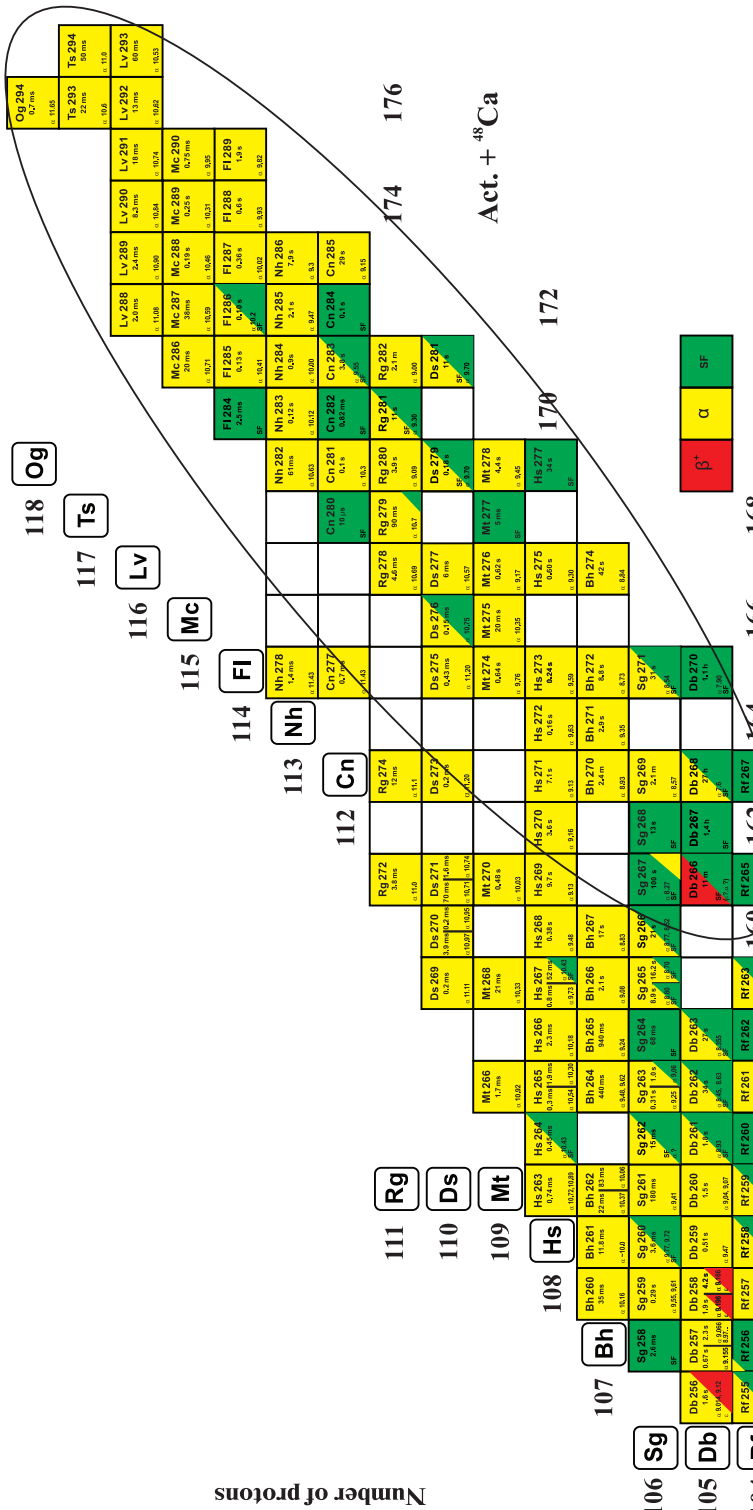


Fig. 3. The "northeastern" region of the chart of nuclides. The nuclei synthesized in reactions with ^{48}Ca are shown in the oval

crease transmission; a second dipole magnet was installed in front of the detection system to reduce background from the scattered ions and light particles; and optical elements with larger apertures were used. A study of the ^{243}Am(^{48}Ca, xn) reaction products showed that, thanks to these design changes, the DGFRS-2 transmission efficiency was more than doubled, while the background was reduced by more than a factor of 200 as compared to the DGFRS-1.

Following the completion of the separator installation, the construction of the necessary infrastructure, and the first short-term experiments aimed at comparing the design and actual characteristics of the new facility, regular experiments on the synthesis and study of the properties of isotopes of superheavy elements were carried out within 2020–2023.

Several series of experiments were performed at the new DGFRS-2 separator to study the excitation functions of the ^{243}Am(^{48}Ca, 2–5n)$^{286-289}$Mc reactions, as well as the characteristics of moscovium decay products. The refined cross section for the 3n channel was approximately twice as high as that in previous measurements.

The study of the reaction products of ^{238}U(^{48}Ca, xn) and ^{242}Pu(^{48}Ca, xn) made it possible to clarify the characteristics of the radioactive decays of copernicium and flerovium isotopes.

Figure 3 shows the "northeastern" region of the chart of nuclides as of 2025. Two regions are clearly distinguished: the region of relatively light isotopes with $Z = 107–113$, synthesized in cold fusion reactions during irradiation of lead and bismuth targets with accelerated ions of medium masses ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn, and the region of the isotopes of superheavy elements with $Z = 113–118$, synthesized in reactions of accelerated ^{48}Ca ions with targets of the isotopes of actinide elements (marked with an oval).

A comparison of the characteristics of reactions with accelerated ions lighter and heavier than ^{48}Ca is of considerable interest to plan the experiments on the synthesis of isotopes of elements with $Z > 118$. The reactions ^{232}Th(^{48}Ca, xn)$^{280-x}$Ds, ^{238}U(^{40}Ar, xn)$^{278-x}$Ds, ^{238}U(^{54}Cr, xn)$^{292-x}$Lv, and ^{242}Pu(^{50}Ti, xn, pxn) were studied for this purpose. Model experiments showed that the achievable sensitivity of experiments in observing one event of the production of superheavy nuclei per year corresponds to 10 fb (10^{-38} cm^2).

During the first four years of operating the new DGFRS-2 separator, the isotopes ^{264}Lr, ^{268}Sg, ^{272}Hs, ^{275,276}Ds, ^{280}Cn, ^{286}Mc, ^{288,289}Lv were observed for the first time. Furthermore, the properties of more than 30 isotopes of elements in the transactinide region were clarified: decay modes — spontaneous fission of ^{279}Rg, alpha decay of ^{268}Db, lifetimes, energies of alpha decays, excitation functions were measured, products of the pxn channel were observed for the first time in the ^{242}Pu + ^{50}Ti reaction, which were not observed in the ^{48}Ca-induced reactions, long-term performance of targets at accelerated ion currents of up to 6.5 pμA was demonstrated.

EXPERIMENTAL RESEARCH AT THE FLNR ACCELERATOR COMPLEX

DISCOVERY AND STUDY OF SUPERHEAVY ELEMENTS

The study of superheavy nuclei (SHN) is currently one of the most important and rapidly developing areas in nuclear physics. This is driven not only by the desire to discover and name a new element but also by enormous scientific significance. Due to increasing Coulomb repulsion forces, SHN are at the borders of nuclear stability. The study of the properties of SHN allows for a deeper understanding of the influence of shell effects on their stability, their structure, and the forces holding nucleons in the nucleus, the development of theoretical nuclear models, and so on. SHN synthesis allows tracing the dynamics of the fusion of two massive nuclei to form a new compound nucleus. These studies address fundamental questions: where are the boundaries of nuclear matter and the regions of increased SHN stability (magic numbers of protons and neutrons Z_{mag}/N_{mag}), what are the radioactive properties of SHN, their structure, what methods are used to synthesize SHN, whether SHN are formed during nucleosynthesis, and many others.

Over a period of 60 years, various theoretical models predicted the existence of a SHN region — a group of nuclei near the doubly magic spherical nucleus $^{298}114$ ($Z_{mag} = 114$, $N_{mag} = 184$) that should be more long-lived than nuclei with fewer or more protons and neutrons, forming a kind of island of increased stability on the nuclide chart. Soon after the first predictions of the SHN region appeared, numerous attempts were made to synthesize them, but all efforts proved vain. Later, it became clear that synthesizing SHN required a significant increase in experimental sensitivity by increasing the intensity of accelerated ions, the thickness of the target layer, the transmission of the separator, and the efficiency of detecting SHN decays.

In 1999, the first successful experiments on SHN synthesis were performed at FLNR JINR. They utilized the DGFRS-1 gas-filled separator (Fig. 4), which allowed the products of complete fusion reactions to be collected by a detecting

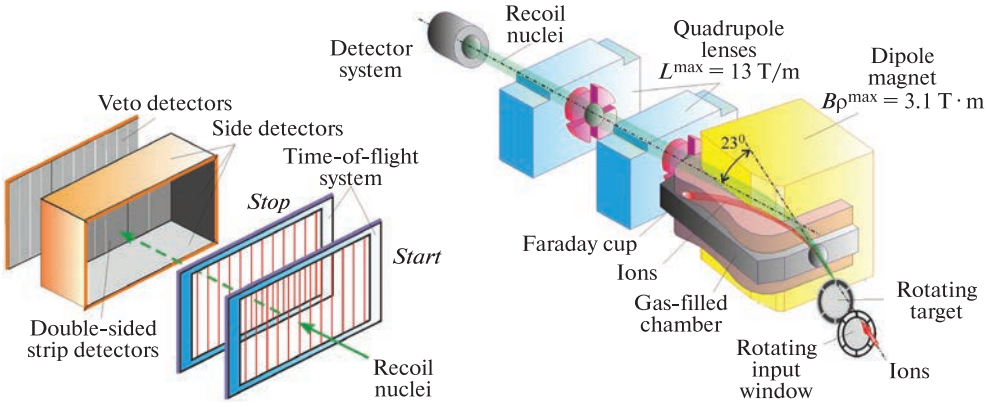


Fig. 4. Schematic of the DGFRS-1 separator and detectors

system and separated from the bombarding ion beam and background reaction products. The detecting system consisted of gas proportional chambers for measuring particle time-of-flight and a system of semiconductor detectors, divided into strips, for recording SHN decays. These and subsequent experiments were carried out in collaboration with the American laboratories in Oak Ridge (ORNL), Livermore (LLNL), Knoxville (UT), and Nashville (VU), as well as with the Russian centers — JSC SSC RIAR (Dimitrovgrad) and RFNC-VNIIEF (Sarov).

The first superheavy nucleus (^{289}Fl) was synthesized on June 25, 1999, in the ^{244}Pu(^{48}Ca, 3n) reaction. The measurement of the excitation function of the reaction at increased energies of ^{48}Ca led to the synthesis of the light isotopes ^{288}Fl and ^{287}Fl. Both the already known ^{287}Fl (a cross-reaction method) and the isotopes ^{286}Fl, ^{285}Fl, and ^{284}Fl were obtained in reactions with the lighter isotopes ^{242}Pu, ^{240}Pu, and ^{239}Pu.

A year later, on July 19, 2000, an isotope of element 116, ^{293}Lv, was discovered in the ^{248}Cm(^{48}Ca, 3n) reaction. The decay properties of the daughter nuclei ^{289}Fl, ^{285}Cn, and ^{281}Ds completely coincided with those observed in the direct reaction with ^{244}Pu. The isotopes ^{292}Lv, as well as ^{291}Lv and ^{290}Lv, were obtained in the ^{248}Cm(^{48}Ca, 4n) and ^{245}Cm(^{48}Ca, 2–3n) reactions, respectively.

Two years later, on March 19, 2002, the new element 118 was synthesized for the first time in the ^{249}Cf(^{48}Ca, 3n)^{294}Og reaction. Again, the decay properties of the daughter nuclei ^{290}Lv, ^{286}Fl, and ^{282}Cn were the same as those in the direct reactions ^{245}Cm(^{48}Ca, 3n), ^{242}Pu(^{48}Ca, 4n), and ^{238}U(^{48}Ca, 4n), respectively.

The first isotope of the odd element 115, ^{288}Mc, was detected on July 24, 2003, in the ^{243}Am + ^{48}Ca reaction. Its alpha decay led to the observation of then-unknown element 113 with mass 284. Later, the neighboring isotopes ^{287}Mc and ^{290}Mc were obtained. Finally, on August 20, 2009, the isotope ^{294}Ts was synthesized in the ^{249}Bk(^{48}Ca, 3n) reaction, and isotope ^{293}Ts, with increasing ^{48}Ca energy.

The results of these experiments subsequently caused widespread interest in the study of SHN at other laboratories, including GSI (Germany), LBNL (USA), RIKEN (Japan), and IMP (China). Some of the experiments with the ^{238}U, ^{242,244}Pu, ^{243}Am, and ^{249}Bk targets were repeated, the properties of SHN and their production cross sections were fully confirmed, and five isotopes in the ^{285}Fl decay chain and the isotopes ^{266}Lr, ^{277}Hs, and ^{280}Ds were synthesized for the first time.

The measured excitation functions of the reactions are shown in Fig. 5. The data on experiments performed at GSI, LBNL, and RIKEN are shown as open symbols.

Experiments at the DGFRS-1 separator resulted in the first observation of six new elements, ranging from 113 to 118, and the study of the properties of more than 50 of the heaviest isotopes. Their decay properties demonstrated a significant decrease in the alpha-decay energy and an increase in stability with increasing neutron number N and when approaching the predicted magic neutron number $N = 184$. For example, the alpha-decay energy of Ds isotopes ($N = 165–171$) decreases by 2.5 MeV when the number of neutrons increases by six. At the same time, their lifetimes increase by almost six orders of magnitude. The stability of a nucleus against spontaneous fission, which is determined by its fission barrier,

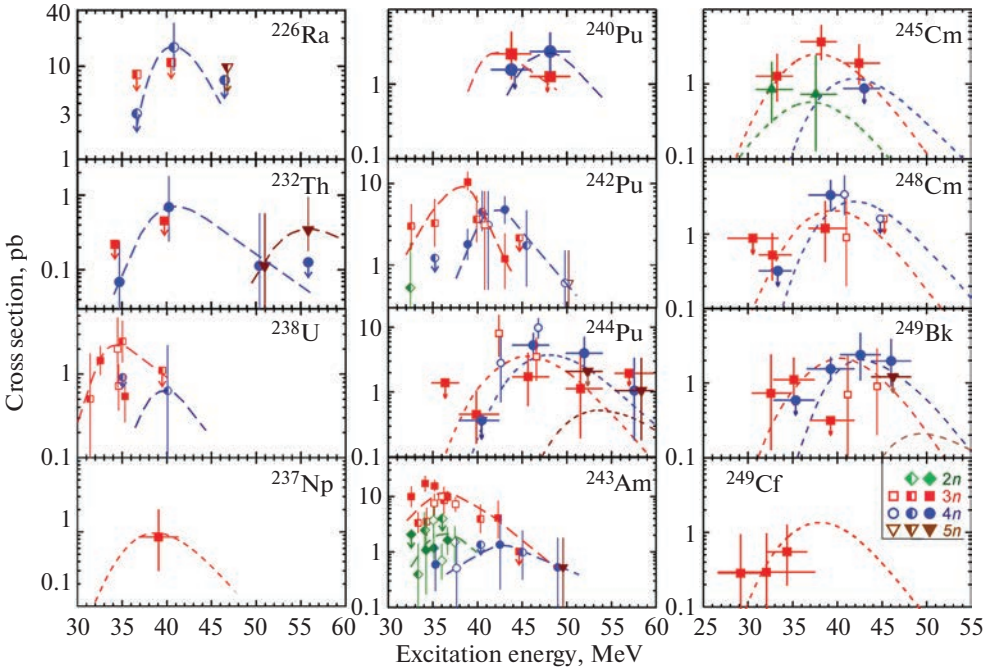


Fig. 5. Excitation functions of 2n–5n channels of ^{48}Ca reactions with the indicated isotopes

increases by two orders of magnitude for Ds, Cn, and Fl isotopes with an increase in N by two neutrons.

The cross section for the formation of xn-channel products in the complete fusion reaction, namely, the survival probability of the excited compound nucleus W_{sur}, also depends significantly on the fission barrier. The theoretically predicted nuclear fission barriers are shown in the lower right panel of Fig. 6. They decrease in the transition from element 102 to 110, then increase and reach a maximum at $Z = 114$, 115. The production cross sections are fully consistent with this dependence. Thus, both the decay properties of nuclei and their production cross sections indicate an increase in their stability as they approach the hypothetical doubly magic nucleus ^{298}114. This served as evidence for the experimental detection of SHN and confirmed the theoretical predictions about the existence of a region of relatively stable SHN.

These experimental studies were further developed: the results were confirmed in subsequent experiments at GSI, LBNL, RIKEN, IMP, the first experiments on the spectroscopy of nuclei in the decay chains of ^{288}Mc, ^{289}Fl (GSI, LBNL, FLNR) and the study of the chemical properties of elements 112, 113, 114, 115 (FLNR, GSI) were performed; the mass number of ^{288}Mc was measured (LBNL); measurements of the masses of nuclei with an accuracy of ≈ 100 keV are being prepared (FLNR); numerous measurements of the nuclear capture cross section and the probabilities for the synthesis of a compound nucleus were carried out (FLNR, ANU).

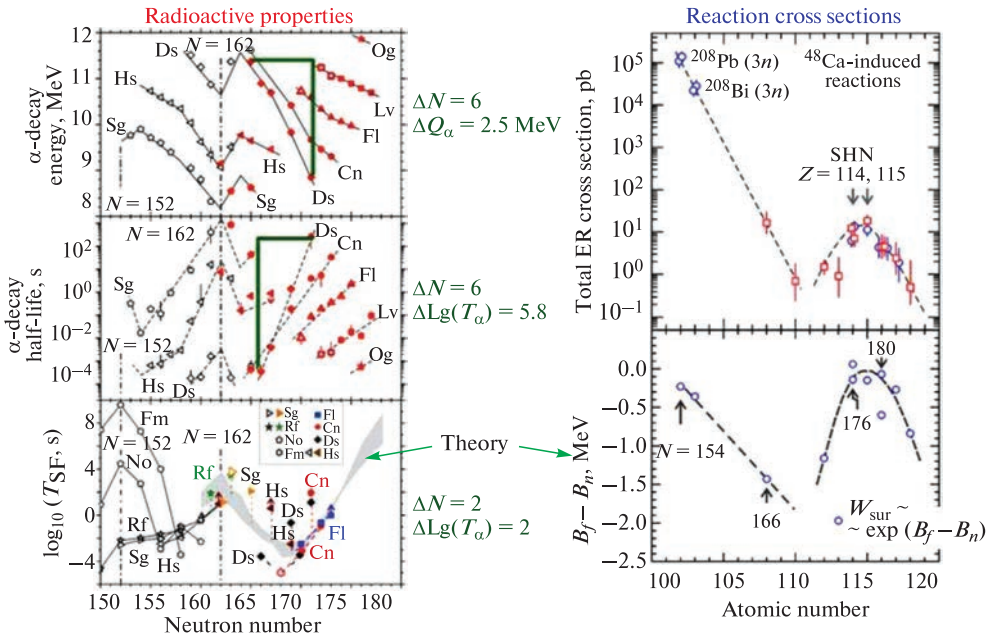


Fig. 6. Left, top to bottom: energies and periods of alpha decay of Sg—Og nuclei, periods of spontaneous fission of Fm—Fl isotopes. Right, top to bottom: cross sections for xn channels of complete fusion reactions, difference in fission barriers and neutron binding energy

However, one fundamental question remains open: where is the center of the stability region of superheavy nuclei Z_{mag}/N_{mag}? Theoretical predictions diverge: $Z_{mag} = 114$, $N_{mag} = 184$ in macro-microscopic models, while in self-consistent models, $Z_{mag} = 120–126$, $N_{mag} = 184$. To clarify this question, new elements 119 and 120 must be synthesized; both the properties of the nuclei and their production cross sections are important.

The first experiments have already been carried out at FLNR, GSI, and RIKEN using the reactions $^{244}Pu + {}^{58}Fe$, $^{238}U + {}^{64}Ni$, $^{248}Cm + {}^{54}Cr$, $^{249}Cf + {}^{50}Ti$ ($Z = 120$), and $^{249}Bk + {}^{50}Ti$, $^{248}Cm + {}^{51}V$ ($Z = 119$). Various levels of experimental sensitivity were achieved (5–580 fb), different accelerated ions were used, but only the cross-section limits were obtained. But what were the chances of success in reactions with ^{50}Ti to ^{64}Ni projectiles, and what target–ion combination is optimal? In such a situation, realistic estimates of the cross sections for the synthesis of new elements become extremely important for planning future experiments and assessing experimental capabilities. According to theoretical concepts and experimental data, light ions are more preferable, since with increasing Z of the accelerated ion, the probability of forming a compound nucleus decreases. Many modern theoretical models describe well the experimentally measured cross sections of ^{48}Ca-induced reactions, but the predicted results for elements 119 and 120 differ by several orders of magnitude.

Further research on superheavy nuclei, the synthesis of new elements, and the study of isotopes at the boundaries of the SHN region required a significant in-

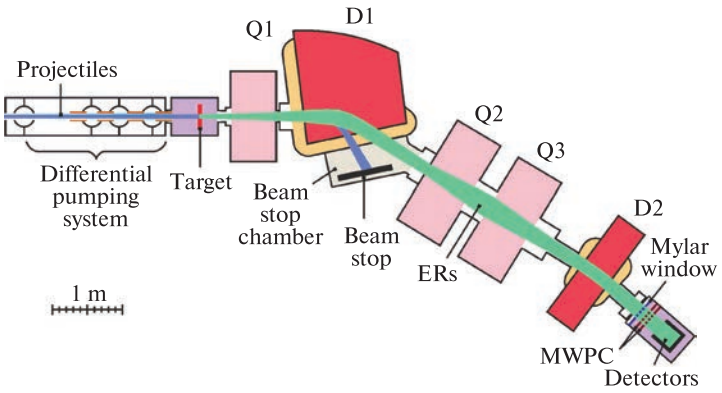


Fig. 7. Schematic of the DGFRS-2 separator

crease in experimental sensitivity. This was achieved at the new accelerator complex at FLNR JINR — the Superheavy Element Factory — due to an order-of-magnitude increase in beam intensity, enhanced transmission efficiency, and higher suppression of by-products at the new gas-filled separator DGFRS-2 (Fig. 7).

To determine the parameters of the new separator and the opportunities of continuing SHN research at a higher level of sensitivity, as well as to study in detail the properties of the isotopes of Mc, Fl, Cn and their daughter nuclei, experiments were carried out to study the reactions of ^{243}Am, ^{242}Pu, and ^{238}U with ^{48}Ca.

The excitation function of the ^{243}Am + ^{48}Ca reaction was studied at six projectile energies in a wide range of 239–259 MeV; ten new decay chains of ^{289}Mc, 110 decay chains of ^{288}Mc, and four decay chains of ^{287}Mc were synthesized; a new isotope ^{286}Mc was discovered, and the properties of 22 nuclei were studied in detail. The total number of Mc isotope decay chains was more than three times higher the number of nuclei synthesized at DGFRS-1 in 2003–2012. The alpha decay of ^{268}Db was detected for the first time, its branch and half-life were measured, and a new isotope ^{264}Lr was synthesized. Spontaneous fission of ^{279}Rg was registered for the first time. The cross section of the 3n-channel turned out to be twice as high as that previously measured.

Twenty-five decay chains of ^{286}Fl and 69 decay chains of ^{287}Fl were synthesized in an experiment with target nuclei of ^{242}Pu at two projectile energies. The cross section was also three times higher than the previous values. Evidence was obtained for a dependence of the decay properties of ^{287}Fl, ^{283}Cn, and ^{279}Ds, namely, alpha decay or fission of ^{279}Ds, on their low-energy levels, and on the decays of the ^{286}Fl nucleus through the first rotational state of the ^{282}Cn nucleus.

The ^{48}Ca intensity reached 6.5 pμA, and 16 ^{283}Cn decay chains were obtained when irradiated with ^{238}U. Reaction cross sections were measured at different ^{48}Ca energies, and the decay properties of approximately 30 isotopes of elements from Lr to Mc were measured in the entire series of experiments.

Experiments were carried out to synthesize Ds isotopes in the ^{232}Th + ^{48}Ca reaction. Their properties are important for the identification of the new element 120 in the reactions ^{249}Cf(^{50}Ti, 3–4n)^{295,296}120 and ^{245}Cm(^{54}Cr, 3–4n)^{295,296}120, since their alpha decays lead to the ^{275,276}Ds isotopes. In addition, the predict-

ed fission barriers of the ^{232}Th + ^{48}Ca reaction products, which characterize the survival probability of excited compound nuclei, are lower than the barriers of the specified isotopes of element 120. The cross section for the reaction with ^{232}Th will allow more accurate prediction of the production cross sections of element 120 isotopes. Seven decay chains of the new isotope ^{276}Ds were synthesized for the first time, the alpha decay of which led to the discovery of two more isotopes: ^{272}Hs and ^{268}Sg. The achieved sensitivity was 70 fb. ^{275}Ds was also synthesized for the first time in the reaction of ^{48}Ca with the nuclei of actinide element and identified through sequential alpha decays leading to the known nuclei ^{271}Hs, ^{267}Sg and ^{263}Rf, previously obtained in the ^{248}Cm(^{26}Mg, $3n$)^{271}Hs reaction.

For the first time since 1983, when the first experiments on the synthesis of Ds isotopes in direct reactions of ^{40}Ar, ^{48}Ca with isotopes of actinide elements (^{232}Th, ^{235,236,238}U) were carried out, the reaction cross section was measured, which turned out to be an order of magnitude lower than the one of the ^{226}Ra(^{48}Ca, $4n$)^{270}Hs reaction. The cross section increases when passing to heavier elements ($Z > 110$) (Fig. 8), reaching a maximum value for elements 114, 115, and then decreases by about a factor of 30 for element 118. This change is in full agreement with theoretical models predicting shells at $Z = 108$, $N = 162$ and $Z = 114$, $N = 184$. Two decay chains of the ^{273}Ds isotope with a cross section of 0.2 pb were registered in the ^{238}U + ^{40}Ar reaction. The properties of nuclei synthesized in the ^{232}Th + ^{48}Ca and ^{238}U + ^{40}Ar reactions indicate the existence of isomeric states in ^{267}Sg, ^{271}Hs, ^{273}Ds and its daughter nuclei.

These first experiments demonstrated the increased sensitivity of experiments at the Superheavy Element Factory and the readiness to synthesize new elements 119 and 120. It is necessary to use projectiles heavier than ^{48}Ca, such as ^{50}Ti, ^{51}V, ^{54}Cr, and to select optimal reactions for the synthesis of new elements to produce elements with $Z > 118$.

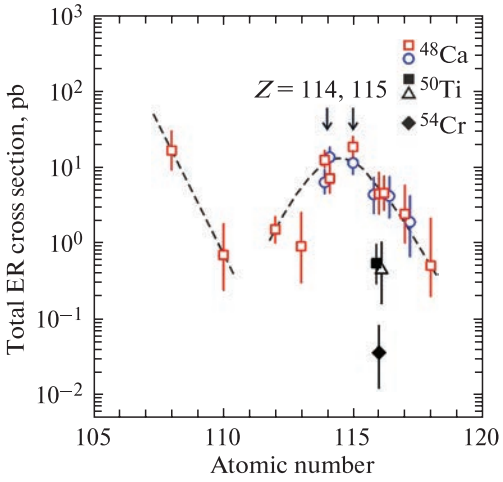


Fig. 8. A maximum of the cross section for the ^{48}Ca reactions with ^{226}Ra — ^{249}Cf nuclei. The results obtained at FLNR are shown by red squares; the results of experiments with ^{50}Ti and ^{54}Cr are shown by closed symbols; the cross section for the ^{244}Pu(^{50}Ti, 4n)^{290}Lv reaction, measured in Berkeley (USA), is shown by an open triangle

The process of SHN production in a fusion reaction of interacting nuclei is divided into three stages: nucleus capture, formation of a nearly spherical compound nucleus, and its survival during de-excitation by neutron evaporation. The aim of the study was to measure and compare the cross sections of complete fusion reactions leading to the production of the same SHN when changing the projectiles from ^{48}Ca to ^{50}Ti and ^{54}Cr. Due to the similar survival probability of the excited nucleus in this case, the difference in the reaction cross sections can be primarily due to the difference in the formation probability of compound nucleus — the least studied characteristic of fusion–evaporation reactions. For this purpose, we selected the ^{238}U + ^{54}Cr and ^{242}Pu + ^{50}Ti reactions, which lead to the formation of the compound nucleus ^{292}Lv.

The cross sections for the 3*n* and 4*n* channels of the ^{242}Pu + ^{50}Ti reaction, which were approximately 320 and 220 fb, were measured at the ^{292}Lv excitation energy $E^* = 41$ MeV. The cross section for the 4*n* evaporation channel of the ^{238}U + ^{54}Cr reaction, leading to the formation of the same compound nucleus, turned out to be 36 fb at $E^* = 42$ MeV, which is lower by about a factor of 15 than that for the cross section of the ^{242}Pu + ^{50}Ti reaction (Fig. 8). Compared with the maximum cross section for the formation of Lv nuclei in the ^{245}Cm + ^{48}Ca and ^{248}Cm + ^{48}Ca reactions, the cross sections for the ^{242}Pu + ^{50}Ti and ^{238}U + ^{54}Cr reactions were approximately 8 and 120 times lower, respectively. However, if we compare the reaction cross sections of ^{48}Ca, ^{50}Ti, and ^{54}Cr ions with ^{244}Cm, ^{242}Pu, and ^{238}U at similar excitation energies, the cross sections decrease by a factor of ~2–10 and ~30–150 when moving from ^{48}Ca to ^{50}Ti and ^{54}Cr, respectively. Thus, the experiment provided for the first time convincing evidence that the reactions of actinide isotopes with ^{50}Ti are an order of magnitude more preferable than reactions with ^{54}Cr projectiles for the synthesis of the new elements 119 and 120.

In addition to the reaction cross sections measurement, three new isotopes were discovered: two alpha-decaying ^{288}Lv nuclei (four decay chains) at $E_\alpha = 11.08$ MeV and with a half-life $T_{1/2} = 2.0$ ms; ^{289}Lv (three chains) at $E_\alpha = 10.90$ MeV, $T_{1/2} = 2.4$ ms; and a granddaughter of ^{289}Lv — the spontaneously fissioning ^{280}Cn, with $T_{1/2} = 10$ μs. The latter isotope was observed via the alpha decay of ^{284}Fl at $E_\alpha = 10.57$ MeV; this decay type was also observed for the first time for the predominantly spontaneously fissioning ^{284}Fl. The decay properties of these new nuclei agree well with the values that could be expected from the systematics of the energies and times of alpha-decay nuclei, as well as the times of spontaneous fission (Fig. 8).

STUDY OF THE PROPERTIES OF RADIOACTIVE DECAY OF HEAVY AND SUPERHEAVY NUCLEI PRODUCED IN REACTIONS WITH ACCELERATED MULTI-CHARGED IONS

In recent years, with the development of experimental techniques in heavy-ion physics, the region of nuclei heavier than fermium ($Z \geqslant 100$) has become accessible for detailed study. The characteristics of the radioactive decay of heavy and superheavy nuclei, synthesized using high-intensity beams of multi-charged ions from the FLNR cyclotrons, provide insight into the properties and stability borders of

nuclear matter. Using separators of complete fusion reaction products and a wide range of detecting setups, FLNR experimenters have made significant progress in understanding the decay properties of nuclei in this region.

In 2004, experiments were launched at the VASSILISSA separator to study the properties of radioactive decay and the structure of nuclear levels of the isotopes of transfermium elements. In collaboration with a group of physicists from French institutes (CSNSM (Orsay) and IPHC (Strasbourg)), a combined detection system, GABRIELA (Gamma Alpha Beta Recoil Investigations with the ELectromagnetic Analyzer), was developed at the VASSILISSA separator.

From 2004 to 2009, the VASSILISSA separator and the GABRIELA detection system obtained the most important data on the spectroscopy of ^{249}Fm, ^{253,256}No, and the decays from the isomeric states (*k* isomers) were registered for the first time for the short-lived isotopes ^{255}Lr, ^{253}No.

Experiments performed in 2013–2024 as part of the GABRIELA project at the new SHELS separator, a major upgrade of the VASSILISSA separator, yielded extensive spectrometric data. *k*-isomeric states in the ^{255,256}No and ^{255}Rf nuclei were identified for the first time. Excitation energies, spins, and parities were determined for the known *k* isomers in the ^{256}Rf and ^{250}No nuclei. Fission prohibition data from *k*-isomeric states were also corrected for the ^{250,254}No nuclei. Transition schemes were constructed for these and several other transfermium nuclei, data on single-particle states in nuclei, and data on octupole moments in excited states were obtained. In addition, the half-life ($T_{1/2} = 38.1 \pm 2.5$ ms) and alpha-particle energy ($E_\alpha = 9129$ keV) were measured, and the branching ratio for spontaneous fission ($b_{SF} \leqslant 0.23\%$) was estimated for the highly neutron-deficient ^{249}No isotope, first synthesized in an experiment at the SHELS separator in 2020. The decay data for this new nucleus were subsequently confirmed in an experiment studying the decay properties of the ^{253}Rf nucleus, a mother nucleus for ^{249}No.

Currently, the GABRIELA detection system, which includes five HPGe clover-type detectors, is used in experiments at the SHE Factory; it is located in the focal plane of the GRAND gas-filled separator (DGFRS-3).

Another key area of research into the decay properties of the heaviest nuclei is the study of nuclear fission properties. Data on spontaneous fission and the fission of weakly excited heavy nuclei provides crucial data on the influence of shell effects on the lifetime of nuclei and the formation of fission fragments.

Significant changes in fission dynamics during fragment formation should be expected during transition into the region of the heaviest nuclei, and especially when approaching the deformed shell $N = 162$. The production cross sections limit the number of nuclei available for study, and the very short lifetimes (up to a few microseconds) place significant demands on experimental technique.

Since 2002, the spontaneous fission characteristics of short-lived nuclei from Fm to Sg have been studied at FLNR. Partial half-lives have been measured (specified), the total kinetic energy of fragments has been estimated, the average number of neutrons per fission has been measured, and neutron multiplicity distributions have been constructed for some nuclei. These experiments are currently being carried out at the SHELS facility in conjunction with the SFiNX (Spontaneous Fission, Neutrons, and X-rays) detector system. SFiNX comprises 116 proportional

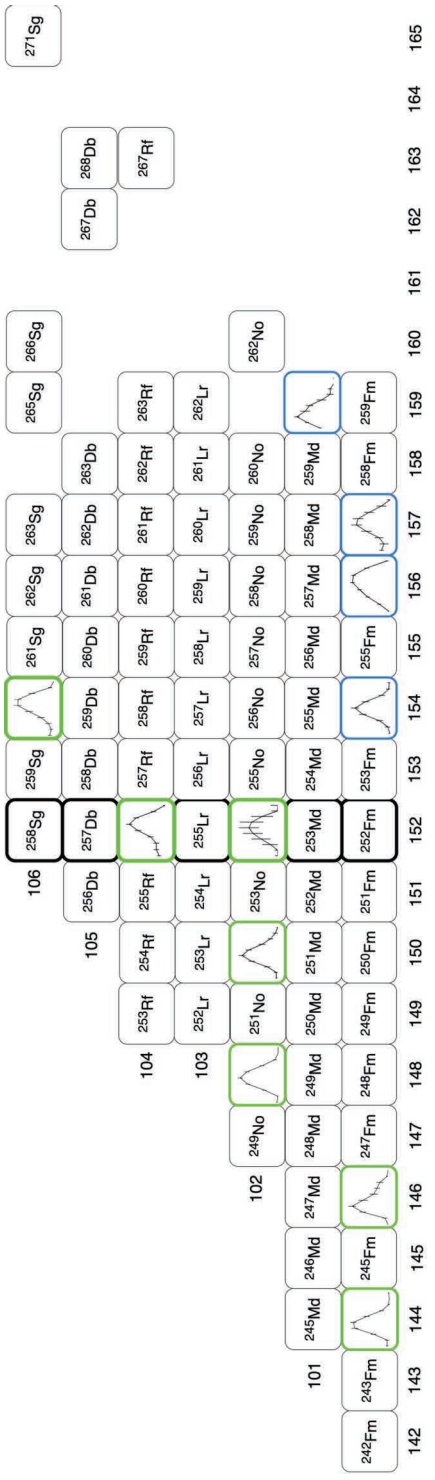


Fig. 9. Data on prompt neutrons produced in spontaneous fission of the heaviest nuclei. The green boxes show the neutron multiplicity distributions for heavy nuclei emitted at the VASSILISSA (SHELS) facility at FLNR

neutron counters mounted around the well-shaped focal semiconductor detector's vacuum chamber. The data on prompt neutrons produced in spontaneous fission of the heaviest nuclei are presented in Fig. 9.

The experiments carried out at FLNR to study the structure of isotope levels from No to Db provide a good methodological basis for preparing studies of the structure of Fl, Lv, and Mc isotopes.

In addition to spectroscopic data on the structure of nuclei in the SHE region, with sufficient statistics (several hundred events), it becomes possible to study in detail the properties of the radioactive decay of isotopes observed in the decay chains of SHE mother nuclei. For example, the issue of the decay properties of the ^{268}Db isotope, the final nucleus in the ^{288}Mc isotope decay chain, remains open. Theoretical calculations indicate that ^{268}Db is highly likely to undergo weak decay (electron capture), while spontaneous fission is experienced by the ^{268}Rf isotope, with a half-life of several seconds (the fission detected in the chain is currently believed to be attributed to ^{268}Db). In this case, it is necessary to detect an X-ray quantum with an energy of 120–140 keV in correlation with spontaneous fission, which will allow for a reliable determination of the decay properties of the Db–Rf isotopes located in this poorly studied region of the isotope chart.

At the same time, statistics of several hundred events make it possible to study the dynamics of spontaneous fission of Db–Rf nuclei with atomic mass $A = 268$. It will be energetically beneficial for the nuclear system to split into two fragments of similar masses with a "near-magic" number of nucleons ($Z = 50$, $N = 82$) during their formation. This will inevitably lead to the emergence of a strong symmetric component in the fragment mass distribution, which will affect the TKE and neutron emission. The study of these characteristics became possible with the placement of the SFiNX detection system in the focal plane of the GRAND separator at the SHE Factory.

CHEMISTRY OF SUPERHEAVY ELEMENTS

In the 2000s, since the launch of the program on the synthesis of superheavy elements at heavy-ion accelerators, the study of the physico-chemical properties of new elements was carried out at FLNR under the supervision of S. N. Dmitriev. He organized a collaboration with researchers from leading nuclear and chemistry scientific centers, and their joint efforts made it possible to observe for the first time relativistic effects in chemical properties of superheavy elements. The experiments performed at JINR have received considerable attention and allowed one to establish a new scientific direction — relativistic chemistry of superheavy elements. The research under the leadership of S. N. Dmitriev on the registration of Db as a decay product of element 115 provided independent evidence for the synthesis of a new element. This bacame a compelling argument for the claim, submitted to the International Union of Pure and Applied Chemistry, on the discovery of new elements with atomic numbers 113, 115, and 117.

The birth of a new element is always of great interest in the study of the electronic structure of a heavy atom and its chemical behavior. Until recently, the primary focus was on elements 104–108. For example, experiments on the chemical



S. N. Dmitriev

properties of elements, such as seaborgium (106), bohrium (107), and hassium (108), showed that they behave in accordance with their position in the Periodic Table (Groups 6, 7, and 8, respectively). However, the chemical properties of superheavy elements can differ significantly from what is expected based on their position in the Mendeleev's Periodic Table. According to quantum electrodynamics, the structure of an atom as a positively charged center and negatively charged electrons moving around the nucleus at large distances is stable up to $Z = 173, 174$. The superheavy elements synthesized over the past twenty years are still far from this limit. However, as the atomic number of a heavy atom increases, the speed of the inner electrons approaches the speed of light thereby leading to a "relativistic compression" of their orbits. This alters the quantum characteristics of the entire electron structure of the atom, including the last electrons responsible for the chemical properties of the element. The rapid increase in the relativistic effect with increasing Z will lead to increasingly strong deviations from the classical (non-relativistic) case. Significant changes in the chemical behavior of the elements are expected as soon as Group 8 of the Mendeleev's Periodic Table is filled.

As a rule, superheavy elements have short lifetimes, which significantly complicates the study of their chemical properties.

The element copernicium, discovered in 1996 at GSI (Darmstadt, Germany), was synthesized as an isotope with mass number 277 in the fusion reaction of ^{70}Zn with ^{208}Pb, but its extremely short half-life (about 200 ms) made chemical study impossible. In 1999, new isotopes of copernicium (Cn) and flerovium (Fl) were synthesized at FLNR in fusion reactions of ^{48}Ca with ^{238}U and ^{242}Pu. The half-life of the isotope ^{283}Cn was about 3 s, with a decay via spontaneous fission. Later experiments at FLNR in 2004 revealed other properties of ^{283}Cn: decay via alpha-particle emission (9.5 MeV) and a half-life of about 4 s, followed by spontaneous fission.

The relatively long lifetimes of the isotopes of Cn and Fl make them the heaviest elements in the Mendeleev's Periodic Table currently available for chemical study. Unique opportunities for chemical research on virtually all elements in Period 7 of the Periodic Table emerged only after the synthesis of 17 isotopes of superheavy elements with $Z = 112–118$ in Dubna.

A pair of homologs of Group 12 of the Periodic Table was studied in the first experiment performed at FLNR in 2007. The adsorption of Cn ($Z = 112$) and Hg ($Z = 80$) on the surface of gold (Au) was measured at different temperatures in order to observe the temperature difference in the formation of [Au–Hg] and [Au–Cn] compounds. The shift of the adsorption peak to lower temperatures (weakening of the [Au–Cn] molecular bond relative to [Au–Hg]) was the first direct experimental observation of the relativistic effect in transactinides. Nevertheless, according to the results of this experiment, the heavy homolog of mercury in Group 12 of the Periodic Table demonstrated its belonging to the noble metal family, although it is possible that at room temperature it will not be liquid, like mercury, but gaseous.

Furthermore, first experiments with element Fl ($Z = 114$) were performed at FLNR. It was found that Fl in its atomic state is volatile and forms a weak adsorption bond with a gold surface. Moreover, the volatility of Fl was higher than that of Cn: it adsorbs on the gold surface at temperatures around –80°C, thereby exhibiting the behavior of noble gases. In 2010, a similar study was carried out at GSI (Darmstadt, Germany). Unfortunately, a small number of events in both experiments does not give a quantitative picture of the transition from Cn to Fl.

STUDY OF THE DYNAMICS AND MECHANISMS OF REACTIONS WITH HEAVY IONS AT ENERGIES NEAR THE COULOMB BARRIER

The study of nuclei far from the stability line is one of the main tasks of modern nuclear physics. The production of nuclei near the "island of stability" and the study of their properties are of particular interest. According to theoretical predictions, the "island of stability" is expected to be near the neutron shell at $N = 184$ and the proton shell at $Z = 114$ or $Z = 120–126$. The heaviest artificial element is oganesson (^{294}Og) with $Z = 118$, obtained in the complete fusion reaction ^{48}Ca + ^{249}Cf. It is necessary to synthesize heavier nuclei with $Z > 118$ to further study the "island of stability". Unfortunately, these nuclei cannot be obtained in reactions with ^{48}Ca ions, since ^{249}Cf is the heaviest target material available for these purposes.

At first glance, the use of ions, such as Ti, Cr, Fe, or Ni, in complete fusion reactions with actinide nuclei seems to produce heavier elements. However, the increase in Coulomb repulsion between interacting nuclei suppresses the cross section for compound nucleus (CN) formation by quasi-fission and deep inelastic transfer processes. Quasi-fission (QF) and deep inelastic transfer reactions are binary processes with complete momentum transfer, in which a composite system divides after the capture into two fragments without forming a compound nucleus. Quasi-fission is the primary mechanism preventing the formation of superheavy elements in the fusion of heavy nuclei, and its probability strongly depends on the



Detectors installed in the CORSET reaction chamber for experiments studying multinucleon transfer reactions

properties of the reaction input channel, such as the Coulomb factor Z_1Z_2, mass asymmetry, average fissility parameter, deformation of the interacting nuclei, interaction energy, and introduced angular momentum.

Experimental studies of heavy-ion reaction mechanisms are carried out at the Flerov Laboratory of Nuclear Reactions using the CORSET facility, a multi-arm time-of-flight spectrometer with a wide range of capabilities for detecting reaction products. The most commonly used spectrometer is a double-arm combination, which allows for simultaneous detection of both fragments of a binary process. Depending on the task at hand, the spectrometer can be used to implement different measurement techniques, namely, the 2V technique, which measures only the time-of-flight of two reaction fragments, and the V–E technique, which measures both the time-of-flight and the energy of each fragment. The fundamental difference between these two techniques is that the 2V method yields the masses of primary fragments, i.e., fragments before they emit neutrons, while the V–E method yields the masses of secondary fragments, i.e., after neutron emission. The CORSET spectrometer can be used to study the properties of both spontaneous fission fragments and fragments of fusion–fission, quasi-fission, and deep inelastic scattering reactions, also known as multinucleon transfer (MNT) reactions.

To study the formation and decay probabilities of $80 \leqslant Z \leqslant 122$ composite systems formed in reactions with ^{36}S, ^{36,40}Ar, ^{40,48}Ca, ^{48,50}Ti, ^{52,54}Cr, ^{58}Fe, and ^{64}Ni ions, depending on the properties of the input channel, a large series of studies were carried out at the CORSET facility on exploring the characteristics of the mass–energy distributions of binary fission-like reaction fragments. The analysis of the observed mass–energy distributions made it possible to estimate the fusion probabilities over a wide range of the Coulomb factor Z_1Z_2 — from 1152 to 2700.

The changes in the properties of the mass–energy distributions of fission-like fragments discovered in these studies indicate a significant increase in the quasi-fission process in reactions with Ti and Cr ions (for nuclear systems with $Z_1Z_2 > 2000$) as compared to Ca ions. This leads to a decrease in the CN production cross section by one (for Ti ions) and two (for Cr ions) orders of magnitude compared to the reactions with ^{48}Ca ions. It was also found that the average interaction time of Ni and Zn ions with actinide nuclei ($Z_1Z_2 > 2500$) decreases by a factor of 2–3 compared to the reactions with Ti and Cr ions, which leads to a sharp decrease in the QF cross section and the dominance of few-nucleon transfer reactions and deep inelastic scattering.

The obtained production probabilities of compound nucleus in cold and hot fusion reactions are presented in Fig. 10. It was found that the fusion probability drops by approximately three orders of magnitude when going from the ^{48}Ca + ^{238}U reaction to the ^{54}Cr + ^{248}Cm reaction and by more than 10^5 times when going to the ^{68}Zn + ^{232}Th reaction. The cross section for the formation of a superheavy element with $Z = 120$ is expected to be several femtobarns based on the obtained value of the fusion probability for the ^{54}Cr + ^{248}Cm reaction. In the case of the ^{64}Ni + ^{238}U and ^{68}Zn + ^{232}Th reactions, the production cross sections are one and two orders of magnitude lower than those in the ^{54}Cr + ^{248}Cm reaction, respectively (Fig. 10).

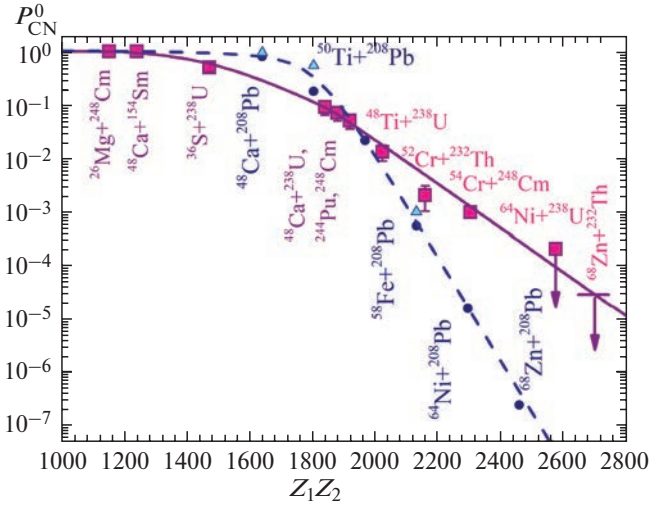


Fig. 10. The production probability of a compound nucleus in cold and hot fusion reactions at energies 5% above the Coulomb barrier depending on the Coulomb factor Z_1Z_2

Unfortunately, complete fusion reactions produce isotopes of transuranic elements with fewer than 184 neutrons, around which an "island of stability" is predicted. An alternative method for producing these nuclei is via MNT reactions, which produce projectile-like fragments (PLF) and target-like fragments (TLF) with complete momentum transfer. According to theoretical calculations, ^{238}U ions are the best bombarding particles for producing superheavy elements in MNT reactions. However, even reactions with lighter ions, such as ^{48}Ca, ^{136}Xe, or ^{209}Bi,

can produce new isotopes of elements with $Z > 100$ near the neutron shell $N = 162$, whose properties are of particular interest.

Therefore, a comprehensive study of the MNT process in reactions with lighter ions is crucial for a deeper understanding of its mechanism and the best structure of future experiments to produce new heavy isotopes in such reactions. Since the sequential fission of heavy TLF is more probable than their survival through de-excitation, experimental identification of two fragments (PLF + TLF) and three fragments (PLF + both sequential fission fragments of TLF) is necessary.

The primary and secondary mass and energy distributions of PLFs, either in coincidence with the surviving TLFs or with both fragments from the sequential fission of excited TLFs, were measured using the CORSET facility to experimentally study the properties of MNT fragments, such as their production cross sections, excitation energies, and survival probabilities, in the ^{136}Xe + ^{238}U reactions at a ^{136}Xe beam energy of 1.11 GeV and the ^{209}Bi + ^{238}U reaction at a ^{209}Bi beam energy of 1.85 GeV. Three-body events produced in the MNT reaction were measured for the first time. This allowed one to restore the primary mass distribution of the fissioning MNT fragments.

A comparison of the primary mass distributions of survived and fissioning heavy fragments of multinucleon transfer showed that the survival probability decreases with increasing their mass and is about $1.8 \cdot 10^{-3}$ for the ^{136}Xe + ^{238}U reaction and $1.9 \cdot 10^{-2}$ for the ^{209}Bi + ^{238}U reaction for fragments with masses 255 amu. The heaviest fragments observed in the mass distribution of fissioning fragments of MNT processes with a cross section of several hundred microbarns have masses around 265 amu ($Z \approx 103$, Lr isotopes) in the ^{136}Xe + ^{238}U reaction and 284 amu ($Z \approx 111$, Rg isotopes) in the ^{209}Bi + ^{238}U reaction. Thus, with approximately identical parameters of the reaction input channel (energy above the reaction barrier, introduced angular momentum), the transfer of nucleons from the projectile nucleus to the target nucleus during the interaction of uranium with bismuth is 19 nucleons greater than during the interaction with xenon ions. Unfortunately, the excitation energy for these superheavy fragments ($M \approx 280–284$ amu), estimated from the measured kinetic energies of these fragments, is approximately 150–200 MeV, which significantly hampers their survival during de-excitation.

The fission of preactinide nuclei has been actively studied over the past decade. Although asymmetric fission of preactinides near the β-stability line has been known since the late 1980s, recent observations of asymmetric fission of the neutron-deficient isotope ^{180}Hg has led to a reinterpretation of this process.

Using the double-arm time-of-flight CORSET spectrometer, the mass and energy distributions of fission fragments of neutron-deficient nuclei ^{178}Pt, ^{180,182,183,190}Hg, synthesized in the ^{36}Ar + ^{142}Nd, ^{144,154}Sm, ^{40}Ca + ^{142,143}Nd, ^{144,154}Sm reactions, and ^{184,192,202}Pb, synthesized in the ^{40,48}Ca + ^{144,154}Sm reactions, were measured. The mass distributions of the fission fragments ^{180,190}Hg and ^{184,192,202}Pb were analyzed within multimodal approach successfully applied to the description of actinide fission. A comprehensive analysis of measured experimental data, as well as existing data for nuclei in this region, such as ^{187}Ir, ^{195}Au, ^{198}Hg, ^{201}Tl, ^{205,207}Bi, ^{210}Po, and ^{213}At, allowed for a more precise determination of the proton and neutron numbers influencing the properties of modal fission in the lead



The CORSET group (left to right): K. V. Novikov, A. A. Bogachev, N. I. Kozulina, G. N. Knyazheva, I. V. Pchelintsev, R. S. Tikhomirov, I. V. Vorobiev, Yu. M. Itkis, E. O. Savelieva. In the center is E. M. Kozulin. 2023

region. It was shown for the first time that proton numbers $Z = 36$ and $Z = 45$ play a stabilizing role in the fission of these nuclei, while no influence of neutron shells on the formation of fission fragments was detected.

A structure at $Z = 38$ was also detected in the fission of heavy actinide nuclei ^{248}Cf and ^{254,256}Fm, produced in the ^{16}O + ^{232}Th and ^{16,18}O + ^{238}U reactions. Furthermore, fragments with $Z = 45$ are additional light fragments for the asymmetric mode in the 142 amu mass range. This suggests the universality of proton shells in the fission of preactinide and actinide nuclei.

These studies were carried out by the CORSET group led by E. M. Kozulin.

PHYSICS OF EXOTIC NUCLEI

The use of radioactive ion beams (RIB) is an efficient method to investigate exotic nuclear systems far from the β-stability line. The experimental program for studying relatively light ($Z \leqslant 20$) exotic nuclear systems with an excess of neutrons or protons is being implemented at FLNR at the ACCULINNA-1 and ACCULINNA-2 fragment separators installed at the primary heavy-ion beam of the U-400M cyclotron (Fig. 11). The energy of secondary beams of ~ 20–40 MeV/nucleon allows for population of the excitation spectra of light nuclei in few-nucleon transfer reactions with a sufficiently high cross section from several μb/sr to 1 mb/sr. Experiments performed at these facilities were aimed, in particular, at studying the structure of neutron-rich nuclei $^{4-7}$H, $^{6-10}$He, $^{9-13}$Li, $^{10-16}$Be, or proton-rich nuclei ^{6}Be, ^{17}Ne, ^{26}S, and other unstable systems[2]. Current and near-term research goals are shown in Fig. 12. The research covers the region of light nuclei, where transfer reactions are an effective tool for exploring the boundaries of neutron or proton stability.

[2] *Fomichev A. S. et al.* // Eur. Phys. J. A. 2018. V. 54. P. 97.

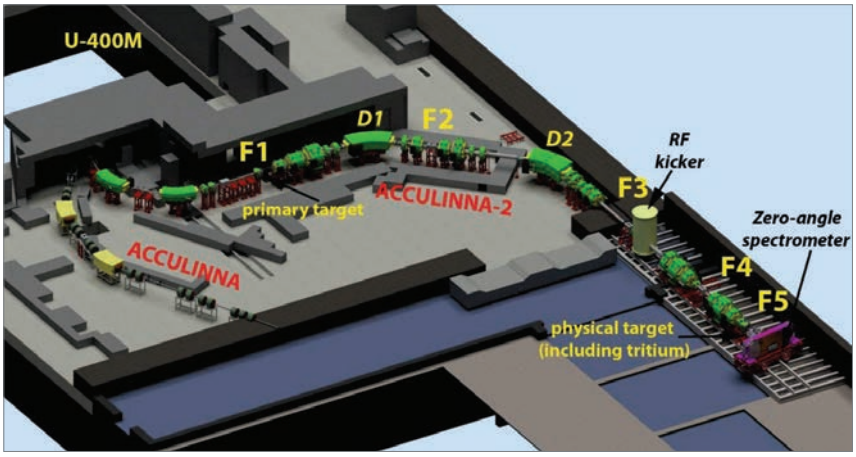


Fig. 11. Layout of fragment separators at the U-400M cyclotron

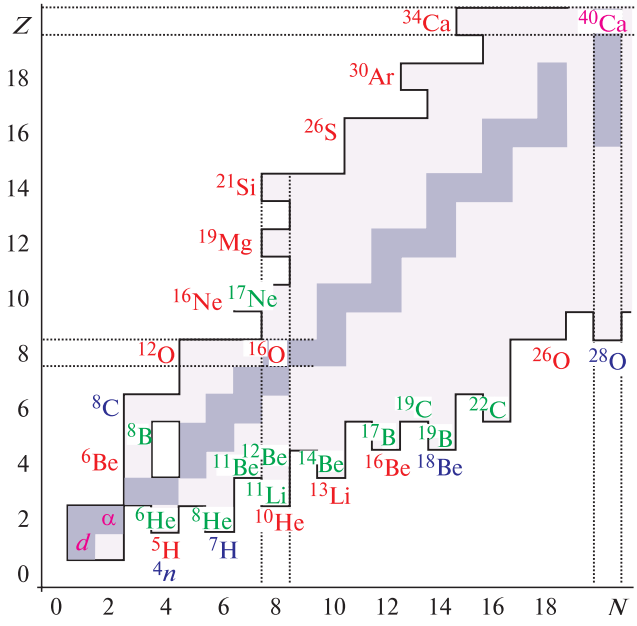


Fig. 12. The lightest exotic nuclei on the nuclide chart. The nucleon stability boundaries are shown as thick solid lines. The stability valley is highlighted in dark shade

The examples of successful experiments previously focused on the study of 1*n*- and 2*n*-emitters beyond the neutron stability boundary include studies of neutron decays of certain states in ^{5}H, ^{8}He, ^{9}He, and ^{10}He. Refined data[3] on the ^{3}H(^{8}He, *p*)^{10}He reaction, obtained at the ACCULINNA-1 separator, confirmed the previously presented results[4]. The new data indicated that the resonance position of the

[3] *Sidorchuk S. I. et al.* // Phys. Rev. Lett. 2012. V. 108. P. 202502.
[4] *Golovkov M. S. et al.* // Phys. Lett. B. 2009. V. 672. P. 22.

^{10}He ground state is located at 2.1 ± 0.2 MeV above the threshold for three-particle decay to ^{8}He + n + n, as well as the existence of intruder states and a violation of the shell filling pattern in the ^{10}He spectrum (as a result of altered spin-orbit interaction). These patterns are expected to be extended to other similar systems.

The first experiments at the ACCULINNA-2 facility recently yielded new data on the ground and excited states of the 4n, ^{6}H, and ^{7}H isotopes. In particular, a system of four neutrons was studied in detail as a low-lying resonance state at an energy of approximately 3.5 MeV. This is one of the key results of the 2018–2020 experimental program, obtained in the nuclear reactions ^{2}H(^{8}He, ^{6}Li)4n and ^{2}H(^{8}He, ^{3}He)^{7}H* → ^{3}H + 4n at the ^{8}He beam energy of 26 MeV/nucleon. The theoretical description of the observed 4n spectrum using the hyperspherical harmonics model for the ^{8}He wave function indicates an extreme peripheral nature of the reaction mechanism and that the main contribution to the appearance of the peak is made by states in the ^{8}He wave function with a hypermomentum $K = 2$. It was demonstrated (Fig. 13) that the resonance position at $E_T(4n) \sim 3$–5 MeV is stable only in the case of a peripheral reaction mechanism with specific neutron correlations in the ^{8}He source and only for the range of transferred momenta $q_\alpha \sim 150$–350 MeV/c.

The neutron-rich ^{6}H nucleus, produced in the ^{2}H(^{8}He, ^{4}He)^{6}H reaction, was studied using double ^{4}He-t and triple ^{4}He-t-n coincidences. The energy spectrum of ^{6}H revealed a structure consistent with the low-lying ^{6}H states at ~6.5 MeV, and the lower limit for the ground state of ^{6}H was found to be ~4.5 MeV. The spectrum of ^{5}H was reconstructed as resulting from the decay of ^{6}H, i.e.,

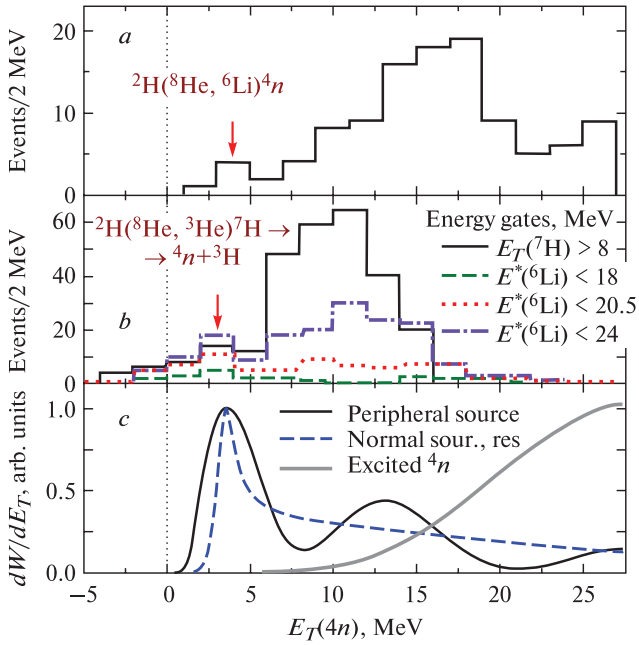


Fig. 13. Comparison of experimental data (a, b) with theoretical results (c), performed for a momentum transfer of $q_\alpha = 250$ MeV/c with due regard for the extremely peripheral reaction mechanism (black curve)

$^{6}H \rightarrow {}^{5}H(g.s.) + n \rightarrow {}^{3}H + 3n$, and a similar conclusion was reached regarding the absence of a low-lying ^{6}H state in the region of $E < 3.5$ MeV.

The following main conclusions could be drawn based on the results of the study devoted to the search for low-lying states of ^{7}H in the $^{2}H(^{8}He, {}^{3}He)^{7}H$ reaction: 1) the position of the ground state of ^{7}H (presumably $1/2^{+}$) is determined as 2.2(5) MeV above the decay threshold to $^{3}H + 4n$ with a width determined by the experimental resolution of ~ 1 MeV; 2) a doublet (presumably $5/2^{+}$–$3/2^{+}$) of relatively narrow states is observed at energies of 5.5(3) and 7.5(3) MeV; 3) rather low population cross section for the ground state of ^{7}H (~ 25 μb/sr) is explained by the extremely peripheral character of the interaction in the $^{8}He + d$ channel.

Figure 14 shows new systematics of the levels of the heavy isotopes ^{4}H–^{7}H and their possible decay schemes. It can be concluded that the decay of the ground state of the ^{7}H nucleus is possible with the simultaneous emission of four neutrons, i.e., this is a "true" five-particle decay $^{7}H \rightarrow {}^{3}H + 4n$. This is the first proven case of the existence of such a nuclear decay mode.

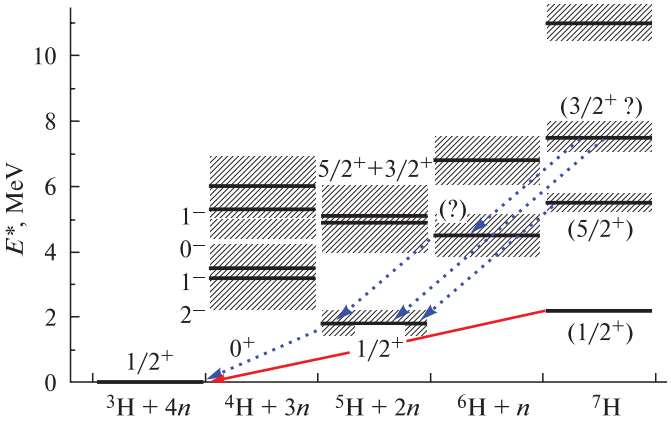


Fig. 14. Systematics of levels of heavy isotopes ^{4}H–^{7}H and their possible decay schemes

Another unique research at the ACCULINNA-2 fragment separator focused on the ^{7}He system, which was studied in the $^{2}H(^{6}He, {}^{1}H)^{7}He$ reaction at the ^{6}He beam energy of 29 MeV/nucleon. The experimental data were analyzed using the dispersion theory of nuclear reactions[5]. It was shown that the observed asymmetry in the angular distribution of ^{7}He decay could be explained by the presence of a low-lying $1/2^{+}$ state in the spectrum. A positive parity state in the ^{7}He excitation spectrum was observed for the first time.

Further studies of the $4n$, ^{5-7}H, ^{7}He systems, as well as heavier neutron-rich isotopes ($^{10,12}He$, $^{10-13}Li$, $^{12-16}Be$, etc.), are planned using the newly developed detector technology (Fig. 15). They will include precise determination of the masses of these nuclei in the ground and excited states. Transfer reactions of the $(d, {}^{3}He)$, (t, α), (t, p) and (d, p) types, observed under inverse kinematic conditions, are most suitable for these purposes. High data statistics and quite good energy resolu-

[5] *Golovkov M. S. et al.* // Phys. Rev. C. 2024. V. 109. L061602.

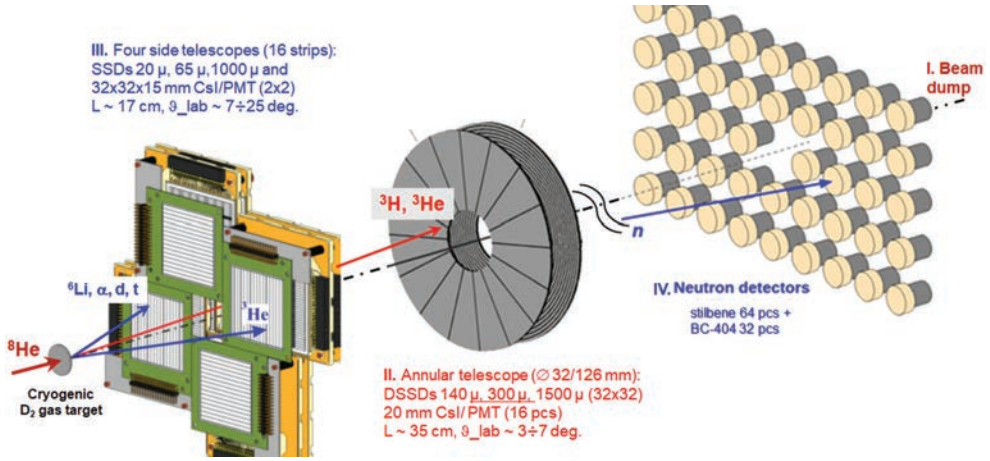


Fig. 15. The upgraded facility for precise studies of excitation spectra and decay schemes of exotic nuclei. It will comprise a new annular telescope, additional layers in the side telescopes (Si 65 μm and a CsI array), and twice the number of neutron modules

tion will be available for complete kinematic measurements performed in studying the resonance states of these little-known nuclei.

Currently (since 2024, following the completion of the U-400M cyclotron upgrade), the ACCULINNA-2 fragment separator is equipped with a number of additional tools to continue experiments with radioactive beams at a qualitatively new level. A vertically deflecting radio-frequency filter (RF kicker) is installed right behind the achromatic focal plane F3 (Fig. 11), providing additional purification of the secondary beam, which is especially important for proton-rich nuclei. The RF kicker has a maximum electric field amplitude of 15 kV/cm and a frequency in the range of 15–22 MHz. The use of the RF kicker allows for the purification of secondary beams of proton-rich nuclei by approximately 20–50 times. A spectrometer for fragments emitted at small angles is installed behind the physical target in the focal plane F5 to reliably separate charged reaction products. This will significantly improve the overall energy resolution of the experiments, provided all products, including beam-like fragments, are detected, and will ensure the separation of charged particles from neutrons. By 2026, a unique cryogenic gas target complex is expected to be operational, ensuring safe work with tritium in gaseous or liquid states. This technique is highly useful for studying nuclei near the neutron stability boundary. Two-neutron transfer reactions involving the interaction of a radioactive beam and a T_2 cryogenic target were an effective tool for studying neutron-rich nuclei ^{5}H, ^{8}He, and ^{10}He. Further experiments will be feasible with a liquid tritium target up to 1.3 mm thick.

The main results obtained at the ACCULINNA-1 facility in 2005–2018 are provided below.

A significant series of experiments using correlation methods in transfer reactions have been performed, measuring excitation spectra in several exotic nuclei, such as ^{5}H, ^{9}He, and ^{6}Be. The interpretation of the observed correlations can be



Installing the target into the reaction chamber. M. S. Golovkov, S. A. Krupko, A. S. Fomichev

unique, as was the case, for example, with the spectrum of ^{9}He populated in the (d, p) reaction at the ^{8}He beam. A characteristic feature of this approach is a certain "instability", because the result depends on the details of the reaction mechanism and the spectral densities of various states, which cannot be predicted in advance.

The study of the soft excitation mode manifested in the ^{8}He spectrum demonstrates the depth of insight into the mechanism of this excitation, which is generated by low-frequency oscillations of the neutron halo relative to the nuclear core. Specifically, the possible origin of the near-threshold anomaly above 2.14 MeV in the ^{8}He missing mass spectrum was explained by the population of the 1^{-} continuum (soft dipole excitation) with a peak energy of approximately 3 MeV.

The correlation measurements and full kinematic studies discussed above are the most common tools for studying the cluster aspect of nuclear dynamics. The importance of the Optical Time Projection Chamber (OTPC) deserves special mention here. It enables full kinematic measurements in experiments in which the count rates of "useful" events are only a few or tens. This is essential for studying exotic nuclear systems produced in small quantities per unit of time. A series of experiments related to the adjustment of the OTPC technique were performed at the ACCULINNA-1 separator. The obtained evidence for neutron emission after the beta decay of ^{8}He to the highly excited state of ^{8}Li indicates that the previously presented ^{8}He decay scheme is incomplete. The use of the OTPC time-projection chamber opened up unique opportunities for studying rare decay branches, for example, the excited ^{8}He nucleus according to the $\alpha + t + n$, ^{7}Li + n, ^{6}He + d schemes, or the beta-delayed emission of one and two protons of the ^{26}P and ^{27}S isotopes.

Another direction for studying the cluster structure concerns the states in ^{6}He with the $t + t$ structure and a possible ^{5}H + t clustering for ^{8}He. Quasi-free scatter-



The ACCULINNA-2 group (left to right): G. M. Ter-Akopian, S. I. Sidorchuk, A. Serikov, A. V. Gorshkov, D. A. Kostyleva, A. S. Fomichev, R. S. Slepnev, V. Chudoba, P. Pluchinski, S. A. Rymzhanova, P. G. Sharov, A. G. Knyazev, S. A. Krupko. 2015

ing (QFS) reactions are particularly sensitive to the cluster aspect of nuclear structure. The choice of the quasi-free knock-out channel clearly determines the cluster discretization of the studied nucleus in this class of reactions. Quasi-free scattering reactions can be effectively applied for defining the halo structure in ^{6}He, ^{8}He, and other exotic nuclei. While the valent nucleon is usually knocked out in QFS, the (α, 2α) process, i.e., the knock-out of the alpha core from the ^{6}He nucleus, was investigated in the work[6], which is also important for clarifying various aspects of the nuclear structure.

The proton stability boundary is fairly well known for nuclei with $Z \leqslant 36$. Only a few isotopes, remaining unknown in this region, could exist with the half-lives long enough to be detected by their time-of-flight in the final focal plane of the fragment separator. The ACCULINNA group searched for the nucleus at ^{26}S stability boundary, obtained by fragmenting the ^{32}S beam nuclei. A half-life limit of $T_{1/2} < 79$ ns was established for ^{26}S in this study.

Two-proton radiative capture on the pathway of the r*p* process has not been studied in detail yet. The so-called waiting point for ^{15}O is important for the r*p* process. Two-proton capture is a possible alternative to the (α, *p*) reaction as a pathway for the r*p* process, allowing for the search for the weak branch of the 2*p* decay of the first excited state $3/2^{-}$ in ^{17}Ne. The decay of this state occurs via the emission of γ quanta, but theoretically, two-proton decay is not forbidden at the level $\Gamma_{2p}/\Gamma_{\gamma} \approx 10^{-5}$–$10^{-6}$. This assumption has not been confirmed experimentally yet, but may be verified later using intense radioactive beams of $Z = 8$–10 at the ACCULINNA-2 facility.

[6] *Sidorchuk S. I. et al.* // Nucl. Phys. A. 2010. V. 840, No. 1.

Taking into account the modern technology and the developed methods, the scientific program with radioactive beams at the ACCULINNA-2@U-400M complex looks quite promising and has been on the level with those of other research centres worldwide.

NRV WEB KNOWLEDGE BASE ON LOW-ENERGY NUCLEAR PHYSICS (NUCLEAR REACTIONS VIDEO)

For many years, the vast amount of experimental data in nuclear physics (e.g., nuclear reaction cross sections and nuclear properties) was available in a text or tabular form, stored in papers or specialized databases, such as NNDC and IAEA-NDS. Moreover, theoretical modeling programs were too complex to use: they required manual creation of input files to run programs with multiple parameters and the use of additional software to analyze the results.

To address this problem, in 1999, Professor V. I. Zagrebaev proposed an idea of creating a unified platform that would combine extensive digitized experimental data with complex computational codes. Active work on this project, entitled the "NRV Web Knowledge Base on Low-Energy Nuclear Physics" (available at nrv.jinr.ru), began in 2000.

NRV became a unique tool thanks to its technological solution. All the users need are a web browser and an access to the Internet. Interaction is performed through simple HTML forms implemented using JavaScript, PHP, and HTML.

The key feature of NRV is that all complex computational programs (written in C++ and Fortran) are hosted and executed on a powerful remote server. This means the user does not need to download cumbersome software. This innovative approach allows for even the most extensive and resource-intensive calculations (which can take from several minutes to several days) without installing any software on the user's local computer. This technical solution makes NRV a unique system, independent of operating system limitations and offering an intuitive graphical interface for preparing input data and visualizing results. Furthermore, all NRV sections are provided with the detailed descriptions and links to relevant publications.

Today, the NRV web knowledge base for low-energy nuclear physics is more than just a data repository; it is a complex that combines digitized experimental data on nuclear properties and nuclear reaction cross sections with a wide range of interconnected computational programs for modeling nuclear dynamics processes. The knowledge base covers virtually all key areas of nuclear physics and a wide range of models for analyzing nuclear reactions, including elastic and inelastic scattering, reactions of transfer, fusion, radiative capture, and fragmentation. The system is a powerful tool for modeling fusion processes accompanied by subsequent fission or "survival" in particle emission channels (neutrons, protons, alpha particles, and gamma quanta). This is achieved by combining the codes for calculating fusion cross sections with a statistical model of the decay of an excited rotating nucleus.

Fusion cross sections and barrier distribution functions are calculated using quantum and empirical channel coupling methods. Both methods take into account the coupling of the relative motion of colliding nuclei with their collective degrees of freedom (rotations or surface vibrations). The empirical model provides for the influence of neutron redistribution channels on the fusion cross section. Accounting for the probability of forming a compound nucleus from a configuration of two touching nuclei is critical for reactions leading to the formation of superheavy nuclei. In NRV, this capability is implemented with the empirical formula proposed by V. I. Zagrebaev for cold fusion reactions.

NRV also allows studying the properties of nuclear decays (alpha decay, beta decay, and fission), the kinematics of nuclear reactions, and the structure of atomic nuclei. It contains programs for calculating single-particle levels (energies and wave functions) for deformed and spherical nuclei using the shell model. A two-center shell model has also been implemented, allowing the calculation of single-particle levels ranging from configurations of two separated nuclei to the compact forms of compound nuclei.

The NRV web knowledge base is now recognized as a unique tool and is widely used for educational purposes and for planning experiments and analyzing obtained data at leading research centers. The system's popularity remains consistently high, as evidenced by the frequent citations of the knowledge base in articles in the most prestigious journals.

RADIATION MATERIALS SCIENCE

Charged particle beams are used in solid-state radiation physics and radiation materials science at all research centers equipped with appropriate facilities as unique tools for modifying material properties. Light and heavy ions with the energy up to 5 MeV are most widely used. This is related to solving practical problems in semiconductor technology, developing nuclear physics analysis techniques (Rutherford backscattering spectroscopy, etc.), and accelerated modeling of radiation damage generated by high-dose neutron irradiation in reactor materials. High-energy heavy ions ($E \geqslant 1$ MeV/nucleon) were used more seldom, owing to the limited number of accelerators capable of producing these energies. The first accelerator for applied research, including radiation materials science, was the IC-100 cyclotron developed at FLNR, commissioned in 1984 and upgraded in 2007. This opened up new opportunities for systematic research into the structural effects of high-density ionization, peculiar only to high-energy ion irradiation. The main areas of this research and the examples of the most significant results are presented below. Regarding the experimental basis for materials science research, it should be noted that it received significant impetus thanks to the close collaboration with the Centre for High Resolution Transmission Electron Microscopy at Nelson Mandela University (Port Elizabeth, Republic of South Africa).

A distinctive feature of ion–matter interactions at such energies is the high level of specific ionization energy loss, that may reach several dozens of keV/nm for some

ion–target combinations. Peculiar structural defects — latent tracks that cannot be reproduced under any other types of radiation exposure — appear in a number of materials starting from a certain threshold level. The determination of the threshold ionization density values, starting from which the tracks are formed, the morphology and size of the tracks are essential to predict the radiation resistance of materials irradiated with high-energy ions. Furthermore, the threshold and track size values are the only initial experimental data for verifying various track formation models.

In addition to developing general fundamental concepts of defect formation under irradiation with high-energy heavy ions, these data are also of great interest for solving a number of applied problems in radiation materials science. Such issues include simulation of the effects caused by fission fragments, i.e., atoms with masses ranging from 80 to 155 and energy of approximately 100 MeV, in ceramic and oxide materials — inert diluents (matrices) for composite nuclear fuel proposed for an efficient and cost-effective transmutation technology for minor actinides. It should be noted that the processes in fission fragment tracks cannot be simulated using easily accessible heavy-ion beams with energy of several MeV, since the effects of high ionization density must be taken into account when selecting candidate matrix materials for inert fuel in fission reactors. This is possible only using high-energy ion irradiation within a wide range of masses and energies, allowing for varying levels of ionization and nuclear energy losses to simulate the effects of fission products. The study of ionization effects in materials with a pre-created defect structure is of high interest as it reproduces changes in inert matrices irradiated in nuclear reactors most accurately.

Transmission electron microscopy (TEM) was used in joint studies with ORNL to determine the threshold of latent track formation in magnesium aluminate spinel ($MgAl_2O_4$) — a ceramic material known for its exceptional radiation resistance to neutron and low-energy ion irradiation. A relatively low threshold of around 8 keV/nm and amorphization upon track overlap accompanied by swelling of the irradiated layer indicate that spinel exhibits poor resistance to fission fragments. This rules it out as a candidate material for inert matrices. Data on the rearrangement of the existing defect structure in $MgAl_2O_4$ under high-density ionization were also obtained. This restructuring can be seen in the dissociation and shrinkage of interstitial loops approximately 5 nm in diameter, which is comparable to the track size, whereas dissociation of larger dislocation loops (~ 30 nm) was not observed.

Moreover, track formation thresholds were determined for Si_3N_4 and Al_2O_3 for the first time. Silicon nitride deserves particular attention, as it is the only nitride ceramics in which tracks have been registered. In our experiments, tracks were detected for the first time in nanocrystalline and polycrystalline, as well as in amorphous and radiation-amorphized Si_3N_4. Figure 16 shows the structure of Si_3N_4 polycrystals irradiated with 200-MeV xenon ions in a wide range of fluence.

Isolated amorphous tracks are visible within the crystalline matrix at the fluence of $1 \cdot 10^{10}$ cm^{-2}. At $1 \cdot 10^{12}$ cm^{-2}, amorphous tracks (bright spots) are observed in an already amorphized material, alongside with the remnants of the crystalline structure. Increasing the fluence to $1.2 \cdot 10^{13}$ cm^{-2} leads to complete amorphiza-

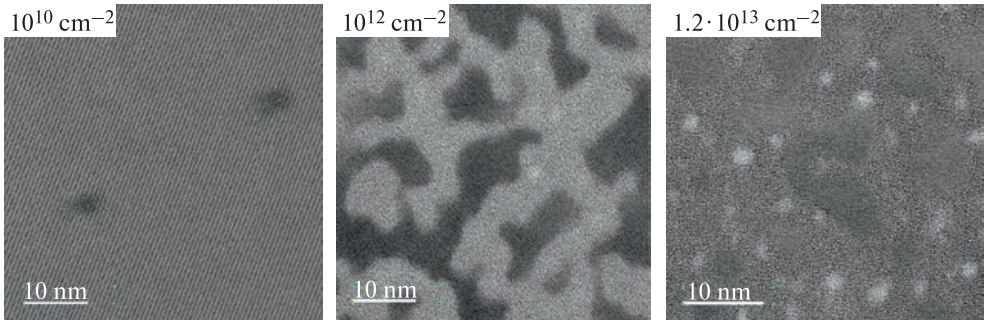


Fig. 16. Bismuth ion tracks in silicon nitride polycrystals

tion, with tracks detected only within the amorphous target. A comparison of track parameters made it possible to establish their dependence on the material's structural state for the first time within one experiment.

A series of research into the effect of high-energy ions on the microstructure of Si_3N_4, carried out in collaboration with Nelson Mandela University, a branch of the Institute of Nuclear Physics, and Gumilyov Eurasian National University (Astana, Kazakhstan), also included the analysis of ion track morphology depending on the concentration of metallic (aluminum) impurities in silicon nitride.

One of the most striking findings concerning the structural response of radiation-resistant dielectrics to high-density ionization was the observation of discontinuous tracks of an unusual rectangular shape in natural zirconium oxide (Fig. 17).

Tracks of xenon ions with the energy of 167 MeV look like segments approximately 30 nm long, formed along the ion trajectory at an angle of 9° relative to the beam incidence direction. It was found that this morphology is due to crystal transition from one crystalline phase (monoclinic) to another (tetragonal), while for most materials transition from the crystalline to amorphous state is more typical.

The most significant results of the microstructural analysis and multiscale modeling of latent track formation are presented below. Irradiation of samples over a wide range of fluence, temperature, ion mass, and ion energy was performed at the IC-100 and U-400 accelerators of the Flerov Laboratory of Nuclear Reactions at JINR and at the DC-60 accelerator (Nur-Sultan, Kazakhstan). High-resolution TEM methods were used to study microstructure of the samples at Nelson Mandela University (Port Elizabeth, Republic of South Africa). Computer simulation

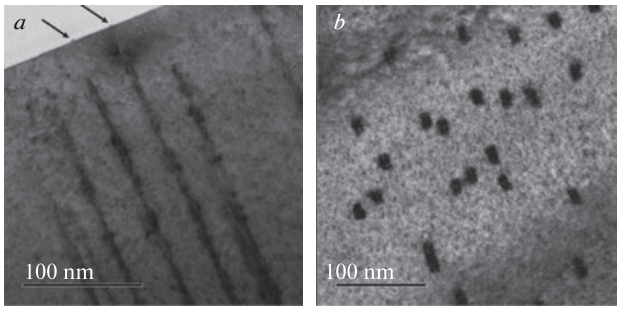


Fig. 17. Bright-field TEM images of xenon ion tracks in ZrO_2 in cross-section (a) and planar geometry (b)

was carried out within an approach combining the original Monte Carlo TREKIS model, which describes excitation of the electronic subsystem and energy transfer to the lattice, and classical Molecular Dynamics (MD) simulation of lattice relaxation.

TRACK FORMATION AND RECRYSTALLIZATION

It was demonstrated that saturation in the number of tracks in aluminum oxide per unit area in the absence of overlapping of visible track areas is caused by recrystallization processes within the existing defective regions by a passing ion. Figure 18 presents a comparison between TEM data and simulation results for structural changes along the trajectory of Xe ions with the energy of 167 MeV in aluminum oxide. Ion passage through matter results in the formation of a discontinuous cylindrical damaged region that is not fully amorphous. Al_2O_3 density analysis re-

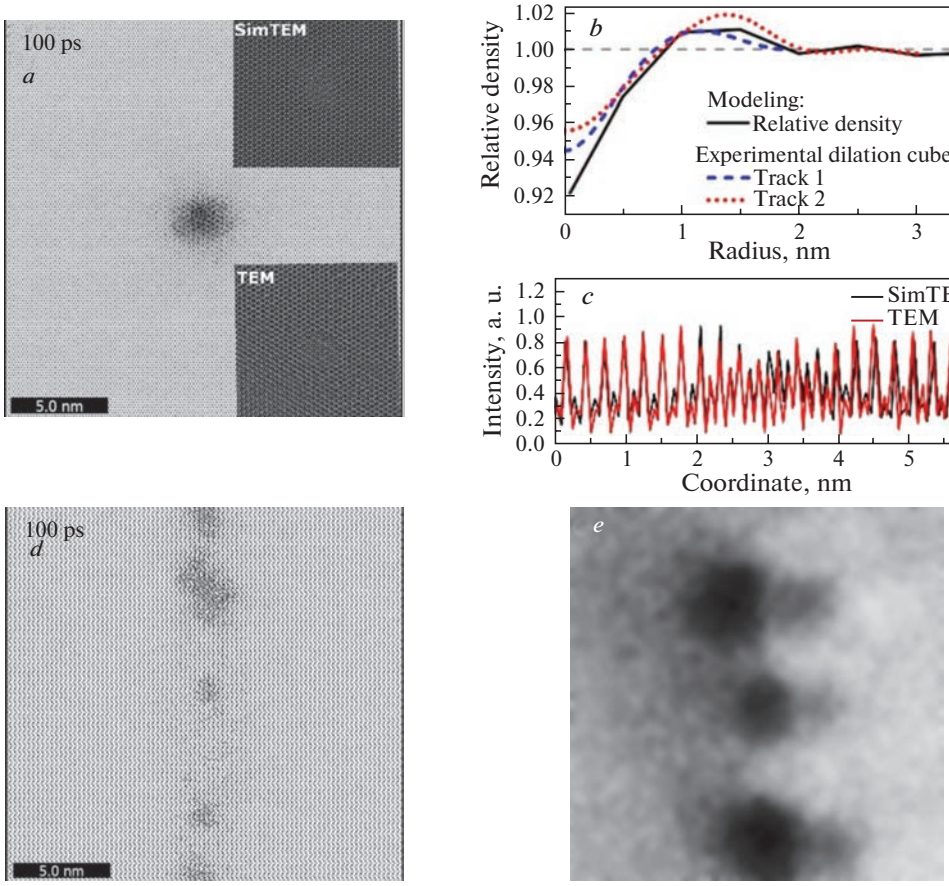


Fig. 18. a) Image of the MD cell after the passage of the 167-MeV Xe ion in Al_2O_3 — projection along the track axis with insets of TEM images at the same scale as the MD image; b) density change determined by TEM and MD; c) linear track profile; d) cross section of the MD cell; e) enlarged image of the TEM cross section at the same scale

vealed that the central, most heavily damaged region has a reduced density and is surrounded by a shell of increased density (Fig. 18, *b*). The threshold for track formation in various ceramic materials was also determined in terms of ionization energy losses of the incident ion.

A comparative experimental and quantitative analysis of the structural response of different dielectrics (MgO, Al_2O_3 and $Y_3Al_5O_{12}$) showed that ion irradiation produces damaged regions in the studied materials that differ substantially in both the structure and size (Fig. 19). MD simulation demonstrated that track size and struc-

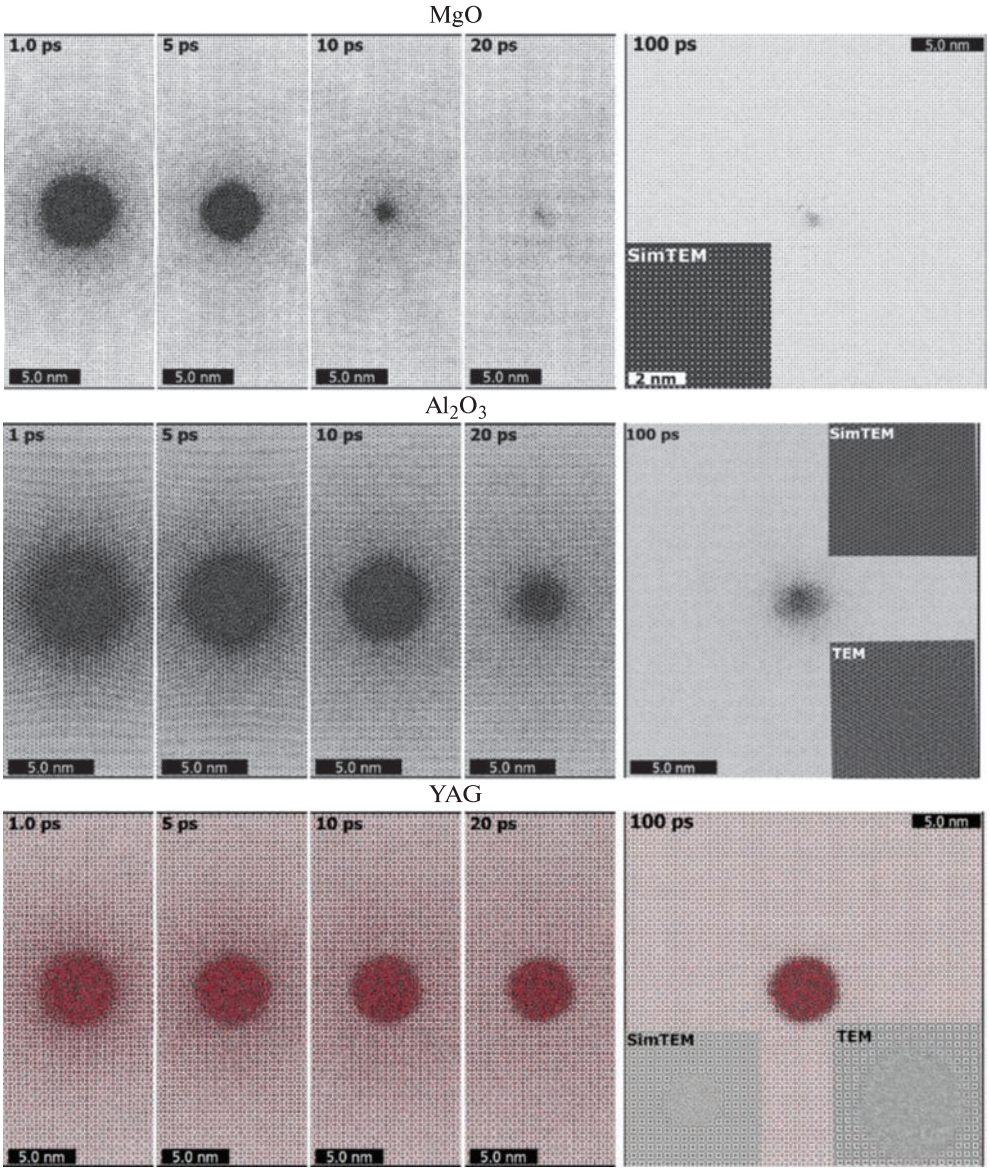


Fig. 19. Kinetics of track formation of 167-MeV Xe ions. Experimental TEM images and simulated TEM images from MD data are shown as insets

ture depend strongly on the ability to recrystallize the initially disordered state. The materials' capacity for recrystallization is largely governed by lattice complexity and the mobility of atoms in the molten material.

TRACK OVERLAP

The importance of accounting for recrystallization processes during irradiation under track-overlap conditions was clearly demonstrated. In aluminum oxide, which exhibited a high degree of structural recovery, nearly complete restoration of existing track regions was observed (Fig. 20, *f*, *j*). As the distance between tracks

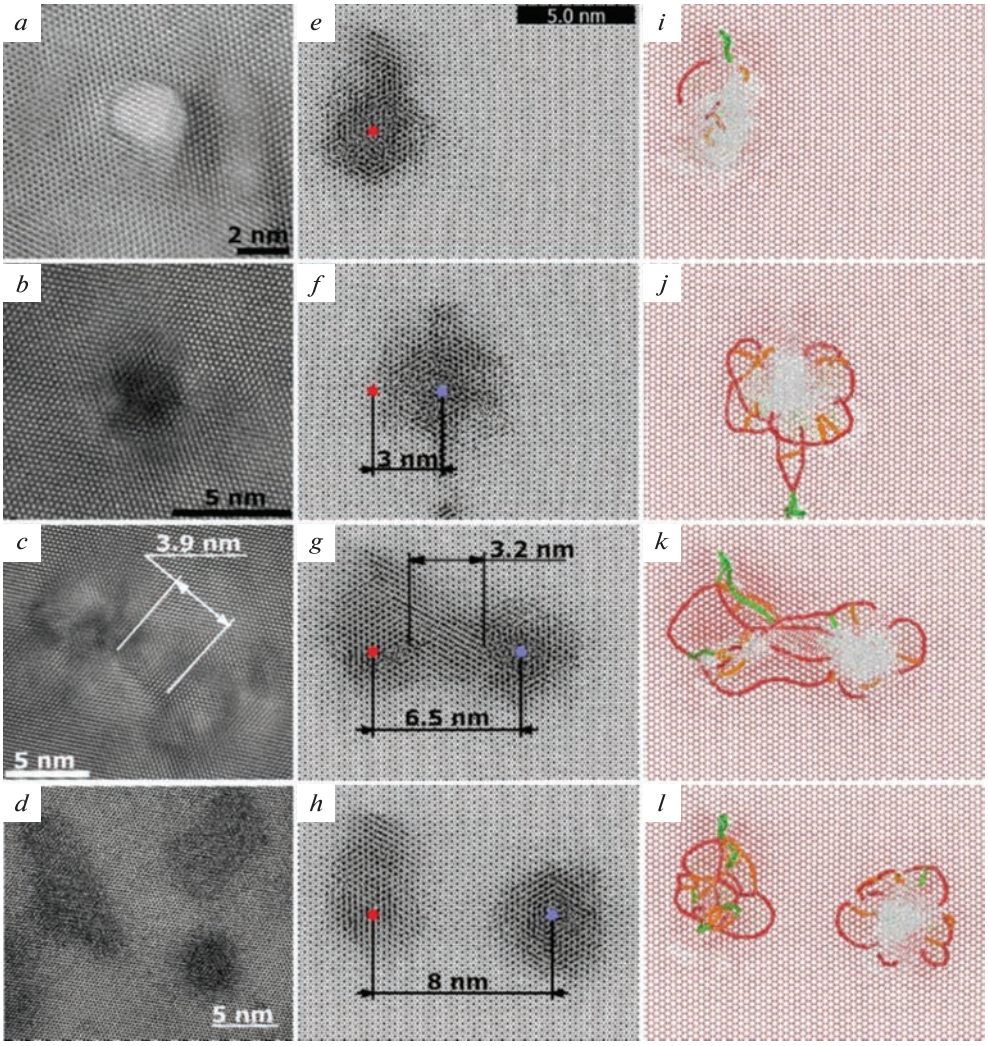


Fig. 20. Tracks of Bi ions in Al_2O_3 with the energy of 700 MeV: a, b) TEM images of a single ion track and overlapping tracks at a fluence of $5 \cdot 10^{11}$ cm^{-2} (c), $6.5 \cdot 10^{12}$ cm^{-2} (d); e—h) results of MD simulation of two successive collisions of Bi ions at different distances from each other; i—l) the dislocation structures calculated for the oxygen sublattice from the corresponding MD cells using the DXA algorithm

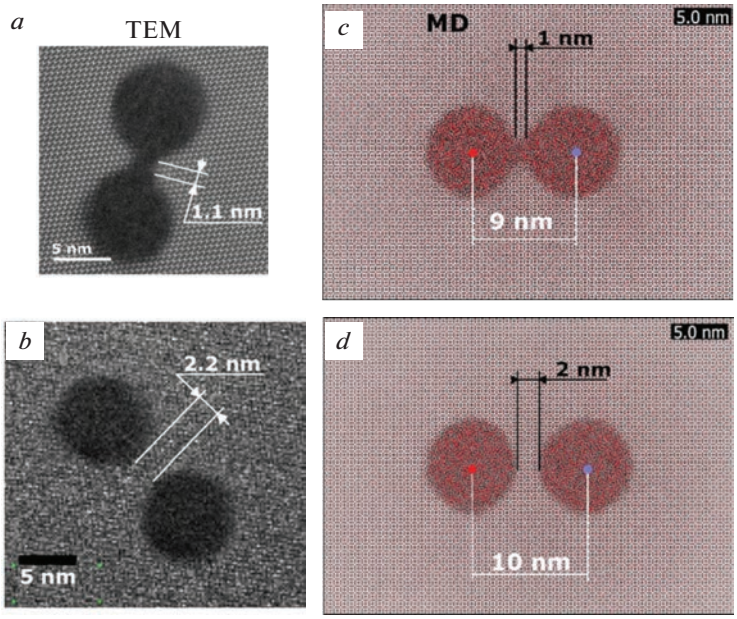


Fig. 21. TEM images of Bi ion with the energy of 1 GeV (a) and 700 MeV (b) in YAG at different distances. c, d) Simulation results for two consecutive flights of Bi ion in YAG at different distances from each other

increases, a defect structure connecting them develops. In YAG ($Y_3Al_5O_{12}$), where recrystallization does not occur, defect structures are formed between tracks at much shorter distances than in Al_2O_3 (Fig. 21).

CORRELATION BETWEEN SURFACE AND BULK RADIATION DEFECTS

The near-surface region of solids and material–fuel interfaces in multicomponent and multilayer structures are especially sensitive to irradiation by high-energy heavy ions. Excess potential surface energy and possible exchange of energy and particles with the environment can significantly alter the material's response to swift heavy-ion irradiation compared to that of the bulk crystal. Therefore, comprehensive experimental, analytical, and numerical studies of swift heavy-ion effects on possible modification of bulk samples and interfacial regions in composite materials used in energy and electronics applications are both necessary and timely task of radiation materials science.

High-resolution TEM images of surface regions in TiO_2 irradiated at different temperatures, obtained in cross-section geometry, reveal that track size in the near-surface region increases with increasing irradiation temperature (Fig. 22). This behavior is qualitatively consistent with the predictions of both thermal spike models. The observed hillocks were found to be crystalline and epitaxial with the original crystal surface, indicating a surface-initiated recrystallization process.

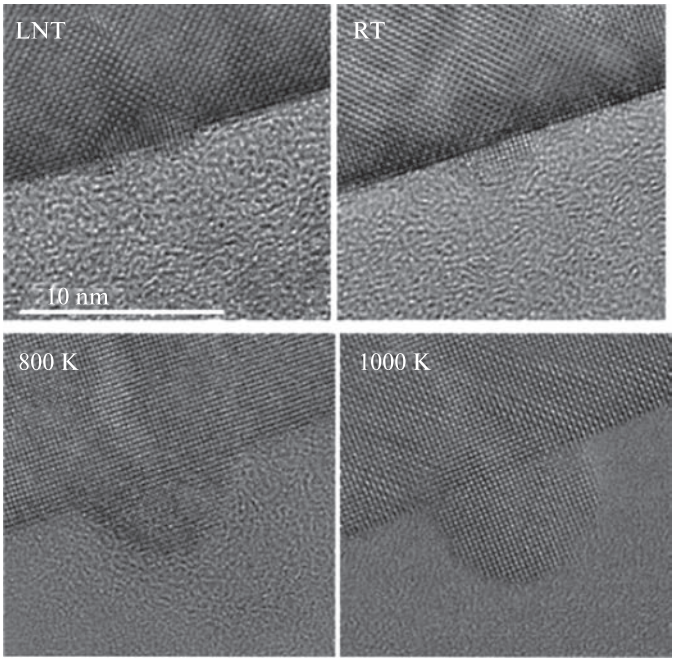


Fig. 22. TEM images of single hillocks on the surface of TiO_2 samples irradiated with Xe ions (220 MeV) at different temperatures

The study of defect structure formation on the surfaces of various dielectrics revealed clear differences in the kinetics of hillock formation between amorphizable and non-amorphizable materials. The comparative TEM and MD analyses (Fig. 23) showed the dependence of the kinetics on the basic material properties: viscosity and surface tension of the molten material, atomic mobility, and recrystallization capability.

These results substantially expanded the database of latent track parameters for a number of radiation-resistant dielectrics relevant to nuclear energy appli-

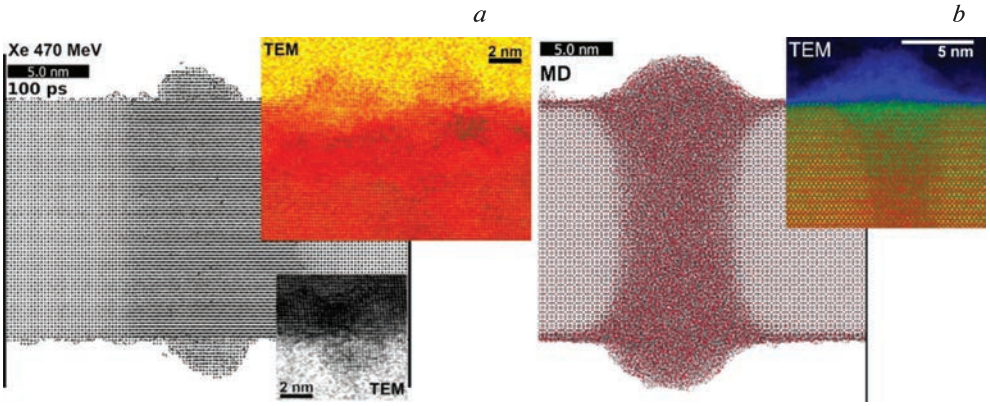


Fig. 23. Hillocks on the surface of MgO (a) and YAG (b) irradiated with swift heavy ions

cations. In particular, threshold values of specific ionization energy loss required for track formation were established for $MgAl_2O_4$, Al_2O_3, Si_3N_4, $Y_2Ti_2O_7$, and $Y_4Al_2O_{12}$ nanoparticles comprising oxide dispersion-strengthened steels. The model, which made it possible to consistently describe the stages of fast heavy-ion track formation, allowed for establishing the crucial role of recrystallization processes that determine the final track structure and for showing the importance of considering track interference at high ion fluences.

TRACK-ETCHED MEMBRANES, MICRO- AND NANOSTRUCTURED MATERIALS PRODUCED WITH HEAVY-ION BEAMS

The beginning of the 21st century was marked by a dramatic rise in demand for new scientific directions, among which life sciences and nanotechnology come first. These fields, though implying constantly improving fundamental knowledge of nature, are also strongly application-oriented. They encompass a broad spectrum of scientific, technological, and engineering issues related to healthcare, environmental protection, biotechnology, new energy sources, bioinformatics, and other relevant aspects of modern society.

Professor Sergey Nikolaevich Dmitriev played a key role in laying a solid foundation for the successful development of applied research at the Flerov Laboratory of Nuclear Reactions. As a successor of Academician G. N. Flerov, an outstanding scientist and his teacher, S. N. Dmitriev poured immense effort into developing manifestations of Flerov's ideas in several directions. His contribution was invaluable throughout the chaotic 1990s when he initiated the establishment of the Centre of Applied Nuclear Physics (CANP) at the Flerov Laboratory of Nuclear Reactions. Dmitriev was known for the breadth and depth of his knowledge, professional skills, and the ability to integrate science findings across fundamental and applied programs. His internationally recognized expertise and leadership skills led to strategic collaborations with high-profile companies in USA, Europe, and China, as well as with Russian research and commercial companies interested in the FLNR applied research results.

Professor Dmitriev was deeply engaged in solving scientific and technical issues and was granted patents for a number of solutions for technical challenges. Track-etched membrane technologies, synthesis of ultra-high purity radioisotopes, development of accelerators for technological applications, establishment of a Nanocentre – these were the projects that attracted most attention and efforts of S. N. Dmitriev and were successfully implemented when he served as head of CANP, Vice-Director and Director of FLNR.

The development of track membrane research at the Flerov Laboratory of Nuclear Reactions could not remain unaffected by these global trends. In 2000–2025, in response to new challenges and emerging ideas, the evolution of research performed at the FLNR Centre of Applied Nuclear Physics underwent substantial changes. In the previous decades, track-etched membranes were regarded primarily as tools for separation processes, particularly in microfiltration and ultrafiltra-



Head of the FLNR Centre of Applied Nuclear Physics S. N. Dmitriev is giving a talk about the applied research at FLNR. 1994



Head of FMBA V. I. Skvortsova on a visit to JINR. S. N. Dmitriev is giving a tour of the Nanocentre. 2022

tion technologies. Analytical applications remained important, too. In the 21st century, however, new research and development directions emerged. "Track" nanopores proved to be highly promising and sought-after objects in nanofluidics. The capabilities of the heavy-ion etching method in polymers were used to make a range of functional microstructured materials, including composite materials. Integrating conventional track-etched membranes with nanoparticles and nanofibers within a single structure opened broad opportunities for designing hybrid materials

with specific useful functions. Immobilization of biologically active components on track membranes led to the production of materials with tailored properties for biomedical applications.

UPGRADED IC-100 CYCLOTRON

The IC-100 cyclotron was extensively upgraded and optimized for applied research. It provided irradiation of polymer materials with high-intensity beams (Ne, Ar, Kr, and Xe) at the energy of 1.2 MeV/nucleon. The specialized beam channel equipped with a vacuum chamber for processing roll polymer films was also signifi-



The IC-100 cyclotron for applied research



Channel for irradiation of polymer films at the IC-100 cyclotron

cantly upgraded. Diagnostic equipment was improved, so irradiation homogeneity across the target surface was enhanced. The cyclotron vacuum system was supplemented with a cryopump, substantially increasing pumping efficiency during irradiation of large volumes of polymer films. Interchangeable modules were developed to produce various angular distributions of heavy-ion tracks in irradiated films. A major contribution to this upgrade was made by B. N. Gikal, V. I. Mironov, and O. M. Ivanov.

FUNCTIONAL MICROSTRUCTURED MATERIALS

Advanced technical solutions for producing microstructured materials with useful features were developed in collaboration with innovation development companies in Germany. It was found that metallic replicas of track membranes, 60–100 μm thick and with pores 5–10 μm in diameter, form surfaces with exceptionally high heat transfer coefficients. Studies aimed at optimizing the parameters of such heat-transfer surfaces were carried out, and prototypes were manufactured for specialized cooling systems. Another innovative approach involved using heavy-ion beams and track-etching techniques to enhance adhesion between polymer and metallic (copper) layers in flexible printed circuit boards. The resulting composite material showed high mechanical strength, thermal stability, and wear resistance under vibration and mechanical loading. Significant contribution to these developments was made by A. Schulz, M. Danziger, G. N. Akapiev, and V. V. Shirkova.

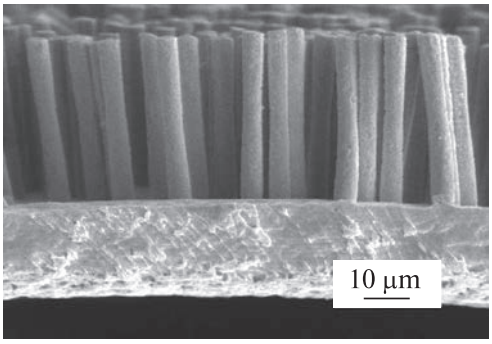


Fig. 24. Structure of a copper surface with a high heat transfer coefficient. A replica of a polycarbonate track-etched membrane produced by electrochemical means

TRACK-ETCHED MEMBRANES AS MODEL CAPILLARY-POROUS MEDIA IN NANOFLUIDICS AND PHYSICS EXPERIMENTS

The first attempts to model processes occurring in biological ion channels by means of nanopores produced by heavy-ion track etching date back to the 1990s. Pursued in international collaboration between Dubna, Darmstadt, and London the work yielded fundamentally new results. It became clear that the electric charge of pore walls determines many of the properties of nanopore behavior in electrolyte solutions (like biological fluids). A basic feature of track-etched membranes is the presence of charged functional groups on the pore walls, making them conve-

nient for investigating electrokinetic phenomena in nanocapillaries. The chemical track-etching technique allows for not only nanometer-scale control over pore size but also for variation of pore geometry. Exploiting this capability, it was established that asymmetric nanopores exhibit diode-like current–voltage characteristics. Methods were developed to control pore channel size and shape over a wide range. Two approaches were proposed and implemented to produce different configurations of asymmetric nanochannels in polyethylene terephthalate films. In addition to modeling ion and molecule transport in confined charged volumes, asymmetric track nanopores have direct practical applications as functional elements in various devices. These include first and foremost molecular sensors operating on the resistive-pulse principle or molecular recognition mechanisms. The discovery of the unique properties of asymmetric track nanopores stimulated research in numerous laboratories worldwide, aimed at the development of practical applications, and lead to hundreds of publications devoted to the results of this work. Besides sensing technologies, track nanopores with diode effects are considered for use as logic elements, valves, ion pumps, and other functional components in nanofluidics and ionotronics. Osmotic effects in symmetric and asymmetric nanopores filled with low-molecular-weight electrolyte solutions were also discovered and quantitatively evaluated. Studies of various nano-objects were supported by scanning electron microscopy, for which specialized methodological approaches were developed. The results contributed significantly to the modern understanding of processes and phenomena occurring in confined volumes with the dimensions of 1–50 nm. Those who contributed most to these studies are P. Yu. Apel, I. V. Blonskaya, O. L. Orelovich, K. Olejniczak, and Y. Yamauchi. Among international partners, key contributions were made by Ch. Trautmann and M. E. Toimil-Molares from the GSI Helmholtz Centre for Heavy Ion Research (Darmstadt, Germany), as well as B. Sartowska from the Institute of Nuclear Chemistry and Technology (Warsaw, Poland).

Track membranes, regarded as objects with precisely defined micro- or nanostructure, continue to play a significant role in a wide range of scientific investiga-

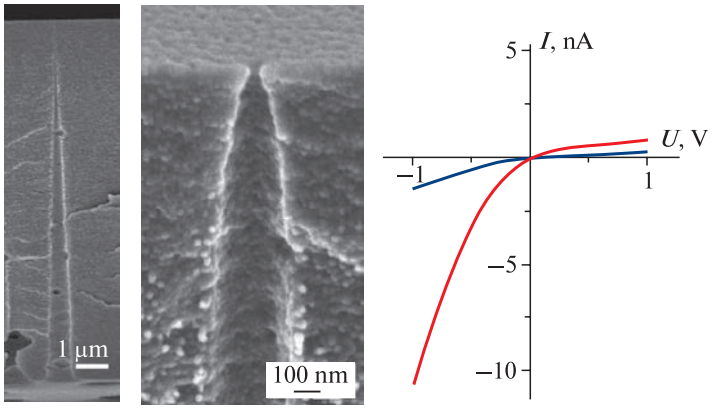


Fig. 25. Electron microscopy images of asymmetric nanopores with different channel configurations. Typical current–voltage characteristics of an asymmetric nanopore measured in potassium chloride solutions

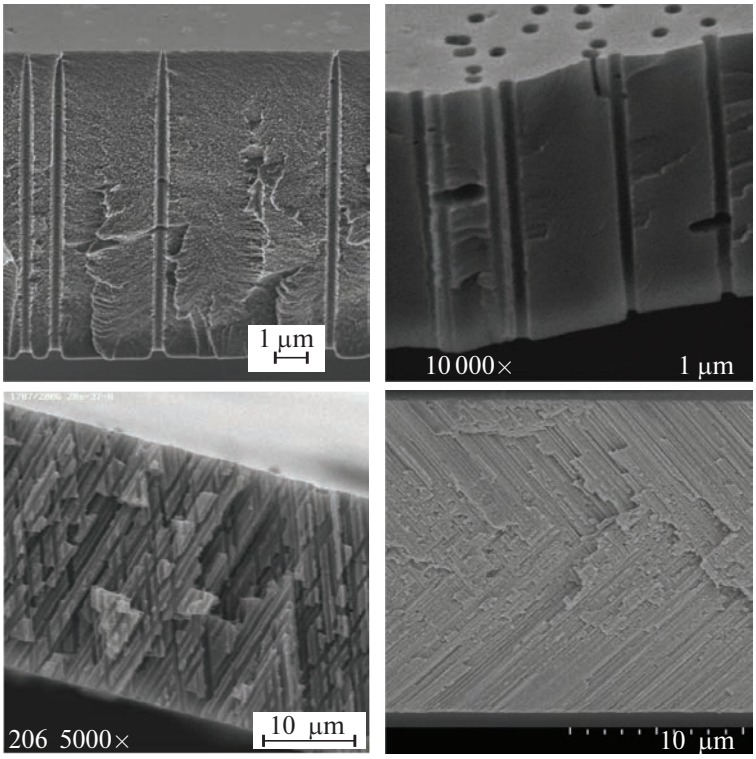


Fig. 26. Porous microstructures with specified orientation, geometry and number of pores used in various physical experiments

tions. Many experiments requiring model porous media cannot be performed without track-etched membranes. Typically, membranes with specified characteristics are fabricated individually, tailored to a particular task. A representative example is a series of studies carried out in collaboration with the Instituto de Acústica (Madrid, Spain) to investigate the propagation of ultrasonic waves through porous media with different pore radii and varying angular distributions of pore channels. These works demonstrated that simultaneous measurement of the intensity and phase of ultrasonic waves transmitted through a membrane makes it possible to determine the pore radius. In joint research with colleagues from the X-ray Astronomy Division of the Lebedev Physical Institute of RAS, the regularities governing the transmission of X-ray and vacuum ultraviolet radiation through track membranes with micro- and submicrometric-sized pores were examined. An important practical outcome of these studies was the conclusion that metallized track membranes can function as diffraction filters in telescopes used for solar radiation research. Track membranes with specified pore geometry were produced for experiments on the quasi-focusing of atomic beams carried out at the Institute of Spectroscopy of RAS (Troitsk). It was shown that conical pores with an entrance diameter of 50 nm can be used to produce nanoimages of macro-objects with a reduction factor of ~ 10^4. Each pore in the membrane acts as a camera obscura. One million parallel images

are simultaneously formed over an area of 1 cm^2 at a pore density of 10^6 cm^{-2}. The proposed method of parallel nanostructure production is quite unique.

Passage of high-energy charged-particle beams, such as alpha particles, through a model porous body can be used to obtain information about the structure of the body. Such experiments were carried out at the Institute of Nuclear Physics (Řež, Czech Republic) with membranes produced at FLNR. A track-etched membrane with pores 35 nm in diameter and a pore density of $5 \cdot 10^9$ cm^{-2} served as a key element in an electrobaromembrane process for separating ions of identical charge. The simultaneous application of two driving forces (a pressure gradient and an electric potential gradient) made it possible to create conditions under which singly charged ions, such as Li^+ and Na^+, move through the membrane nanochannels in opposite directions. This result has considerable practical significance in view of the challenges of lithium extraction, which is a critically important element for the modern industry.

A system of cylindrical pores, either perpendicular to the membrane surface or inclined at a specified angle, is a simple and easily described model for analyzing fracture of a body under mechanical stress. The use of track membranes with defined structural parameters made it possible to identify several important regularities in the behavior of porous materials under applied mechanical stress, including the determination of stress concentration fields, clarification of the role of interactions between neighbouring pores, and formulation of conclusions regarding possible fracture mechanisms in composite materials.

A substantial contribution to these studies was made by the representatives of partner research centers and universities: T. E. Gómez Álvarez-Arenas (Instituto de Acústica, Madrid, Spain), A. V. Mitrofanov (Lebedev Physical Institute, Moscow), V. I. Balykin (Institute of Spectroscopy of RAS, Troitsk), J. Vacek (Institute of Nuclear Physics, Řež, Czech Republic), V. N. Nikonenko (Kuban State University, Krasnodar), and I. V. Razumovskaya (Moscow Pedagogical State University, Moscow).

COMPOSITE AND HYBRID TRACK-ETCHED MEMBRANES

A composite material is a material formed from two or more components with substantially different physical and/or chemical properties, whose combination results in new functionality. A track membrane, being a highly uniform and robust porous film, can serve as a matrix for applying additional components (layers, nanoparticles, nanofibers, etc.) to achieve practically useful effects. If chemical interactions occur between the components of a composite material, the term “hybrid” is also used.

Over the past two decades, several types of composite materials based on polyethylene terephthalate track-etched membranes (PET TM) have been proposed. Various methods were developed to apply hydrophobic polymers onto membrane surfaces, including by polymerization from an active gas phase and electron-beam sputtering. The formation of a thin hydrophobic polymer layer, such as ultra-high molecular weight polyethylene or polytetrafluoroethylene, is accompanied by the

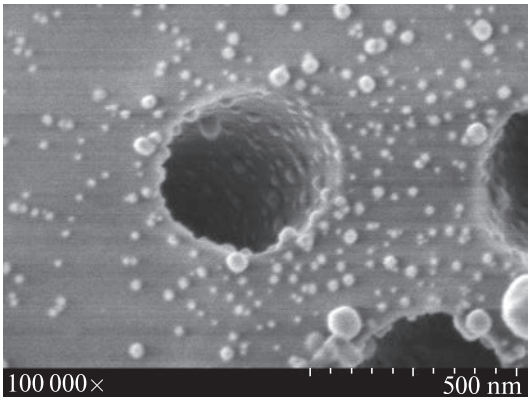


Fig. 27. Surface of the composite track membrane with silver nanoparticles

development of micro- and nanorelief features, which are key to attaining the desired properties of the composite membrane. The chemical composition and surface morphology provide superhydrophobic behavior. An alternative method involved applying a titanium binding layer onto PET TM followed by the formation of polyvinylidene fluoride nanofibers. These composite membranes can be successfully applied in energy-efficient membrane distillation processes.

The collaboration with South African partner institutions played a major role in advancing electrospinning techniques for nanofiber fabrication. Nanofibers produced from various polymers, including biocompatible, provide new functionalities for composite membranes beyond the basic sieving mechanism of track membranes. By grafting functional groups onto nanofibers, materials capable of selectively absorbing cesium ions from solution were obtained. Moreover, cesium in the dispersed phase is also captured by the composite membrane. Based on this principle, membranes for removing radioactive contaminants can be designed.

Great efforts have been made on composite membranes with sensing capabilities. A track-etched membrane immobilized with metal nanoparticles and exhibiting plasmon resonance effect is capable of performing several tasks simultaneously: accumulation of the target material, its preliminary purification, and detection via its Raman scattering spectrum. Owing to the Surface-Enhanced Raman Scattering (SERS) effect provided by the nanoparticles, the sensitivity of such sensors is extremely high. Raman signal enhancement factors of up to 10^8 are achieved when silver nanoparticles are used. Sensors of this type can be used to detect low concentrations of toxic substances in environmental samples or biological fluids.

Major contribution to research on composite membranes was made by A. N. Nechaev, L. I. Kravets, A. Rossouw, O. V. Kristavchuk, I. I. Vinogradov, and E. V. Andreev. It is also important to acknowledge the key role of L. Petrik (University of the Western Cape, RSA) in advancing this research direction.

Composite membranes for biomedical applications are of particular interest. A bilayer composite consisting of a porous substrate and a nanofibrous coating made of biopolymers (chitosan and collagen) is a promising wound-healing material. SERS-based membrane sensors are especially relevant for their ability to

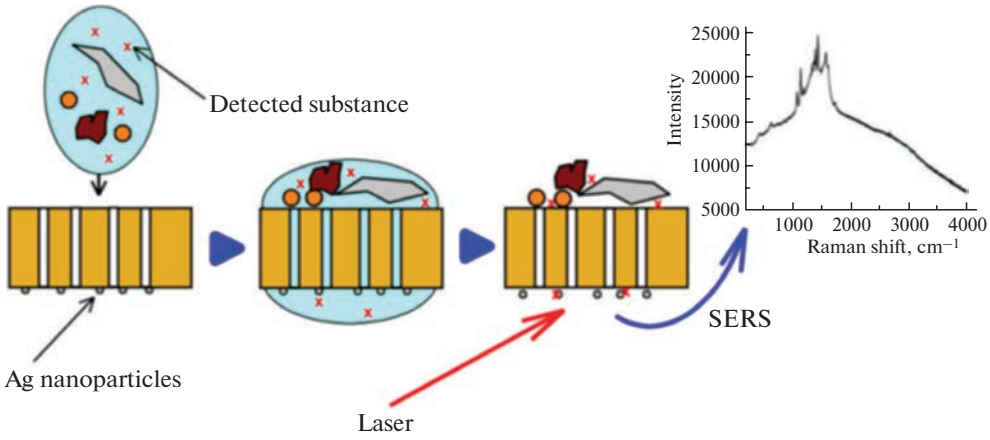


Fig. 28. Operation of the track-etched membrane sensor with SERS effect

register biological objects, primarily viruses. Selectivity and sensitivity to viruses were increased by immobilizing oligonucleotide aptamers on silver-coated track-etched membranes. Due to the selective affinity of the aptamer to the viral envelope proteins, such an aptasensor has a sensitivity of no worse than 10 influenza A virus particles per milliliter, which exceeds the sensitivity of the standard PCR method. This research continues on a broad front, with new technical solutions including both modifications of the track membrane matrix and the architecture of the final composite.

Furthermore, studies on the virucidal activity of track membranes modified with various agents were carried out. Pore diameters of the track-etched membranes exceeded the tested virus sizes, and thus the sieving mechanism could not separate the virus particles from the liquid phase. Nevertheless, by immobilizing silver and curcumin nanoparticles on the membrane surface and in the pores, a substantial part of herpes and stomatitis viruses was inhibited. In this case, the membrane surface charge was changed to the opposite by adsorption of polyethylenimine in order to enhance the interaction of viruses passing through the pores with their walls. Another innovative development was a track-etched membrane selectively sorbing DNA through immobilization of a protein with the characteristics typical of extremophilic microorganisms. Such membranes enable extraction and accumulation of extracellular DNA from biological solutions for subsequent analysis. V. I. Kukushkin (Osipyan Institute of Solid State Physics, Chernogolovka), E. G. Zavyalova (Moscow State University, Moscow), R. Arutyunyan (Yerevan University, Armenia), and E. V. Kravchenko (DLNP JINR) have made important contributions to this research.

Biomedical applications of track-etched membranes are receiving special attention. This area is regarded as having particularly strong innovation potential. The promotion of innovative research, including a wide range of interdisciplinary studies and developments, is coordinated by a team led by N. S. Dmitriev.

DEVELOPMENT OF THE FLEET OF EQUIPMENT AND ESTABLISHMENT OF A SPECIALIZED LABORATORY (NANOCENTRE)

At FLNR, the priority has always been given to instrumentation necessary for applied research. The rapid advancement of nanotechnology and materials science has been accompanied by continuous progress in scientific instrumentation and the emergence of fundamentally new tools to study the structure and composition of matter on the nanometer scale. By 2010, it had become clear that a substantial modernization and expansion of the instrumentation base of the FLNR Applied Nuclear Physics Centre was required. Within the framework of the International Innovation Nanotechnology Centre (IINC) project, it was decided to construct a specialized laboratory building. Its construction was completed in 2014 under the leadership of FLNR Director S. N. Dmitriev. The purchase of the state-of-the-art scientific equipment was funded by the Rusnano State Corporation. The newly commissioned equipment enabled a broad spectrum of investigations into the morphology and composition of micro- and nanostructured materials. These capabilities included scanning electron microscopy, X-ray photoelectron spectroscopy, energy-dispersive X-ray elemental spectroscopy, infrared and UV-Vis spectroscopy, as well as a wide range of equipment for chemical laboratory, etc. D. V. Shchegolev played a leading role in the design and engineering support of the Laboratory building. In subsequent years, the fleet of instrumentation was further expanded and included a transmission electron microscope, devices for thermal analysis of polymers, Raman spectrometers, a nanoparticle analyzer, electrospinning systems



The FLNR new laboratory building



In the laboratories of the Nanocentre



Seminar dedicated to the 50th anniversary of research on track-etched membranes

for nanofiber production, an atomic force microscope, an atomic emission spectrometer, and equipment for the mechanical testing of materials. The implementation of these new capabilities elevated research and development activities to a fundamentally higher level.

The scientific direction established by Academician G. N. Flerov is still relevant. Over the course of half a century, research on track-etched membranes and, more broadly, on nano- and microstructures produced by heavy-ion beams, has evolved into a substantial and influential field of applied science. A new generation of scientists and engineers, who have taken up this work in the 21st century, is introducing novel approaches and techniques into ongoing research. The integration of the achievements of FLNR into the contemporary landscape of membrane technologies, materials science, nanotechnology, biomedical engineering, and micro- and nanofluidics is a significant contribution to the technical progress.

NEUTRON PHYSICS

The Joint Institute for Nuclear Research continues to be a world leader in neutron physics and neutron research. The Frank Laboratory of Neutron Physics (FLNP) has played a key role in this success, providing the scientific community with unique experimental capabilities and making outstanding contributions to the advancement of both fundamental science and applied research.

The history of neutron physics at JINR begins with the creation of the world's first pulsed fast reactor (IBR), physically started up in June 1960. This historic moment marked the era of pulsed reactors as neutron sources for a wide range of fundamental and applied research in nuclear and condensed matter physics. The development of the IBR reactor led to the creation of a more powerful and advanced reactor, the IBR-2, which was commissioned in 1984. A significant upgrade of the IBR-2 reactor, conducted between 2007 and 2010, transformed it into one of the best neutron sources in the world, providing one of the highest flux densities of thermal and cold neutrons in the global scientific community. Currently, the upgraded IBR-2M reactor continues to operate successfully, confirming its importance for the development of neutron science.

The Frank Laboratory of Neutron Physics of JINR is known for breakthrough discoveries that have shaped modern neutron physics. In particular, ultracold neutrons were discovered here with the participation of F. L. Shapiro, V. I. Lushchikov, Yu. N. Pokotilovski, and A. V. Strelkov. This discovery launched an entire field of fundamental research, including experiments studying the gravitational quantization of neutrons and verifying the weak equivalence principle. The quantization of neutron levels in the Earth's gravitational field, theoretically predicted by FLNP scientists V. I. Lushchikov and A. I. Frank, was experimentally confirmed in 1999 at the Institut Laue–Langevin (France), demonstrating the depth of fundamental research conducted at FLNP.

Research into fundamental symmetry violation in neutron–nucleus interactions represents another area of outstanding achievement for the Laboratory. The Polyana facility and other experimental complexes at FLNP enabled pioneering measurements of spatial parity violation in p-wave resonances of various nuclei, as well as studies testing time-reversal

invariance. This work contributed to a deep understanding of fundamental interactions in nuclear physics.

Over the past two decades, the Frank Laboratory of Neutron Physics has made significant progress in developing new research methods and facilities. The development and improvement of Fourier diffractometers (HRFD, FSD, and FSS) at the IBR-2 reactor have opened up new possibilities for structural studies of materials with unprecedented resolution at relatively short flight paths. These facilities, developed in collaboration with specialists from the Konstantinov Petersburg Nuclear Physics Institute, the Technical Research Centre of Finland, and many foreign institutes, have become world leaders in the field of high-resolution neutron diffractometry.

The development of small-angle neutron scattering and neutron reflectometry methods has enabled the Laboratory to conduct research on nanosystems with a spatial resolution ranging from 1 to 1000 nm. Research on dendrimers, polymer structures, magnetic fluids, and other nanosystems has received recognition in the international scientific community and is regularly presented at major international conferences.

Research in neutron activation analysis (NAA) has made a significant contribution to the development of applied neutron physics. The Regata facility at the IBR-2 reactor has become a powerful tool for solving problems in ecology, materials science, biology, and even archaeology. The UN program on the state of air pollution in Europe based on the analysis of moss biomonitors was coordinated from 2014 to 2022 under the leadership of FLNP staff, emphasizing the international recognition of this research in Dubna.

The tagged neutron method, developed in collaboration between FLNP and other JINR laboratories, has found application in both fundamental and applied fields, including portable neutron analyzers for determining the elemental composition of soils and other materials in real time.

The development of a facility for neutron radiography and tomography at the IBR-2 reactor and the subsequent expansion of this area to Kazakhstan and Uzbekistan demonstrates not only the scientific achievements of the Laboratory but also its role in developing the scientific infrastructure of JINR Member States. Neutron radiography and tomography methods have opened up new possibilities for the non-destructive analysis of cultural heritage objects, modern materials, and products.

The international User Program within the FLNP scientific infrastructure provides a broad access to experimental equipment for scientists from the JINR Member States and other countries, facilitating the implementation of diverse research projects and the strengthening of international scientific cooperation. Particular attention is paid to supporting young scientists and developing human resources through JINR

school programs and opportunities to conduct research under the supervision of experienced specialists.

This section is devoted to the history, achievements, and state of neutron physics at JINR over the past two decades. The Frank Laboratory of Neutron Physics remains the flagship of neutron science at JINR and continues to make a significant contribution to the development of this field globally.

PHYSICS OF INTERACTION OF NEUTRONS WITH NUCLEI

PULSED NEUTRON SOURCES IBR, IBR-30, IBR-2, AND IREN

June 2025 marked the 65th anniversary of the physical startup of the world's first pulsed fast reactor (IBR) at JINR, which started the era of pulsed reactors as neutron sources for a wide range of fundamental and applied research in nuclear and condensed matter physics. Its more powerful successor, the IBR-2 reactor, began its long and fruitful service in neutron research in 1984, which continues today after a significant upgrade. A detailed history of the development and use of JINR pulsed neutron sources for research in nuclear and condensed matter physics, as well as in a number of applied fields, is presented in the collection[1].

The pulsed mode of neutron sources is designed for studying neutron-induced reactions using the time-of-flight method, according to which neutrons of different energies are emitted into a vacuumized neutron guide, and the time of their arrival at the target permits determining the dependence of the cross sections of the corresponding reactions on their energy for each pulse. Furthermore, the pulsed mode of neutron sources allows for a significant increase in the instantaneous flux density of neutrons incident on the target. This enables, for example, the IBR-2 reactor to achieve one of the highest thermal and cold neutron flux densities in the world.

The pulsating mode for the first IBR reactor was achieved by rotating a small portion of the core (the reactivity modulator) relative to its two stationary components. However, due to the problem of heat removal from the reactivity modulator, this reactor mode imposed serious limitations on the permissible fission power of the core and the duration of the neutron pulse, and, consequently, on the achievable density of the pulsed and average neutron fluxes. Another principle for varying the power was employed for the more powerful IBR-2 reactor, namely, the use of a rotating, fissile-free, massive metal reflector located close to the subcritical core. This, certainly quite complex, movable reflector (MR) could be cooled by a flow of gaseous helium, while the compact core was cooled by liquid sodium. The average power of such a reactor could reach several megawatts with a pulse power of more than a gigawatt and a pulse duration of about 200 μs, providing an instantaneous neutron flux density on the moderator surface of up to 10^{16} $cm^{-2} \cdot s^{-1}$.

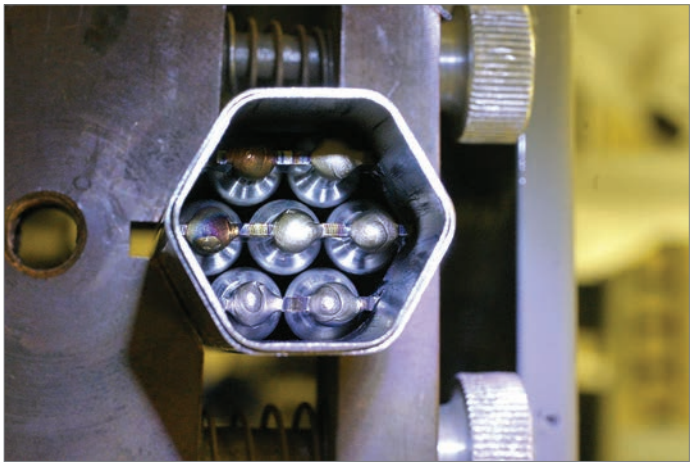
[1] Dubna — an Island of Stability: Essays on the History of the Joint Institute for Nuclear Research (1956–2006) / Eds. V. G. Kadyshevsky, A. N. Sissakian, Ts. Vylov. Moscow: Akademkniga, 2006.

By the mid-1990s, after the IBR-2 reactor had successfully operated for over 15 years in experimental service, the experience of its intensive operation led to the recognition of the need for significant timely upgrade. FLNP Chief Engineer V. D. Ananyev and Laboratory Director V. L. Aksenov, along with the active participation of NIKIET and other Rosatom organizations, initiated a program for upgrade of the IBR-2 reactor to replace most of its units, whose service life was expected to expire by 2007.

The upgrade program[2] of the IBR-2 research reactor facility was successfully implemented with substantial financial support from Rosatom between 2007 and 2010. Along with replacing some of the equipment, key components, such as the reactor vessel, stationary reflector, control and protection actuating units, and external neutron moderators, were simultaneously upgraded to increase reliability and durability. It is worth noting that the IBR-2 modernization work began earlier, with the replacement of the reactivity modulator (PO-3 movable reflector) and the periodic power pulse modulation device in 2004, as well as the fabrication of a batch of fuel assemblies (FA) for the core of the new IBR-2M reactor in 2006 using components and fuel rods supplied to JINR by Rosatom enterprises. Fitting up a fuel assembly is a unique operation for a scientific organization; however, the work was successfully completed by FLNP JINR employees at a specially created assembly site, with a Rostekhnadzor license issued for this type of activity.

Since 2012, after the completion of the physical and power startups, the upgraded IBR-2M reactor has again been operating in a routine mode to conduct physical experiments on the extracted beams.

In developing the IBR-2 upgrade project, a new concept for the composition and placement of neutron moderators around the IBR-2M reactor was used to create optimal conditions for the efficient use of upgraded and new spectrometers, as well as to expand the possibilities of using cold neutrons in line with the growing



Fitting-up of the IBR-2M fuel assembly

[2] *Ananyev V. D., Vinogradov A. V., Dolgikh A. V., et al.* Power Startup of the Upgraded IBR-2 Reactor (IBR-2M). JINR Commun. P13-2012-42. Dubna, 2012.



Installation of the new IBR-2M reactor vessel

interest in research into nano- and mesoscopic structures in solid-state physics and biology. The project, implemented as a cryogenic moderator complex consisting of the CM-201, CM-202, and CM-203 cryogenic moderators, which use distilled water in the pre-moderator chamber and a frozen mixture of aromatic hydrocarbons (mesitylene and m-xylene) in the form of pellets with a diameter of 3.5–3.8 mm at a temperature of 30–40 K, filled into the cryogenic chamber of the moderator, was initiated after the startup of the upgraded reactor and is currently ongoing (Fig. 1).

The IBR-2 upgrade, conducted between 2007 and 2010, primarily affected the reactor itself, as well as the control, monitoring and protection systems. Taking into account that the IBR-2 reactor, commissioned in 1984, is planned to be used as a neutron source for scientific research for an extended period, until 2042, it is of particular importance to maintain the operational condition of the facility's pro-



Physical startup of the IBR-2M

cess equipment, power supply system, and structural components — the elements essential for the continued operation of the nuclear facility. To this end, FLNP technical specialists, with the assistance of specialized organizations (if necessary), regularly extend the service life of the IBR-2M safety-critical equipment. Thus, the IBR-2M facility's service life was extended by eight years in 2014 and by another ten years in 2022.

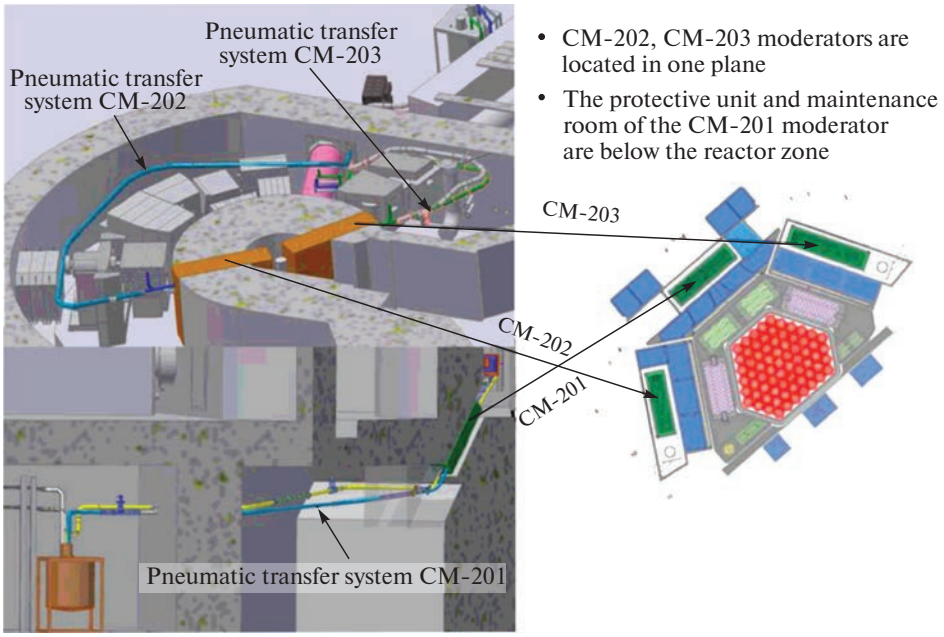


Fig. 1. Complex of cryogenic moderators of the IBR-2

In addition to extending the service life of reactor systems, obsolete equipment is being replaced. A significant amount of work has been completed to reconstruct the IBR-2M reactor's power supply system.

Despite the fact that the service life of the reactor's sodium cooling system equipment was extended until 2032, the FLNP Directorate decided to replace well in advance the secondary circuit air heat exchangers of the sodium cooling system, which had been in harsh operating conditions for over 40 years and were repaired in 1995 and 2018 due to leaks in the tube bundles. Two additional tube bundle leaks in each heat exchanger, which occurred before 2023, indicated a high probability of further similar incidents and the need to replace the air heat exchangers with new ones. This led to the decision to shut down the reactor to upgrade the core's sodium cooling system.

The actual equipment replacement took approximately three years before the IBR-2M reactor was commissioned. This work required supervision by Rostekhnadzor and the appropriate license for JINR, which had expired by that time. It took more than a year to obtain a new license, and FLNP staff, together with the specialized organization, were able to start the work only in May 2024, after receiving the new license. A large amount of work to replace two air heat exchangers was completed in less than a year. This work was complicated by the fact that, due to the size and weight of the equipment, its replacement required dismantling (and rebuilding) the concrete roof slabs of the room housing the heat exchangers. Specialists from the IBR-2M sodium technology service, together with the staff of the specialized organization, successfully completed the task, demonstrating the high level of expertise.

On February 12, 2025, a test run of the IBR-2M reactor was conducted after a long shutdown to confirm the readiness of its systems for normal operation. On February 17, 2025, the IBR-2M reactor completed its first operating cycle with the possibility of conducting experiments on beamlines.

A significant amount of equipment upgrade was completed during the forced downtime of the IBR-2M reactor. However, further equipment replacements are planned and already underway, allowing the IBR-2M service life to be extended until the 2040s. This goal is achieved through the availability of a backup movable reflector, manufactured by JSC Votkinsk Machine Building Plant and delivered to JINR in 2019, as well as the planned production of an additional batch of fuel for the reactor core. Thus, the IBR-2M reactor, the basic facility of FLNP JINR, will remain among the world's top five neutron sources for time-of-flight research on extracted beams of slow neutrons for a long time to come.

Following the startup of the first IBR reactor in 1960, with an average power of approximately 1 kW, a pulse power of up to 5 MW, and a pulse width of up to 80 μs, it quickly became clear that it needed to increase its average power and significantly reduce the neutron pulse duration to provide greater capabilities for neutron nuclear physics experiments. This marked the beginning of a near-constant upgrade of the IBR reactor, so that by 1970, the upgraded IBR-30 reactor had a power output of up to 25 kW (versus the design power of 30 kW) and a neutron pulse duration of 4.5 μs in booster mode, when the reactor served as a photoneutron multiplier, producing an electron beam from the LUE-40 linear accelerator on a target located

within the subcritical core. The accelerator's 35 MeV electron beam pulse (the designed value being 40 MeV) was phased with mechanical modulation of the IBR-30 plutonium core's reactivity by rotating a section of it (a steel disk with two enriched uranium inserts). This ensured a multiplication factor of approximately 200 at a pulse repetition rate of up to 100 Hz and produced an integrated neutron yield of up to $5 \cdot 10^{14}$ s^{-1}. Combined with its advanced experimental infrastructure, including a unique polarizer for resonance and fast neutrons and the ability to polarize target nuclei, the IBR-30 + LUE-40 booster became the most luminous neutron source in Europe with moderate energy resolution.

The availability of such a source at JINR enabled a series of pioneering measurements of the effects of spatial parity violation in neutron–nucleus interactions, as well as the first acquisition of unique data on the energy dependence of P-even and P-odd angular correlations of fission fragments in neutron resonances of the ^{236}U and ^{240}Pu compound nuclei. Theoretical analysis of these data provided fundamentally new insights into the quantum nature of nuclear fission.

In the early 1990s, before the IBR-30 reactor's mechanical equipment and fuel load had been exhausted, the FLNP leaders began discussing a design for a new high-resolution neutron source (HRNS) for nuclear physics research. At the same time, the newly formed JINR Directorate proposed shutting down the IBR-30 + LUE-40 basic facility as obsolete. As a result, preliminary technical specifications were formulated for a new booster source of resonance neutrons[3] (IREN), consisting of a compact fast (with a short neutron lifetime) subcritical plutonium core serving as a multiplier for photoneutrons generated in a helium-cooled converter target by a 200 MeV electron beam from a linear accelerator. The multiplication factor K_p was chosen to be relatively small ($K_p \approx 30$) to significantly reduce the fast neutron pulse duration (to 0.43 μs) and ensure high resolution of the neutron time-of-flight experiments. The power of the LUE-200 accelerator was required to reach 10^{-12} kW with a cycle rate of up to 200 Hz to achieve a high average neutron yield. Collectively, the IREN facility was required to provide an average neutron yield of up to 10^{15} s^{-1}, and the LUE-200 accelerator was required to have an acceleration rate of at least 25 MeV/m to fit within the existing building of the IBR-30 + LUE-40 complex. Achievement of these design parameters could place IREN among the world's best resonance neutron sources.

Preliminary discussions within the announced competition for the LUE-200 accelerator design resulted in the selection of the option[4], proposed by the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (INP SB RAS). The Rosatom institutes NIKIET and State Specialized Design Institute agreed to lead the design of the multiplier target and the engineering design of the IREN facility.

The IREN project was officially approved by the JINR Scientific Council in the summer of 1994. However, the first decisive step in the implementation of

[3] *Aksenov V. L. et al.* Proposal for the Construction of the New Resonance Neutron Source (IREN). JINR Preprint E3-92-110. Dubna, 1992.

[4] *Novokhatski A. V., Alexandrov A. V., Avilov M. S., et al.* Linear Accelerator for Intense Resonance Neutron Source (IREN) // Proc. 2nd Workshop on JINR Tau-Charm Factory. 27–29 April 1993, Dubna. D1,9,13-93-459. Dubna, 1994. P. 197–211.

the project had actually been taken six months earlier, when, by decision of JINR Vice-Director A. N. Sissakian, a 60 MW SLAC 5045 klystron, necessary for the construction of the LUE-200 accelerator, was purchased from Stanford University (USA).

Due to the Institute's financial difficulties, the IREN project was deprived of the funds necessary to fulfill the three-year schedule approved by the JINR Scientific Council from the very beginning. Significantly delayed, two LUE-200 accelerator sections were built at INP SB RAS and delivered to JINR, and their bench testing had begun by the end of 2000. By that time, the Mayak Production Association had completed the fabrication of fuel rods for the multiplier target. In 2001, as part of the IREN project, the IBR-30 + LUE-40 neutron source, which had served for over 30 years and exhausted its safe operating life, was shut down, and work began in conjunction with the State Specialized Design Institute to prepare for the dismantling of its activated equipment. By the end of 2004, the fuel rods for the multiplier target were delivered from the Mayak Production Association to JINR. Almost simultaneously, NIKIET and the State Specialized Design Institute completed the technical and engineering designs for the IREN facility. Their results revealed that the resources required to fully implement the project significantly exceeded the preliminary estimates approved in the original decision of the JINR Scientific Council in 1994.

After extended discussions within the Program Advisory Committee for Nuclear Physics and the JINR Directorate, a difficult but realistic decision was made to exclude the subcritical multiplier assembly from the IREN project, limiting it to a water-cooled tungsten neutron-producing target for the electron beam of the LUE-200 accelerator.

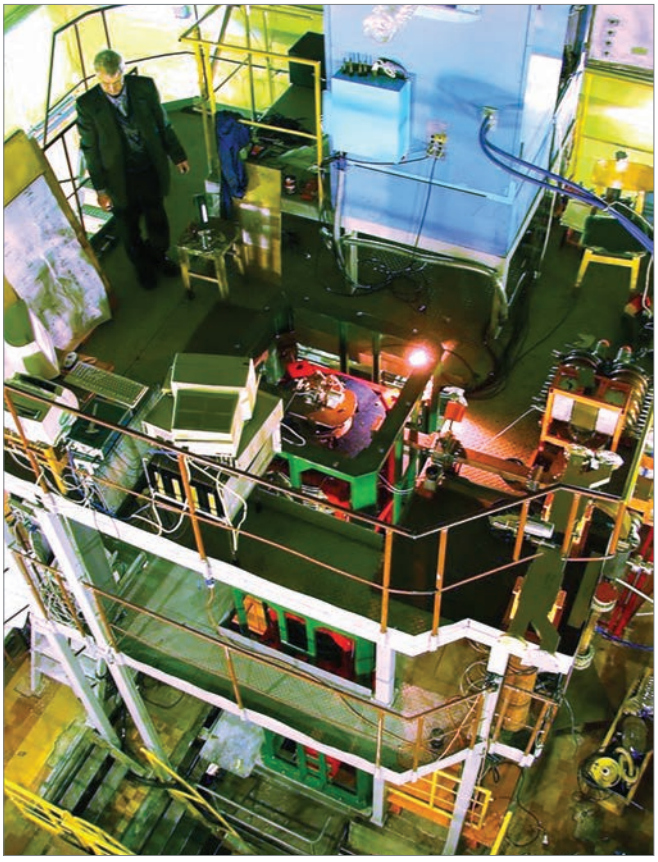
The dismantling of the LUE-40 accelerator and the IBR-30 reactor was completed in 2006, and installation of the LUE-200 accelerator equipment began after decontamination and renovation of the premises. Unfortunately, the SLAC 5045 klystron was damaged during the equipment installation process in 2007, and the



The IREN facility team after physical startup



Left to right: I. N. Meshkov, V. V. Kobets, V. N. Shvetsov, and A. P. Sumbaev discussing the IREN parameters



The LUE-200 accelerator

TH2129 klystron from the French company Thomson, which had a third of the power, had to be used to launch the first stage of the IREN facility as part of a single accelerator section. In January 2009, the physical startup of the first stage of FLNP's new basic facility took place, and an integrated neutron yield of $3 \cdot 10^{11}$ s^{-1}

was obtained at the end of the year at a pulse repetition rate of 50 Hz with a duration of ≈ 100 ns.

With these parameters, the facility operated in the experiment for several thousand hours and after that work began on adding a second accelerator section and exploring potential for increasing the LUE-40 accelerator's power. During this work, significant shortcomings in the initial LUE-200 design were identified, preventing the accelerator from achieving its originally formulated parameters. Computational and theoretical work is currently underway with INP SB RAS to address these shortcomings.

The history and results of this long-term work are described in detail in the publication[5]. The neutron yield was actually increased to $1.2 \cdot 10^{12}$ s^{-1}. The IREN facility has been regularly operating in this mode for approximately 10 years.

DISCOVERY OF ULTRACOLD NEUTRONS AND EXPERIMENTAL RESEARCH WITH THEM

The Frank Laboratory of Neutron Physics of JINR is where ultracold neutrons (UCNs) were discovered. A team led by F. L. Shapiro and including V. I. Lushchikov, Yu. N. Pokotilovski, and A. V. Strelkov performed an experiment at the IBR reactor, with an average power of approximately 6 kW, demonstrating the feasibility of long-term storage of UCNs in material traps. For thirty years thereafter, FLNP staff worked with UCNs at sources both domestically and internationally, participating in experiments measuring the free neutron lifetime, investigating the causes of UCN storage anomalies, etc.

By the beginning of the 21st century, UCN research concentrated at the Institut Laue–Langevin (ILL, Grenoble, France), where one of the world's most intense UCN sources has been successfully operating since the 1980s. Groups led by A. V. Strelkov and A. I. Frank conducted a series of experiments to investigate the so-called weak heating of UCNs during storage in material traps, quantum effects during UCN interactions with non-stationary objects, and other areas. Collaboration with PNPI continued in an experiment to measure the neutron lifetime at the KOVSH facility, created jointly by ILL and PNPI in the mid-1980s. Research into the properties of low-temperature hydrogen-free fomblin oils, carried out by Yu. N. Pokotilovski, made it possible to select the most suitable coating for the walls of the KOVSH trap and conduct an experiment with the world's best accuracy in determining the neutron lifetime.

The discovery in 1999 at ILL of the phenomenon of quantization of ultra-low-energy neutron levels ($\sim 10^{-12}$ eV) in the Earth's gravitational field, predicted in 1977 by V. I. Lushchikov and A. I. Frank, enabled a series of experiments to be performed within the GRANIT (GRAvitational Neutron Induced Transitions) collaboration, formed with the participation of the FLNP physicists. The gravitational spectrometers created in this collaboration made it possible to detect

[5] *Sumbaev A. P., Golubkov E. A., Zhironkin I. S., et al.* LUE-200 Accelerator. Status, Possibilities, and Development Problems. JINR Commun. P9-2025-16. Dubna, 2025.

resonance transitions between different neutron levels in the Earth's gravitational field and precisely measure the energies of the levels themselves.

The works of A. V. Strelkov's group, which began at the end of the last century and were focused on identifying the causes of the so-called anomaly in the storage time of UCNs in material traps, resulted in the discovery of the effect of small heating of UCNs using a large gravitational spectrometer developed at FLNP. It was demonstrated that this phenomenon was caused by the scattering of UCNs by nanoparticles bound to the trap surface. Subsequently, this research led to the study of the interaction of cold and very cold neutrons with nanoparticle powders and the development of nanodiamond powder coatings that significantly increase the probability of neutron reflection from the nanopowder surface, enabling the development of reflectors and traps for storing cold and very cold neutrons.

A number of experiments investigating nonstationary quantum effects during the interaction of UCNs with various objects were performed by A. I. Frank's group using the UCN monochromatization technique with Fabry–Pérot interferometer implemented at FLNP. Thus, in 2004, the splitting of the monoenergetic ultracold neutron line formed by the interferometer was discovered during its interaction with a rotating diffraction grating. This technique was subsequently used in experiments to study the influence of accelerated matter motion on changes in the spectrum of UCNs passing through it and in a series of experiments to test the weak equivalence principle for the neutron, which established the equality of the neutron's inertial and gravitational masses with an accuracy of 0.1%.

SEARCH AND STUDY OF THE EFFECTS OF VIOLATION OF FUNDAMENTAL SYMMETRIES IN NEUTRON-NUCLEAR INTERACTIONS

Following the discovery by Ch. Wu's group of the violation of spatial parity (P-parity) in the weak interaction during the beta decay of cobalt, interest naturally arose in testing P-parity in nuclear interactions, particularly in neutron–nucleus interactions, since the neutron has no Coulomb barrier. Early theoretical estimates showed that the probability of detecting P-parity violation was highest in heavy nuclei due to the collective nature of the interaction of a slow neutron with nucleons. However, initial experiments were inconclusive due to insufficient precision. Finally, in 1964, success arrived: Yu. G. Abov and P. A. Krupchitsky from ITEP discovered P-parity violation in the radiative capture of polarized slow neutrons by ^{113}Cd nuclei. Novosibirsk physicists O. P. Sushkov and V. V. Flambaum then developed a model that, in addition to the collective nature of neutron–nucleus interactions, known as dynamic amplification, also predicted an increase in P-parity violation in nuclear resonances. This is due to the fact that, when a neutron interacts through the compound nucleus stage, it spends much more time in the nucleus than when simply passing through the nucleus. This means that any desired interaction has more time to manifest itself. The first experiments to test P-parity in neutron–nucleus resonance reactions were performed at FLNP by V. P. Alfimenkov and L. B. Pikelner's group at the Polyana facility. The facility included a neutron polarizer based on a polarized proton target and allowed for measurements of

total neutron–nucleus interaction cross sections. P-parity violation was observed in the *p*-wave resonances of lanthanum and some isotopes of tin, cadmium, and bromine. The violation effect was particularly strong in the lanthanum resonance with an energy of 0.73 eV. These results generated enormous interest — similar facilities were built in Japan and the USA, where systematic studies of P-parity violation in the *p*-resonances of many nuclei were conducted. However, the measured P-odd effects in heavy nuclei did not allow the determination of the value of the nucleon–nucleon matrix element associated with parity violation. Therefore, Yu. M. Gledenov's group at FLNP performed a series of experiments to test P-parity in slow-neutron reactions with the light nuclei ^{6}Li and ^{10}B. Dynamic and resonant amplifications are absent on light nuclei; nevertheless, the group managed to measure the violation effect on lithium with unprecedented accuracy at the level of 10^{-8}. In parallel with the study of P-parity violation in total neutron cross sections and reactions with light nuclei, experiments were conducted to test it in fission. The first experiments were performed by G. V. Danilyan's group at ITEP using a thermal neutron beam with uranium and plutonium nuclei. Similar experiments were later carried out in Gatchina and at FLNP JINR with both thermal and resonance neutrons until the end of the IBR-30 operation.

The discovery of parity nonconservation in nuclear reactions sparked an interest in testing time invariance (T-invariance) — the symmetry of nuclear interactions under time reversal. Such experiments are much more complex and, in some cases, require not only a beam of polarized neutrons but also polarized or aligned nuclear targets. Furthermore, there may be a number of factors leading to spurious effects. Full-scale experiments have not yet been performed. However, in the 1990s, A. L. Barabanov from the Kurchatov Institute of Atomic Energy proposed an original model that allowed some information about such interactions to be obtained from angular correlations during the radiative capture of unpolarized neutrons. These experiments were conducted at FLNP by E. I. Sharapov and V. R. Skoy on nuclei of cadmium and tin isotopes. The obtained results made it possible to establish an upper limit on the interaction magnitude that violates T-invariance.

An experiment to study these effects in more detail is currently being prepared at the IREN neutron source. Work is underway to create a neutron polarizer based on ^{3}He with optical excitation to continue studying P-parity violations and, possibly, T-invariance.

APPLICATION OF THE TAGGED NEUTRON METHOD FOR FUNDAMENTAL RESEARCH

V. M. Bystritsky (DLNP) proposed studying tagged neutron methods (TNM) at FLNP using beams from the Van de Graaff EG-5 electrostatic accelerator. The first experiments began in 1999. A. P. Kobzev, I. A. Chepurchenko (FLNP), V. M. Bystritsky (DLNP), and a large group of VBLHEP staff members — N. I. Zamyatin, V. A. Nikitin, V. L. Rapatsky, Yu. N. Rogov, M. G. Sapozhnikov, and V. M. Slepnev — participated in them.

The basic idea of the tagged neutron method is to detect alpha particles in the deuterium–tritium fusion reaction:

$$d + t \rightarrow {}^4\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV}), \quad Q = 17.6\ \mathrm{MeV}.$$

According to the reaction kinematics, alpha particles (^{4}He) should be emitted in the direction opposite to the direction of neutron propagation. As a result of the inelastic interaction of fast neutrons with the nuclei of the substance under study, the excited nuclei release part of the acquired energy by emitting gamma rays with a spectrum characteristic of each element. This makes it possible to determine the elemental composition of the studied substance remotely, without any sampling.

The first deuteron beam facility, the EG-5, featured a 1.7 Ci tritium target, a single-channel ZnS-based alpha detector, and a NaI(Tl) crystal gamma detector 200 mm in diameter. The facility was "battle tested" when the spectra of only the most basic elements — graphite, water, and alcohol — were measured. While no mathematical apparatus for determining mass concentrations of substances existed, there were already people interested in the practical applications of this method — representatives of the Russian Customs Committee, attracted by Yu. K. Nedachin (Scientific Production Center ASPECT). Customs officials inspected the facility, learned that the spectra of graphite, water, and alcohol could be distinguished based on their spectral patterns, and conducted a test: they dropped a graphite cube into a container of alcohol. When the physicists, excitedly, admitted that they had never obtained such a spectrum, that it contained lines of both carbon and oxygen, but not in the ratio typical for alcohol, the fate of the development of the tagged neutron method was decided positively.

In 2001–2002, the first portable neutron generator operating in the so-called pump mode was developed at JINR under the leadership of I. P. Ivanov (VBLHEP). The generator's operating life was 50 h, after which the tritium target had to be replaced.

In 2002, the EG-5 facility expanded, various alpha detectors — plastic and silicon — were tested, and gamma detectors based on LySO and BGO were verified. The first publications appeared, and a topic was added to the JINR Topical Plan for TNM research. The JINR Director, Academician V. G. Kadyshevsky, provided significant support for the development of TNM.

In 2013, the idea arose to formalize activities related to the tagged neutron method as a project that combines the efforts of several JINR laboratories, as well as other interested institutes from Russia and the JINR Member States. At that time, a multidetector spectrometric system based on NaI(Tl) scintillation detectors manufactured at the Institute for Scintillation Materials (Kharkov, Ukraine) was developed at FLNP. This system was well suited for studying the angular distributions of gamma rays produced in the inelastic scattering of 14.1-MeV neutrons, making it possible to begin experiments with tagged neutrons immediately after the project was approved by the JINR PAC.

FLNP, DLNP, LRB, the Dukhov Automatics Research Institute (Moscow), Moscow State University (Moscow), the Ruđer Bošković Institute (Zagreb, Croatia), and the Institute for Nuclear Research and Nuclear Energy (Sofia, Bulgaria) were the main participants in the project. The ING-27 neutron generator with

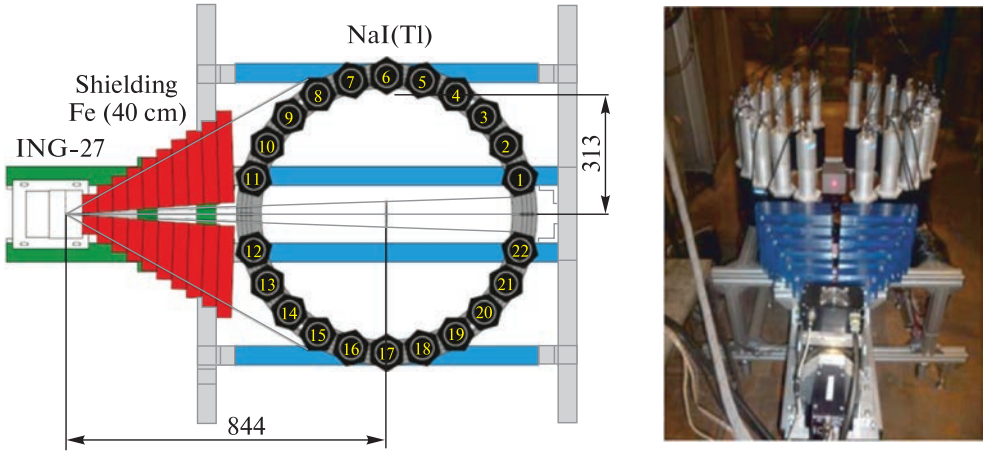


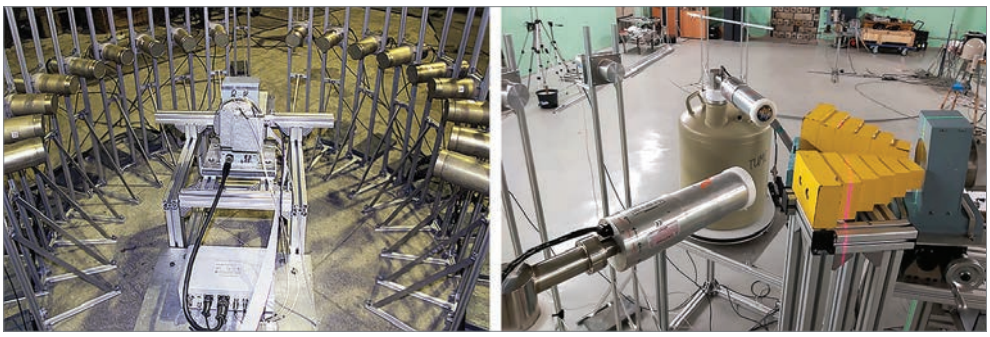
Fig. 2. Diagram and photograph of the Romashka facility

a built-in 64-pixel position-sensitive alpha particle detector was provided by the Dukhov Automatics Research Institute as a voluntary contribution to the project. Yu. N. Kopatch (FLNP) was elected project head, V. M. Bystritsky (DLNP) as deputy project head, and I. N. Ruskov (INRNE BAS, Bulgaria) as coordinator. The project was named TANGRA, short for TAgged Neutrons & Gamma RAys.

Gamma-ray detectors were optimized and protected from direct neutron radiation, and the Romashka facility (Fig. 2) based on 22 NaI(Tl) detectors was developed during the first stage of the project.

This facility was used to measure the angular distributions of γ-rays emitted in the inelastic scattering of 14.1-MeV neutrons on a number of samples. Specifically, the most accurate data on angular distributions for carbon were obtained. A method for determining the elemental composition of bulk ores was also developed, and a bench for testing nuclear planetology instruments was created during the first stage of the project.

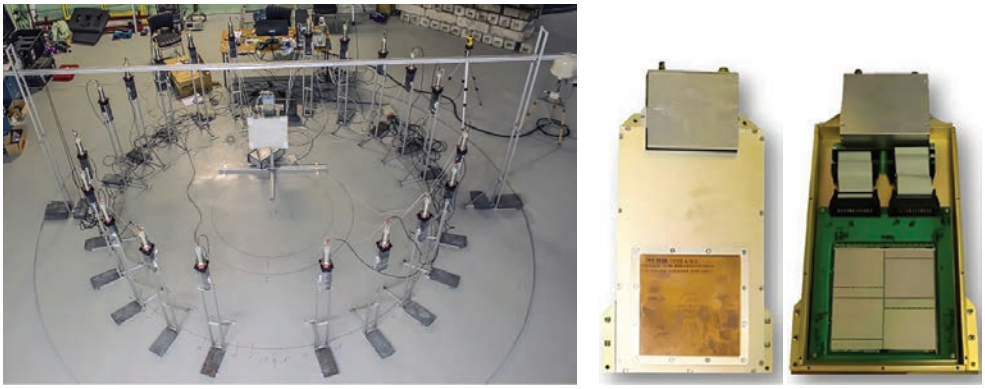
The experimental facility was subsequently expanded with two other configurations: one based on 18 BGO detectors and one based on a high-purity germanium (HPGe) detector. Measurements of the angular distributions of gamma rays in



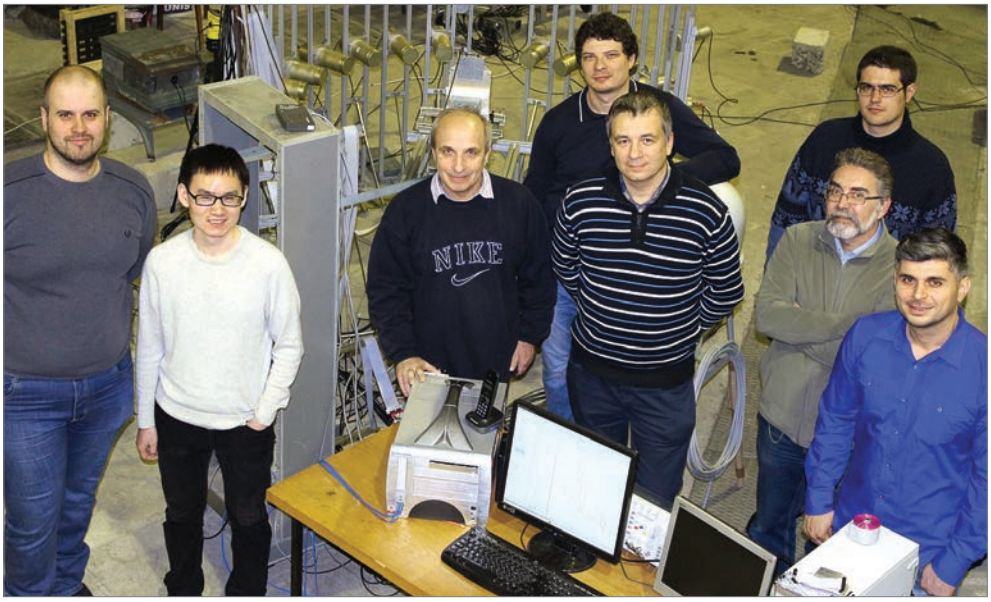
The facility with 18 BGO (left) and HPGe (right) detectors

inelastic neutron scattering on various samples during the strongest gamma transitions were continued using the BGO detector facility, while the HPGe detector facility measured the gamma-ray yields in the same reactions.

The TANGRA project also studied the differential cross sections of elastic and inelastic neutron scattering in addition to gamma-ray yields and angular distributions. Carbon was chosen as the target, as its excitation levels can be fairly well identified by measuring the scattered neutron energy using the time-of-flight method. This was accomplished using an array of 20 plastic scintillators located 2 m apart around the studied carbon target, irradiated with beams of tagged neutrons.



An array of 20 plastic neutron detectors (left) and fast neutron detectors (right)



Participants of the TANGRA project. Left to right: D. N. Grozdanov (Bulgaria), Wang Dongming (China), I. N. Ruskov (Bulgaria), C. Hramco (Moldova), Yu. N. Kopatch (Russia), V. R. Skoy (Russia), N. A. Fedorov (Russia), and F. Aliev (Azerbaijan). 2017

In collaboration with a group led by N. I. Zamyatin (VBLHEP), a unique two-coordinate position-sensitive fast neutron detector (FND) was developed based on silicon strip detectors with a resolution of 1.8 mm. A gamma radiography technique with a time-modulated randomly coded aperture was developed and tested in collaboration with Wang Dongming from Xi'an Jiaotong University (Xi'an, China).

V. R. Skoy, C. Hramco, F. Aliev, T. Yu. Tretyakova, P. S. Prusachenko, and P. Kharlamov actively participated in the development and application of the tagged neutron method at FLNP. D. N. Grozdanov, N. A. Fedorov, and S. Dabylova defended their candidate dissertations on this topic. More than 20 students prepared and defended their bachelor's and master's theses. The project included collaborations with Alexandria University, Egypt (M. S. Badawy, M. Hamada), Banaras Hindu University, Varanasi, India (A. Kumar, A. Gandhi), University of Novi Sad, Serbia (N. Jovančević, D. Knežević), and Pabna University of Science and Technology, Bangladesh (P. K. Das).

SPECTROMETERS AND RESEARCH AT IBR-2

FLNP INTERNATIONAL USER PROGRAM

The Joint Institute for Nuclear Research, celebrating its 70th anniversary in 2026, is one of the leading international centers for fundamental and applied research in nuclear physics, materials science, neutron physics, and related disciplines. The Frank Laboratory of Neutron Physics, part of JINR, plays a key role in providing the scientific community with unique experimental capabilities, giving access to modern neutron sources and facilities.

One of the most important mechanisms that promotes the development of science and international cooperation at FLNP is the User Program. It aims to provide broad access to the laboratory's experimental equipment to scientists from various countries and organizations, facilitating the implementation of a variety of research projects – from fundamental experiments studying the structure of matter to applied research in materials science, biology, and medicine.

The FLNP User Program is characterized by transparency and objectivity of the project selection process. Each application undergoes a thorough expert review, taking into account the scientific significance, innovativeness, and technical feasibility of an experiment. This approach ensures high-quality research and the efficient use of the laboratory's resources.

The program gives special attention to the support of young scientists and postgraduate students. The opportunity to conduct experiments on modern equipment under the guidance of experienced FLNP specialists contributes to the development of human resources and the formation of a new generation of researchers prepared to tackle complex scientific problems.

The international nature of JINR and FLNP facilitates the active exchange of knowledge and experience between scientists from different countries, strengthening scientific ties and creating a platform for joint projects. The User Program is a

key tool for implementing this strategy, integrating the efforts of research teams and expanding the horizons of scientific research.

Over the seven decades of their existence, JINR and FLNP have made significant contributions to the development of neutron physics and related fields. The User Program has been a key factor in this success, ensuring a steady flow of new ideas and the implementation of cutting-edge scientific projects. In the future, the program will continue to evolve, introducing innovative technologies and expanding the range of available experiments, allowing JINR to maintain its leading position in global science.

Thus, the FLNP User Program is not simply a mechanism for accessing equipment, but an important element of the JINR scientific ecosystem, promoting the development of international cooperation, supporting young scientists, and achieving new heights in natural science research.

FOURIER DIFFRACTOMETERS AND FLNP'S ROLE IN DEVELOPING THE METHODOLOGY

Neutron diffraction studies of the atomic and magnetic structures of crystalline materials, as well as their microstructural organization, often require high resolution of the experimental facility — the diffractometer. This resolution is typically defined as the relative width of the diffraction peaks: $R = \Delta d/d$, where d is the interplanar spacing. The level of resolution largely determines the type and complexity of problems that can be solved with a specific diffractometer. For example, analyzing the structure of a polycrystal with a unit cell volume of ~1000 Å^3 or more, including refining the thermal factors of atoms in anisotropic mode, is only possible with high-resolution diffractometers, specifically when $R \leqslant 0.001$.

For pulsed neutron sources, such as the IBR-2 reactor, the value of Δd is largely determined by the source pulse width Δt and the distance L that neutrons travel from the source to the sample and then to the detector. Simple calculations show that values of $R \leqslant 0.001$ can be achieved if $\Delta t \leqslant 20$ μs and $L \geqslant 80$ m. Such characteristics are achievable with accelerator-based neutron sources (SNS sources), but the flight distance would be too long for the IBR-2, with a pulse width of approximately 350 μs, requiring pulse reduction using some type of fast chopper.

In the late 1980s, following joint discussions involving specialists from FLNP, PNPI RAS (Gatchina), and the Technical Research Center (Espoo, Finland), a decision was made to develop a high-resolution diffractometer at the IBR-2 using a fast multislit chopper. This device, known as the *Fourier chopper*, comprises a rotating disk (rotor) with a regularly spaced, equal-width, transparent and non-transparent gaps for thermal neutrons and a stationary stator with the same slit configuration as that of the rotor. The periodic, sawtooth transmission function of such a chopper is close in shape to a sinusoid, and, as mathematical analysis shows, for a fixed modulation frequency of the primary neutron beam, the intensity of scattered neutrons is a function close to the corresponding Fourier harmonic of the scattering cross section. The scattering cross section can be reconstructed by varying the rotor speed from zero to a certain maximum and performing an inverse Fourier transform. The large number (~1000) and small width (~1 mm) of the

Fourier chopper slits allows for an increase in transmission to 25% (instead of the standard 0.5%) and a reduction in the effective pulse width to 10 μs. However, the significant overlap of spectra from adjacent pulses requires the use of correlation methods to reconstruct the scattered neutron spectrum.

Specialists from Gatchina and Espoo already had experience in using this method (it later became known as *Fourier diffractometry*). In the mid-1980s, a mini-SPHINX diffractometer was built at the PNPI reactor, demonstrating the main advantage of the method — the ability to achieve high resolution over a very short flight distance (approximately 6 m instead of 80 m). However, a problem with using Fourier diffractometry at a stationary neutron source was the high level of specific correlation background, proportional to the total recorded intensity. It then became clear that this background component could be significantly reduced in case of a pulsed source by taking into account the correlation between the signals from the detector and the source's power pulse, thereby increasing the diffractometer's efficiency many times.

The necessary model calculations for the new facility at the IBR-2, called the HRFD (*high-resolution Fourier diffractometer*), were completed in 1989. This led to the formation of a joint project between JINR (Dubna), PNPI (Gatchina), and VTT (Espoo), with the primary funding provided by the state scientific and technical program "High-Temperature Superconductivity". Part of the necessary funds were allocated by JINR with support from the BMBF (Germany). The correlation electronics for the HRFD and the Fourier chopper with its control system were manufactured in Espoo, the mirror neutron guide and detector were manufactured at PNPI, and FLNP undertook the neutron beam transmission and software development. Experience with the mini-SPHINX diffractometer facility helped overcome emerging problems, and by the summer of 1992, the first diffraction spectra were recorded on a prototype HRFD, the characteristics of which fully confirmed the model calculations. It was shown that with a flight distance from the chopper to the sample location of only 20 m, the diffractometer resolution could reach (depending on the chopper rotor speed) $R = 0.0009$. Approximately the same resolution was obtained with the HRPD diffractometer operating at the ISIS SNS source (UK), but using a five times greater flight distance (approximately 100 m).

Many employees from the Department of Condensed Matter Physics (headed by Yu. M. Ostanevich) and the Department of Radioelectronics and Computer Engineering (headed by G. P. Zhukov) at FLNP, V. A. Trunov's laboratory (PNPI), and Professor P. Hiismäki's group (VTT, Espoo) participated in the modeling, design, manufacture of individual components, installation and commissioning of the HRFD. Yu. M. Ostanevich and A. M. Balagurov negotiated the JINR–PNPI–VTT agreement for the development of the HRFD, and they also determined the location of the HRFD in the IBR-2 experimental hall. FLNP Director V. L. Aksenov played a key role in securing the necessary funding and concluding contracts for the manufacture of the HRFD main components. The following staff members from the Department of Condensed Matter Physics and the Department of Radioelectronics and Computer Engineering took an active part in the subsequent work: A. A. Bogdzel, V. V. Zhuravlev, V. E. Novozhilov, E. V. Serochkin, A. P. Sirotin, Yu. V. Taran, V. G. Tishin, and V. G. Simkin. A. P. Bulkin, V. A. Kudryashev,

V. G. Muratov, V. A. Trunov, and V. A. Ulyanov (all from PNPI) and O. Antson, H. Pöyry, A. Tiitta, and P. Hiismäki (all from VTT) actively participated in the installation of the equipment and the execution of the first experiments. A. I. Ostrovnoy (FLNP), D. A. Balagurov, and V. B. Zlokazov (MLIT JINR) made the main contribution to the preparation of the software for data accumulation, visualization, and analysis. V. L. Aksenov and A. M. Balagurov coordinated all the works.

The HRFD facility was completed by 1994, after which its stationary operation and scientific program began. Over the years, a large number of scientific diffraction experiments have been conducted at the HRFD. The structures of high-temperature superconductors (HTSC), hydrogen-containing compounds, various oxides (perovskites, spinels, brownmillerites, etc.), metal alloys, and other materials were refined. These were typically not isolated experiments, but rather series of experiments, for which collaborations were organized, including specialists in crystal synthesis, macroscopic certification, neutron diffraction spectral measurements, and data analysis. The most notable were the series of works on the structure of mercury HTSC (jointly with the laboratory of E. V. Antipov, Moscow State University), on the phenomenon of phase separation in manganites with the effect of colossal magnetoresistance (A. R. Kaul, Moscow State University), on the nature of the giant isotope effect in manganites (N. A. Babushkina, NRC KI), on phase transitions in cobaltites (I. O. Troyanchuk, Minsk), on microstructural effects in simple oxides (N. Mironova-Ulmane, Riga), and on the structural states of iron–gallium alloys with the effect of giant magnetostriction (I. S. Golovin, NUST MISIS).

An important feature of the HRFD is the ability to easily switch between high-resolution ($\Delta d/d \approx 0.001$) and high-aperture medium-resolution ($\Delta d/d \approx 0.010$) modes. Neutron diffraction patterns measured at high resolution (typically requiring 1–3 h) are used for precise structure refinement and analysis of diffraction peak profiles. In the second mode, the full diffraction spectrum can be measured with the required statistics in 1–5 min and is used to analyze phase transformations in a material, for example, during continuous heating to 1200 K and subsequent cooling at a temperature change rate of one to several degrees per minute. This mode is also used to study processes in electrochemical power sources during their continuous charge and discharge.

Soon after the launch and successful completion of the first experiments at the HRFD, the idea arose to apply neutron Fourier diffractometry to the study of residual mechanical stresses in various materials and products. Professor J. Schreiber (Institute for Non-Destructive Testing, Dresden, Germany) was one of the initiators of this area of applied research. He provided significant assistance to his colleagues at FLNP for many years. The first stress experiments at the HRFD began in 1993 and were quite successful due to the high resolution of the diffractometer. However, the need soon became evident for a second Fourier diffractometer — the FSD (*Fourier Stress Diffractometer*) — to be built at the IBR-2 reactor. This device would be optimized for the study of residual stresses in bulk components and new advanced materials and would be equipped with specialized tools. The FSD project began in 1998, and the first experiments were completed in 2000. Colleagues from PNPI (A. P. Bulkin, V. A. Kudryashev, V. A. Trunov), as well as a large

team of FLNP JINR employees (V. L. Aksenov, A. M. Balagurov, G. D. Bokuchava, I. V. Papushkin, A. V. Tamonov, E. S. Kuzmin, A. A. Bogdzel, V. V. Zhuravlev, V. A. Butenko, V. A. Drozdov, A. P. Sirotin, A. I. Kirilov, T. B. Petukhova, S. M. Murashkevich), actively participated in the development of the FSD.

Numerous experiments were conducted during the operation of the FSD, characterizing the main directions of this research area: studying the mechanical properties of materials under various loading conditions (S. Guk, TU Bergakademie Freiberg, Germany), various welded joints (P. Petrov, IE BAS, Sofia, Bulgaria), structural components of various industrial products, new promising materials (R. Fernandez, CENIM, Madrid, Spain), gradient structures, and composites. The results of these experiments demonstrated the high efficiency of the FSD for solving a wide variety of problems in physical materials science.

Experience in using Fourier diffractometers to analyze the structural characteristics of various materials has shown that one of the most important diffractometer parameters is the instrument's luminosity, which is determined by the presence of a sophisticated detector system. This is especially important when conducting experiments that require high luminosity, such as analyzing minor impurity phases, studying weakly scattering materials, measuring residual stresses in a small scattering volume deep within an industrial sample, etc. In this regard, a unique detector system with scattering angles $2\theta = 90°$ has been recently developed at the FSD. This system consists of two wide-aperture ASTRA detectors based on a ZnS(Ag)/^{6}LiF scintillator with an angular aperture of 40° in the horizontal scattering plane and a total solid angle $\Omega = 0.55$ sr.

In 2025, an annular backscatter detector ($2\theta = 133–175°$) based on a ZnS(Ag)/^{6}LiF scintillator with a record-breaking solid angle $\Omega = 2$ sr was installed at the HRFD. This increased the diffractometer's luminosity approximately sixfold, and, accordingly, the number of experiments performed by approximately two to three times. The new detector system also ensured high accuracy of the obtained structural information and significantly expanded the diffractometer's capabilities for conducting experiments involving various external influences on the sample, studying fast processes, etc.

Another important step in the development of Fourier diffractometry was the introduction of a new method for recording all experimental events (reactor starts, detector signals, chopper pickup signals) in list mode. The original idea for accumulating RToF data in the list mode was proposed by colleagues from PNPI V. A. Kudryashev, V. A. Trunov, V. G. Muratov, and A. M. Pirogov back in 1996 at the First European Conference on Neutron Scattering, ECNS'96 (Interlaken, Switzerland). However, the electronics available at that time did not provide the required characteristics to implement this approach at a reasonable cost. This idea was finally realized on Fourier diffractometers in 2014, when a new unified MPD unit based on ALTERA FPGA chips was developed at FLNP JINR. This unit was designed for recording and collecting raw data in the list mode from individual neutron counters or detector modules. This data acquisition method enabled the use of new capabilities unavailable in the first versions of RToF analyzers and significantly improved the quality of high-resolution diffraction spectra.

In 2014, another Fourier diffractometer — the *Fourier Strain Scanner* (FSS) — was installed at the IBR-2 reactor. It was successfully operated from 1990 to 2010 at the FRG-1 stationary reactor at the GKSS Research Center (Germany) to study residual stresses in materials and products. In 2010, the FRG-1 reactor was finally decommissioned. Following this, the FSS diffractometer was transported to FLNP JINR and installed at the IBR-2 reactor. The FSS's key components and equipment have been upgraded over the past few years. In particular, a new reflector neutron guide and a new, faster Fourier chopper were installed, a new list-mode data acquisition system was implemented, work began on a new detector system, etc. This significantly improved the instrument's resolution and luminosity, allowing for the launch of regular neutron diffraction experiments on various crucial tasks in physical materials science. Thus, all the three existing Fourier diffractometers (HRFD, FSD, and FSS) are currently operating successfully at the IBR-2 pulsed reactor.

In general, practical experience in the operation of Fourier diffractometers has demonstrated that neutron correlation Fourier diffractometry, based on a combination of the reverse time-of-flight method for data collection and the use of a fast Fourier chopper for modulating the intensity of the incident neutron beam, makes it possible to achieve a high level of diffractometer resolution over a wide range of interplanar spacings d_{hkl} with relatively short flight paths both at stationary reactors and at pulsed neutron sources. Fourier correlation diffractometry is also a worthy alternative to long-flight-path ToF diffractometers with multiple chopper systems, providing an optimal balance between intensity and resolution in neutron diffraction experiments and enabling highly accurate determination of various structural parameters of modern materials, extraction of microstructural characteristics of materials using precision diffraction peak profile analysis, measurement of residual strains and stresses in various industrial samples and products, etc. Fourier correlation diffractometry is particularly effective when used with a long-pulse neutron source such as the IBR-2 reactor, enabling it to conduct unique precision experiments and rank it among the best neutron sources in the world.

NEUTRON STUDIES OF NANOSYSTEMS AT IBR-2

The last few decades have been significant for the IBR-2 in terms of extensive neutron research on nanosystems — objects whose properties are determined by structural features at the nanoscale of 1–100 nm. Nanosystem research methods — small-angle scattering and reflectometry — have received a powerful boost in development at the IBR-2, resulting in numerous fundamental and applied experiments on a wide range of objects as part of the user policy.

Small-angle neutron scattering

After the turn of the millennium, FLNP developed a new concept of small-angle neutron scattering (SANS), a well-known and effective method for studying fundamental problems and solving critical technological challenges. This method is widely used in studies of the nanoscale structure of matter in the 20–1000 Å range.

The idea of a multi-detector facility, proposed and implemented on beamline 4 of the IBR-2, was subsequently implemented with multiple variations on many small-angle instruments: 1) at the European Spallation Source, where a conical-shaped detector was proposed, essentially collecting all neutrons; 2) at the ILL at a stationary reactor using four choppers with different combinations of them, near and far detectors; 3) at a reactor of a similar design, OPAL, in Australia.

The YuMO spectrometer has always been undergoing upgrade for solving new challenging scientific problems within the user policy program. In particular, the development of a multidetector system at the facility made it possible to conduct experiments and obtain results in a new area of polymer science — dendrimers. The development of a multidetector system on the SANS spectrometer was complicated by a special data normalization system. However, it was possible to maintain the absolute scale of scattering intensity, as well as the ability to normalize data to a vanadium standard. Yu. S. Kovalev, A. V. Rogachev, T. N. Murugova, and other laboratory staff actively assisted V. I. Gordeliy, A. Kh. Islamov, and A. I. Kuklin at various stages of the projects.

Dendrimers. The tasks accomplished using the new configuration of the spectrometer were developed by V. I. Gordeliy with the involvement of outstanding scientists such as A. M. Muzafarov and A. N. Ozerin (see Fig. 3). The work began with simple models, but unique and unexpected results were obtained thanks to the small-angle scattering group of A. I. Kuklin, A. Kh. Islamov, R. Mukhamedzyanov, and later A. V. Rogachev and A. Yu. Cherny.

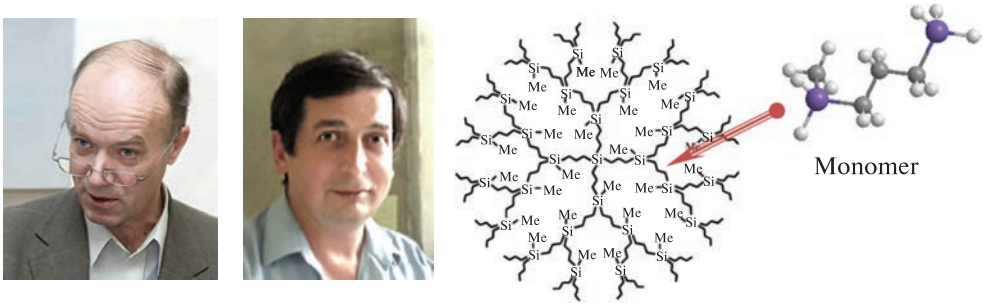


Fig. 3. Left: A. N. Ozerin and A. N. Muzafarov (Institute of Synthetic Polymeric Materials, RAS); right: a schematic representation of polyallylcarbosilane dendrimers

Dendrimers, a new class of polymers synthesized in the mid-1980s, have been studied using numerous methods. However, questions about dendrimer structure remain unresolved. These include, in particular, the possible presence of internal cavities and solvent penetration into the dendrimer. The emergence of this new class of substances with a pronounced monodisperse size and shape distribution requires the development of an adequate model to describe the experimental scattering curves. The approach developed by A. Yu. Cherny, A. V. Rogachev, and A. I. Kuklin

offers a dendrimer model consisting of spherical sectors sharing a common vertex. The number of sectors is selected based on the dendrimer's functionality. This model may be of interest not only for dendrimer samples but also for many other macromolecular systems. Moreover, the results of such modeling may demonstrate the need for experiments with a specific sample orientation. Conversely, the averaging model can enable the presence (or absence) of solvent within a dendrimer to be determined using small-angle neutron scattering. The demonstrated anisometry of the dendrimer macromolecular shape, which contradicts atomic force microscopy data, was confirmed by molecular dynamics results.

The range of momentum transfer in which the simulation was carried out was chosen based on experimental data obtained on the YuMO spectrometer in a two-detector version.

The last measurements with dendrimers before the reactor shutdown in 2006 were carried out in a configuration not only with three detectors (including the direct beam detector), but also with a position-sensitive detector (PSD).

A position-sensitive detector with a central hole for small-angle scattering was added to the project in 2002. Tests were conducted beginning in 2003, and the detector was used in its standard configuration in 2006, including with dendrimer solutions. This new, unique detector with a central hole was developed by an international team including A. I. Kuklin, A. S. Kutuzov, A. Gabriel, P. K. Utrobin, A. A. Smirnov, A. A. Bogdzel, A. Kh. Islamov, V. Kompar, J. Koskas, G. Eckold, and V. I. Gordeliy. The detector's uniqueness lay primarily in its multiwire chamber with a central hole. Testing and operational results of this unique PSD with a central hole and a sensitive area of 580×580 mm demonstrated high resolution and good differential and integral homogeneity. This detector features a single-chamber design, high spatial resolution (the spacing between the wires being 2.5 mm), and a central hole that allows the detector to be used in both forward and backscattering geometries. The data acquisition system for the time-of-flight method has a rate of at least 1.7 megaevents/s. Tests of the detector have been conducted with X-rays (Grenoble, France) and with neutrons at a stationary reactor (LLB, Saclay, France). The experiments demonstrated the high resolution and uniform sensitivity of the detector.

Tests of the detector on IBR-2 beamline 4 were conducted with single crystals and polycrystals in backscattering geometry. The obtained scattering patterns demonstrate the detector's performance in time-of-flight mode, high resolution, and ability to operate under intense fluxes of fast and thermal neutrons. The detector was also tested in normal operation in a two-detector configuration. Scattering patterns were obtained from both weakly and strongly scattering samples, both isotropic and anisotropic. It was shown that the scattering curves on the absolute intensity scale coincide for the PSD and the annular detector. The tests demonstrated not only the detector's high resolution but also its expanded range for the transmitted pulse, as well as the suitability of the detector for use in the multi-detector system of the YuMO facility. Similar detectors can also be effective on spectrometers with a backscattering detection option. The detector's electronics are currently being replaced, and control software is being developed as part of the SONIX+ software package.



Young members of the small-angle scattering group from the project to create a position-sensitive detector and upgrade the YuMO spectrometer. Left to right: Yu. S. Kovalev, A. V. Rogachev, and A. I. Ivankov. The computer displays the small-angle scattering pattern obtained with the position-sensitive detector from an oriented sample

The development and installation of a high-pressure hydrostatic chamber (the PVT facility of up to 4 kbar) on a small-angle scattering spectrometer enabled the study of phase transitions in micellar solutions over a wide range of temperatures, pressures, and surfactant concentrations. The kinetics of the micelle–solid phase transition was studied, the phase diagram of the solutions was determined, and the dependence of the transition rate on temperature, pressure, and surfactant concentration was shown. The two-phase coexistence of micelles and precipitates (solid phase) was observed under specific conditions of concentration, pressure, and temperature. Experiments carried out on the upgraded IBR-2M reactor using the PVT facility for lipid membrane mixtures demonstrated for the first time that a simultaneous jump in isothermal compressibility and the repetition interval occurs in lipid mixtures in excess water.

It was shown how to separate the nuclear and magnetic contributions to scattering intensity using a facility without a magnetic field and polarized neutrons. It was demonstrated that the contributions of the nuclear and magnetic components can be separated using the contrast variation method in an experiment with unpolarized neutron small-angle scattering. This, as noted, was a completely new result at the time.

The results of research in the field of magnetic fluids, lipid membranes, proteins and protein complexes, the supramolecular organization of rhodopsin in the photoreceptor membrane, polymers and polymer solutions, metallic nanoobjects and other nanosystems investigated by A. I. Ivankov, A. Kh. Islamov, T. N. Muru-



Participants of the 3rd International Conference on Small-Angle Scattering, dedicated to the 80th anniversary of the birth of Yu. M. Ostanevich. In the front row, left to right: T. Kurkin, A. Kh. Islamov, D. Uhríková, A. I. Kuklin, G. Pépy, T. N. Murugova, A. V. Belushkin, V. L. Aksenov, T.-S. Stuhrmann, H. Stuhrmann (developer of the contrast variation method), A. Balaşoiu, and R. Erhan. 2016

gova, A. V. Rogachev, M. Balasoiu, D. I. Soloviev and, of course, V. I. Gordeliy, N. Kučerka, and, more recently, A. V. Vlasov, Yu. L. Rizhikov, and A. Nabiev, are beyond the scope of this work. It should only be noted that small-angle experiments have shown that ultrastructural rearrangements occur in the mitochondria of the rat liver and heart when the volumetric regulation system is activated.

The capabilities of the team and the facility also explain the interest of the scientists participating in three international conferences on small-angle scattering, which are held every 5 years. The plenary sessions of the conferences were always held as an open discussion. Among the leading scientists who attended them and presented papers at various times are: H. Stuhrmann, J. Teixeira, G. Zaccai, A. Wiedemann, A. N. Ozerin, A. Khokhlov, G. Pépy, P. Balgavi, V. I. Gordeliy, D. Katzaras, D. Uhríková, J. Pedersen, R. Heenan, V. Isaev-Ivanov, D. Lebedev, V. Lebedev, V. Runov, N. Kučerka, G. Eckold, J. Pleštil, G. Pospíšil, and L. Almásy. The small-angle neutron scattering group has always been international, including German colleagues F. Heusler, N. Gorski, and M. Hempel, Czech and Slovak scientists J. Pleštil, G. Pospišil, N. Kučerka, and M. Bel ička, Polish scientists A. Rajewska, and Romanian scientists M. Balasoiu, R. Erhan, and E. Anitas. P. Balgavi, D. Uhríková, L. Yaguzhinsky, L. Barsukov, J. Pleštil, H. Pospišil, J. Kalus, N. Melik-Nubarov, and L. Almásy often visited Dubna and conducted experiments. Over 50 students completed master's, bachelor's, and undergraduate work at the JINR schools on the small-angle scattering facility and with members of the YuMO group. Many colleagues came not only from the JINR Member States but also from friendly states.

Neutron reflectometry

Thermal neutron reflectometry is used to analyze the reflection of a plane-collimated beam directed at grazing angles onto a planar interface, which may have a complex heterogeneous structure. The objective of the experiment is to determine the distribution of the optical potential of the medium–neutron interaction (the scattering density) in a near-boundary region up to 500 nm thick. The method is primarily used to study low-dimensional layered nanostructures on solid surfaces. In addition to external surfaces, the penetrating nature of neutron radiation allows for highly efficient study of hidden interfaces, including those containing liquid phases. A separate area of research concerns the sensitivity of neutrons to magnetic ordering at interfaces, which determines the development of polarized neutron reflectometry technique for studying magnetic heterostructures on surfaces. The magnetism of nanolayers is currently of not only fundamental but also applied interest, driven by the development of spintronics, which combines methods for storing and processing information based on the spin states of electrons in a medium.

Reflectometric research has been conducted at FLNP since the 1980s, when the world's first polarized neutron spectrometer at a pulsed source was launched at the IBR-2 (D. A. Korneev, A. Bajorek). This served as the basis for the subsequent development of world-class reflectometers, which today support a separate scientific field — neutron optics. Thus, in 1994, the specialized polarized neutron reflectometer REFLEX (D. A. Korneev, L. P. Chernenko, V. I. Bodnarchuk) was commissioned, and in the early 2000s, it was used to experimentally confirm the effects of Zeeman splitting when neutrons are reflected from magnetically non-collinear media, predicted by V. K. Ignatovich (D. A. Korneev, V. I. Bodnarchuk, S. V. Kozhevnikov, Yu. V. Nikitenko, V. L. Aksenov), and various approaches in time-of-flight mirror reflectometry to the study of thin films were tested (D. A. Korneev, V. K. Ignatovich, S. P. Yaradaykin, V. I. Bodnarchuk). In recent years, a methodological direction has been developed at REFLEX. The facility was actively used in collaboration with FZ Jülich (Germany) as a basis for the development of fundamentally new techniques using polarized neutrons, for example, spin-echo small-angle neutron scattering, in studies of already bulk nanosystems (A. I. Ioffe, V. I. Bodnarchuk, V. V. Sadilov).

In 2004, the REMUR spectrometer for scattering polarized neutrons at grazing incidence (V. L. Aksenov, Yu. V. Nikitenko, H. J. Lauter, V. Lauter-Pasyuk, A. V. Petrenko, K. N. Zhernenkov, S. V. Kozhevnikov) was developed on the basis of the initial SPN reflectometer (D. A. Korneev, V. V. Pasyuk, A. V. Petrenko, E. B. Dokukin) with the support of the JINR–BMBF (Germany) collaboration program. With the participation of PNPI RAS, a fan-shaped analyzer of neutron beam polarization was developed and successfully tested for REMUR (V. M. Pusenkov, N. K. Pleshanov, B. G. Peskov, V. G. Syromyatnikov, V. A. Ulyanov, A. F. Shchebetov). REMUR implemented full three-dimensional reflectometry, allowing the recording of various reflection channels: mirror reflection, diffuse scattering, and small-angle scattering at grazing angles, with full polarization analysis. Landmark results were obtained during those years in collaboration with KFKI SzFKI (Hungary) and TU München (Germany) in the study of magnetic domains in multilayer



Participants in the launch of the REMUR reflectometer in the IBR-2 experimental hall. Left to right: Yu. V. Nikitenko, A. V. Petrenko, H. J. Lauter, V. L. Aksenov, S. V. Kozhevnikov, and V. A. Ulyanov. 2003

heterostructures (D. L. Nagy, L. Bottyán, H. J. Lauter, V. Lauter-Pasyuk, A. V. Petrenko). In 1998–2001, V. L. Aksenov and Yu. V. Nikitenko proposed a method for recording changes in the spin state of a neutron in a resonantly enhanced neutron wave field with total reflection of polarized neutrons from a multilayer quasi-two-dimensional nanostructure, which in 2004–2020 formed the basis of a series of studies at REMUR on proximity effects in flat nanolayered superconductor/ferromagnet heterostructures (V. L. Aksenov, Yu. V. Nikitenko, K. N. Zhernenkov, Yu. N. Khaidukov, V. D. Zhaketov). During the same years, a method was proposed for enhancing the secondary radiation of intranuclear processes after neutron capture by impurity atoms in resonant multilayer structures (V. L. Aksenov, Yu. V. Nikitenko, Yu. M. Gledenov, N. A. Gundorin, A. V. Petrenko, P. V. Sedyshev). The method forms the basis for isotope-sensitive neutron reflectometry, first developed at FLNP. From 2015 to 2019, channels for recording secondary radiation — charged particles and gamma rays — were implemented at the REMUR neutron reflectometer (Yu. V. Nikitenko, V. D. Zhaketov). This created the world's only experimental base for a new field in neutron diffractometry — resonance neutron reflectometry. REMUR also developed research into neutron-optical phenomena in layered

waveguides, which, using longitudinal channeling, produce neutron microbeams with record-breaking widths (down to a few micrometers) (S. V. Kozhevnikov). Such beams can be used to study locally nonhomogeneous microstructures, including magnetization distribution, with high spatial resolution. A joint study with the Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences on layered Fe/Cr/Gd superlattices may be distinguished among the numerous polarized neutron reflectometry experiments conducted in recent years at REMUR as part of the user policy. In these superlattices, the exchange interaction between the 3*d* (Fe) and 4*f* (Gd) layers of ferromagnetic metals occurs through a layer of antiferromagnetic Cr. As a result, it was demonstrated that a non-uniform spatial magnetization profile is formed in the Gd layer (M. V. Ryabukhina, V. V. Proglyado, E. A. Kravtsov).

In 2013, as part of the development of user policies in JINR Member States, the GRAINS neutron reflectometer (M. V. Avdeev, V. I. Bodnarchuk, L. A. Bulavin, V. I. Petrenko, I. V. Gapon, A. V. Nagorny, A. V. Tomchuk) was launched for studying interfaces with liquid media. The facility was developed in collaboration with PNPI of the NRC "Kurchatov Institute" (V. A. Ulyanov, S. I. Kalinin, A. P. Bulkin) and with the support of the JINR–BMBF (Germany) collaboration program. The presence of a liquid medium in the studied system allows for contrast variation through H/D isotopic substitution without altering the chemical structure of the interface, expanding the information capabilities of the reflectometric experiment. The primary focus of time-of-flight reflectometric experiments is on *in situ* studies, which allow for the time evolution of interfaces to be followed under changing external conditions. In this regard, a sample environment system is developed, and specialized experimental cells are created to expose the studied systems to controlled external conditions, including temperature, humidity, and electromagnetic field. The GRAINS scientific program was developed in close collaboration between FLNP JINR and the Faculty of Physics of the National University of Kyiv (Ukraine) under the supervision of M. V. Avdeev (FLNP) and L. A. Bulavin (National University of Kyiv). Within the user policy, GRAINS developed areas traditional for liquid reflectometers, including adsorption of biological macromolecules on lipid layers (N. Kučerka, P. Hrubovčák), adsorption of micellar aggregates of surfactants on polymer coatings (L. A. Bulavin, V. I. Petrenko, A. P. Artikulny, M. M. Avdeev), and glass transition of thin polymer and composite layers (T. V. Tropin, N. Jargalan). A number of important applied studies related to the behavior of liquid colloids at the interface with a solid substrate under various conditions were conducted. Thus, in collaboration with CFATR (Romania), IEP (Slovakia) and UP (South Africa), the adsorption of nanoparticles from magnetic fluids onto a solid surface was investigated. The influence of the aggregation stability of magnetic fluids, as well as the effects of external magnetic and electric fields, was examined (M. V. Avdeev, V. I. Petrenko, I. V. Gapon, A. V. Nagorny, L. A. Bulavin, M. Balasoiu, L. Vekas, M. Rajnak, M. Karpets, V. Zavisova, M. Timko, P. Kopčanský, P. Selyshchev). A series of studies were conducted from 2017 to 2021 in collaboration with the MSU Faculty of Chemistry to investigate the structure of planar interfaces for promising high-capacity lithium energy storage devices with metal electrodes. Neutron reflectometry proved to be a unique tool for tracing the



Participants in the launch of the GRAINS reflectometer for users (left to right): A. V. Nagorny, I. V. Gapon, A. V. Tomchuk, V. I. Petrenko, V. I. Bodnarchuk, L. A. Bulavin, and M. V. Avdeev. 2013

structural evolution of the buried layer deposited on the metal electrode during electrochemical cell charging, at the initial stage of lithium deposition. This layer determines the quality and stability of the electrode during cyclic operation of the lithium storage device. The influence of non-electroactive additives on the microstructure of this layer, tested in practice as an antidendritic agent in lithium batteries of this type, was studied (D. M. Itkis, L. V. Yashina, I. V. Gapon, V. I. Petrenko, V. I. Bodnarchuk, A. V. Tomchuk, E. Kosyachkin, M. V. Avdeev).

NEUTRON RADIOGRAPHY AND TOMOGRAPHY AT IBR-2 AND OTHER NEUTRON SOURCES IN JINR MEMBER STATES

Using the neutron radiography method, due to the varying degrees of attenuation of the intensity of the neutron beam when passing through materials of different chemical composition, density, and thickness of the components of the studied object, it is possible to obtain information about the internal structure of the studied materials with a spatial resolution at the micrometer level. This non-destructive neutron analysis method allows for obtaining images and three-dimensional reconstructions of the internal structure of studied objects with a spatial resolution of about hundreds of micrometers. The significant penetration depth of neutrons makes it possible to obtain fundamentally new information using neutron radiography and tomography compared to X-ray methods. Therefore, it is not surprising that the trend in recent years has been the development of experimental neutron radiography and tomography facilities at most modern neutron sources worldwide.

As early as 1985, V. M. Nazarov and his colleagues conducted the first neutron radiography studies at the IBR-2 pulsed high-flux reactor at the Laboratory of Neutron Physics. However, the state of development of image recording technologies at that time limited the quantitative analysis of the obtained data, therefore those studies were not continued. Significant advances in digital image recording and processing technologies in the following decades opened up new prospects for these methods. Between 2012 and 2016, at the initiative of D. P. Kozlenko, a specialized neutron radiography and tomography facility was built on reactor beamline14 at FLNP JINR (S. E. Kichanov, E. V. Lukin, G. D. Bokuchava, A. V. Belushkin). Since 2014, a multidisciplinary scientific program for the analysis of the internal structure of a wide range of objects — technological (S. E. Kichanov, D. P. Kozlenko), engineering (V. V. Sumin, G. D. Bokuchava, I. Yu. Zel), paleontological (A. V. Pakhnevich), geophysical (S. E. Kichanov, I. Yu. Zel), etc. — has been successfully implemented on the specialized facility.

Since 2017, at the initiative of I. A. Saprykina, a researcher at the Institute of Archaeology of the Russian Academy of Sciences, successful study has been carried out using non-destructive neutron analysis of cultural heritage objects (S. E. Kichanov, K. Nazarov, B. A. Bakirov, V. S. Smirnova). This collaborative work has yielded ample data on the internal structure and phase composition of coins of Ancient Greece and Bulgaria, objects of ancient Russian cultural heritage, items of personal piety, fragments of weapons and utensils, gold and silver jewelry of Scythian and Sarmatian tribes, and ceramic fragments from ancient pottery workshops.

Taking into account the relevance and wide application possibilities of neutron radiography and tomography methods, as well as the experience accumulated by FLNP JINR staff, a joint working group (D. P. Kozlenko, S. E. Kichanov, E. V. Lukin, V. N. Shvetsov, B. Mukhametuly, E. A. Kenzhin, K. Kadyrzhanov) was formed to create a facility for research using the neutron radiography and tomography method on the basis of the WWR-K reactor. The WWR-K stationary research nuclear reactor is one of the basic facilities of the Republican State Enterprise "Institute of Nuclear Physics" (RSE INP) (Almaty, Republic of Kazakhstan). Between 2017 and 2019, work was completed on designing the new facility, ordering and acquiring specialized equipment and materials, placing the main components of the facility and biological shielding elements in the experimental hall of

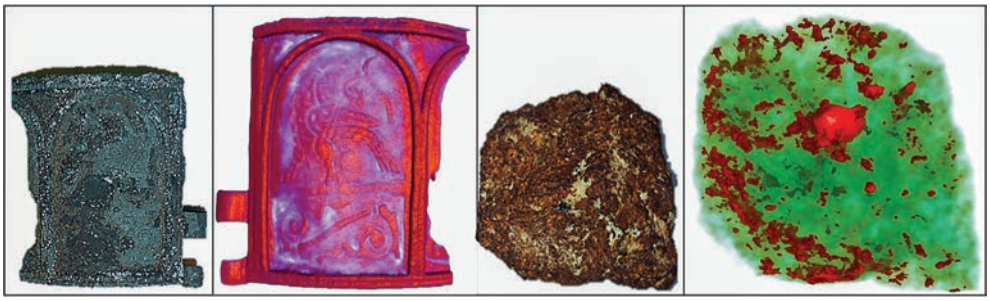


Fig. 4. Several examples of studies conducted at the neutron radiography and tomography station at the IBR-2 reactor: a photograph and neutron image of a fragment of an ancient Russian bracelet from the Tver treasure and the Kunya-Urgench meteorite



A joint group of FLNP JINR and RSE INP (Republic of Kazakhstan) at the experimental station for neutron radiography and tomography at the WWR-K reactor

the WWR-K reactor. The facility was commissioned in November 2019. Currently, joint research is being conducted on the created facility to analyze the internal composition of structural, geophysical and archaeological materials (K. Nazarov, M. Kenesarin, B. Mukhametuly, S. E. Kichanov).

In 2020, a new scientific infrastructure facility was created at the WWR-SM research reactor of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan to implement scientific research using neutron radiography and tomography methods.

An experimental neutron tomography station was developed at the initiative of Uzbek colleagues (M. Yu. Tashmetov, B. S. Yuldashev), through the efforts of a joint FLNP JINR – INP AS RUz working group (S. E. Kichanov, E. V. Lukin, B. A. Abdurakhimov, A. R. Saidov, N. B. Ismatov), which is currently a unique facility of its kind in the Republic of Uzbekistan. Its technical parameters allow for the successful conduct of scientific experiments analyzing the internal structure of technological, engineering, archaeological, and geophysical objects. The phase composition and spatial distribution of various phases within a copper–silver dirham of the Kara-Khanid period of the 10th–12th centuries CE were obtained. Furthermore, in collaboration with the Abdullayev Institute of

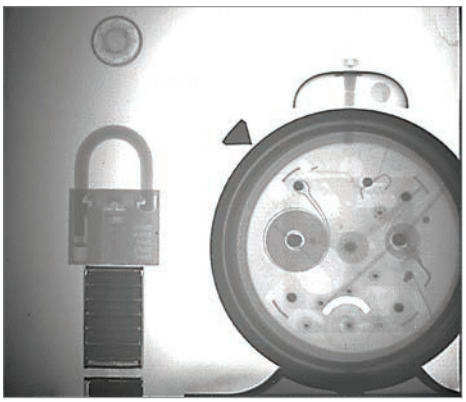


Fig. 5. The first neutron images obtained at the newly developed neutron radiography and tomography station



The detector system and the sample rotation stage for the tomographic mode of the neutron radiography station at the WWR-SM reactor at INP AS RUz

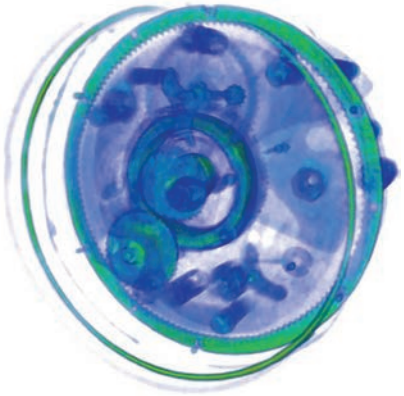


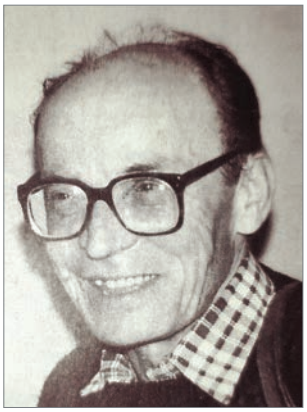
Fig. 6. The first three-dimensional model of an alarm clock reconstructed from neutron radiographic projections

Geology and Geophysics (Tashkent, Uzbekistan), non-destructive neutron analysis was used to obtain the size and orientation distributions of internal inclusions within lamprophyre igneous dikes, indicating the possible direction of magma flow in these natural conduits (I. Yu. Zel, S. E. Kichanov, B. A. Abdurakhimov). The station's methodological capabilities have opened up the potential for a broad range of research on ancient materials from the Uzundara fortress (Surkhandarya Region, Uzbekistan). The first results have already been obtained (M. Yu. Tashmetov, S. E. Kichanov, S. M. Adizov, N. D. Dvurechenskaya) from a non-destructive structural study of a copper Heliocles coin and two silver Demetrius coins, dating to the 2nd century BC, from archaeological excavations of the Uzundara fortress of the ancient Greco-Bactrian Kingdom. The results of the research made it possible to identify the features of the internal structure of the objects of study, analyze their manufacturing technology, and clarify their origin.

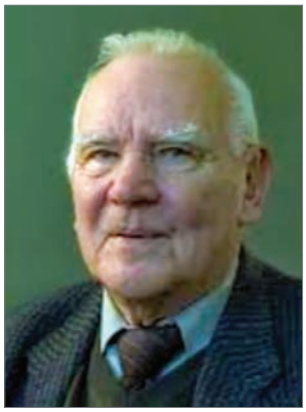
THE DEVELOPMENT OF INELASTIC SCATTERING AT FLNP AND ITS PLACE IN THE GLOBAL RESEARCH LANDSCAPE

The history of inelastic neutron scattering at the Frank Laboratory of Neutron Physics began in the 1960s under the direction of A. Szkatula from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow, Poland. The first simple-geometry cold neutron spectrometer used quasi-elastic neutron scattering (QENS) and inelastic neutron scattering (INS) to study the dynamics of thermal vibrations in water and other organic substances, such as benzene and naphthalene.

In 1962, A. Bajorek from IFJ PAN, together with T. A. Matchekhina, at the suggestion of F. L. Shapiro, developed a method for measuring INS in inverse geometry. A series of studies of molecular groups in crystals (for example, NH_4 in NH_4ClO) were carried out using the prototype spectrometer. In the second half of



A. Bajorek



J. Janik



I. Natkaniec



D. Chudoba at the upgraded NERA facility

the 1960s, a group led by Professor J. Janik (including I. Natkaniec, K. Parliński, A. Bajorek, and M. Sudnik-Hrynkiewicz) conducted studies of Be–Cu, Li–Mg, and Na–Pb alloys. I. Natkaniec modified the spectrometer, relying on B. Buras's idea, and added a diffraction measurement unit to perform structural analysis of the samples. This made it possible to simultaneously study structure and dynamics.

In 1970, the Krakow–Dubna inverse geometry spectrometer (KDSOG) began operation on beamline 1A of the IBR-30 reactor. Its successor, the NERA spectrometer[6], was commissioned at the IBR-2 reactor in the 1990s. The team, led by I. Natkaniec for many years, conducted research on phase transitions and the dynamics of various substances. Mounted on the 100-m flight path of the IBR-2 reactor, the spectrometer provided good resolution and a wide energy transfer range.

The team of physicists from the Leypunsky Institute of Physics and Power Engineering (Obninsk, Kaluga Region), led by V. P. Parfenov, who developed the DIN-2PI direct geometry spectrometer[7] with a multidetector recording system, is also noteworthy. The spectrometer was used primarily to study the dynamics of metal alloys and superfluid helium until the termination of its work in 2021.

The NERA spectrometer, which has been operating at the IBR-2 pulsed reactor at FLNP JINR for over three decades, has proven to be a highly successful neutron spectroscopy instrument. A project was initiated in 2020 to develop a new time-of-flight (ToF) spectrometer for inelastic neutron scattering in inverse geometry to maintain and expand the research tradition using cutting-edge technologies. The primary purpose of this instrument is to provide a wide energy transfer range of up to 400–500 meV, combined with exceptional neutron intensity and resolution.

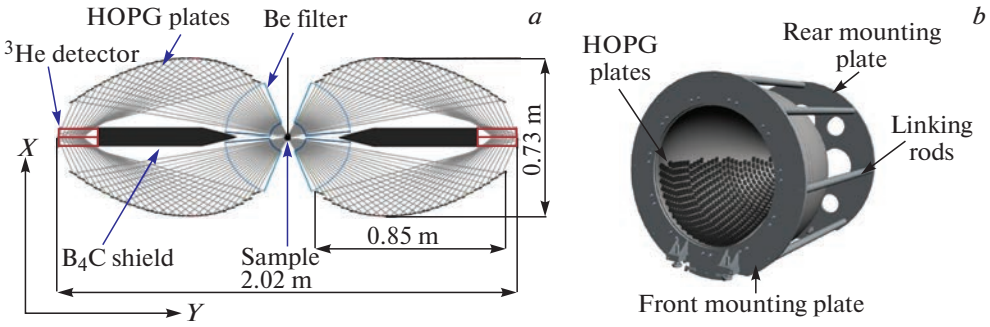


Fig. 7. a) The basic concept of the secondary spectrometer: placing a set of HOPG (highly oriented pyrolytic graphite) analyzing plates, which together resemble the shape of a bell, on either side of the sample; b) visualization of one part of the new BJN spectrometer

A. V. Belushkin, E. A. Goremychkin, and M. Klepacka, under the leadership of D. Chudoba, made an active and decisive contribution to the development of the new BJN (Bajorek–Janik–Natkaniec) facility[8].

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[6] *Natkaniec I., Chudoba D., Hetmańczyk Ł., Kazimirov V. Yu., Krawczyk J., Sashin I. L., Zalewski S.* Parameters of the NERA Spectrometer for Cold and Thermal Moderators of the IBR-2 Pulsed Reactor // J. Phys.: Conf. Ser. 2014. V. 554. 012002.

[7] *Kalinin I. V., Morozov V. M., Novikov A. G., Puchkov A. V., Savostin V. V., Sudarev V. V., Bulkin A. P., Kalinin S. I., Pusenkov V. M., Ulyanov V. A.* Characteristics of the DIN-2PI Spectrometer with a Neutron Concentrator // Tech. Phys. 2014. V. 84, issue 2.

[8] *Klepacka M., Belushkin A., Goremychkin E., Chudoba D.* High Luminosity Inverse Geometry Inelastic Neutron Scattering Spectrometer at Pulsed Fast Reactor // Rev. Sci. Instrum. 2025. V. 96. 033902.

COLD NEUTRON MODERATORS

The history of cold moderator development at FLNP

Beginning in the 1960s, a cold neutron moderator based on polyethylene, consisting of a stack of thin films (to ensure free release of radiolytic hydrogen) with a beryllium reflector, was developed and operated for several years at the IBR-1 and IBR-30 reactors at FLNP. A liquid hydrogen moderator was considered for the IBR-2 reactor design due to the poor radiation resistance of polyethylene. The Chernobyl disaster of 1986 significantly toughened nuclear safety concerns; therefore, the work on developing a liquid hydrogen moderator was stopped. E. P. Shabalin proposed using a solid methane moderator instead of a liquid hydrogen moderator at the IBR-2 reactor. A flow moderator or a moderator with a rapid change of the operating medium in the chamber was considered to address the issues associated with the poor radiation resistance of methane. In this case, frozen pellets of solid methane, filling the moderator chamber and cooled by cold helium, would be continuously replaced by a new portion. In 1990, a decision was made to develop a methane moderator for the IBR-2 reactor, but the flow moderator design was rejected due to the lengthy and expensive engineering and physics studies. In 1994, the first comb-shaped moderator, the SM1, was developed[9], but during startup and testing, its chamber ruptured due to hydrogen release. A new cold moderator, the SM2, was designed later[10]. It had a flat chamber with a slit near one wall to allow freer hydrogen escape (Fig. 8, from paper[11]). The presence of a beryllium reflector doubled the cold neutron yield. Adding a few percent of ethylene to the methane reduced the hydrogen yield by half. Tests were conducted in 1999 and 2000, examining the following characteristics: the effects of operating temperature and time, the amount of methane in the moderator chamber, the concentration of hydrogen absorbers, and the annealing procedure. The maximum moderator operating time was 4 days. Despite the fact that 30% of the methane was converted to hydrogen, ethane, and high-molecular-weight hydrocarbons during this time under irradiation, no loss in cold neutron intensity due to degradation was detected.

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[9] *Gundorin N. A.* The Comb-Shaped Moderator. JINR Commun. P3-80-721. Dubna, 1980. 10 p.;
Shabalin E. P. et al. Solid Methane Cold Moderator at the IBR-2 Reactor: Test Operation at 2 MW // Proc. of the 2nd Intern. Meeting on Pulsed Advanced Neutron Sources. Dubna, 1994. P. 217–234;
Beljakov A. A. et al. First Experience of Cold Moderator Operation and Solid Methane Irradiation at the IBR-2 Pulsed Reactor // Proc. of the 16th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-XII). Abingdon, 1993. RAL Report 94-025. V. 2. P. 144–155.

[10] *Belyakov A. A. et al.* Solid Methane Cold Moderator at the IBR-2 Reactor // J. Neutron Res. 1996. V. 3. P. 209–221;
Beliakov A. A. et al. Solid Methane Cold Moderator for the IBR-2 Reactor // Proc. of the Intern. Workshop on Cold Moderators for Pulsed Neutron Sources. Argonne, 1997. P. 73–78;
Belyakov A. A., Tretiakov I. T., Shabalin E. P. First Experience with the New Solid Methane Moderator at the IBR-2 Reactor // Proc. of the 15th Meeting of the International Collaboration on Advanced Neutron Sources / Ed. by S. Itoh et al. Tsukuba, 2000. V. 1. P. 1026–1036;
Shabalin E. P., Beliakov A. A. Solid Methane Cold Moderator for the IBR-2 Reactor: Present Status // Proc. of German–Russian User Meeting "Condensed Matter Physics with Neutrons at IBR-2". Dubna, 1998. P. 25–32.

[11] *Shabalin E. P.* Cold Neutron Moderator // Part. Nucl. 2005. V. 36, No. 6. P. 1425–1442.

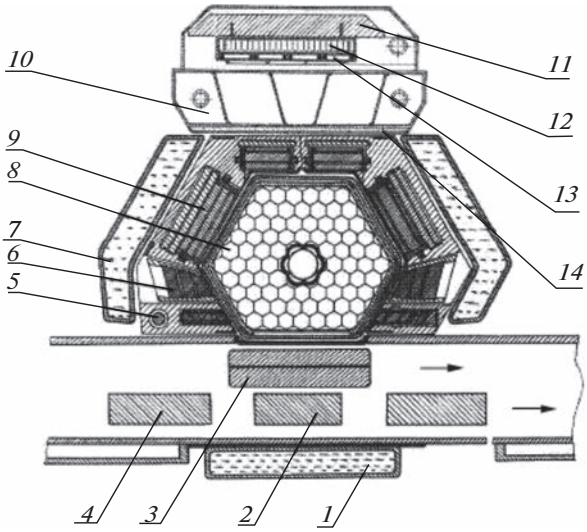


Fig. 8. The IBR-2 reactor with a solid-methane moderator[11], horizontal section at a scale of 1:8: 1, 7 — water moderators; 2, 4 — middle and outer blades of the additional movable reflector; 3 — blade of the main movable reflector (design before 2004 is shown); 5, 6, 9 — control units in the stationary reflector; 8 — fuel assembly; 10 — water pre-moderator of the cold moderator; 11 — beryllium reflector; 12 — methane cavity of the cold moderator; 13 — cooling helium cavities; 14 — boron filter

The cold moderator made of solid methane was installed in place of one of the three water moderators of the IBR-2 reactor. The density of the cold neutron flux emitted from its surface was comparable to that of the most intense pulsed neutron sources in operation at the time.

Despite all its advantages, the methane cold moderator required improvements due to temperature instability caused by radiation effects in methane (hydrogen annealing) and long breaks (about a day) for methane replacement. This negatively impacted the performance of the spectrometers and significantly worsened the results of neutron physics experiments.

The operating life of the methane moderator was limited due to the accumulation of radicals, resins, and soot. The moderator chamber was filled with radiolysis products by 40–50% after just 1000 h of operation. To extend its operating life, the moderator chamber was protected from fast neutrons by a 9-cm-thick layer of water (compared to the 3-cm layer required for preliminary moderation), which reduced the cold neutron flux by a factor of three. Therefore, with the start of the IBR-2 upgrade in 2006, the Laboratory set the task of developing a cold moderator that would operate reliably for at least 7 days in a physics experiment without temperature fluctuations at higher radiation doses (approximately 0.5 kGy/s) and have an operating life of at least 10 000–15 000 h.

Based on the results of work carried out within the URAM-1 and URAM-2 projects, as well as in close cooperation with the Collaboration on Advanced Cold Moderators (ACoM) and Professors I. Natkaniec (Poland) and R. Granada (Argentina), it was proposed to use mesitylene, which has radiation resistance an order

of magnitude better than methane, as a moderating substance for the upgraded IBR-2 reactor.

Mesitylene, and especially its mixture with m-xylene, or pseudocumene[12], is a very suitable substance for a cold moderator in modern medium-intensity neutron sources (research reactors with a power of 1–5 MW or high-current proton accelerators with a beam power of 0.2–1 MW) as an alternative to methane and hydrogen moderators.

The main advantages of mesitylene over other cold moderator materials (methane, hydrogen, propane, water, etc.) are high radiation resistance, a wide operating temperature range, and improved safety (in relation to explosion hazard and flammability). Mesitylene moderators offer a good compromise between physical (cold neutron yield) and technological (radiation resistance, ease of use, and safety) properties. These considerations led to the selection of mesitylene as the operating substance for the cold neutron moderator in the upgraded IBR-2 fast pulsed reactor.

An important requirement for such a cold neutron moderator was that it should operate in a cyclic mode, including the stages of loading "fresh" material before the start of the reactor cycle and unloading waste material after its completion. Therefore, preference was given to the option with solid frozen pellets for the mesitylene moderator design[13].

The design and operating principle of pelletized mesitylene-based cold neutron moderators

The mesitylene-based cold neutron moderator combined with room-temperature water moderators are the bispectral moderators of the IBR-2 reactor (Fig. 9). The spectrometers from virtually all of the reactor's beamlines "look" at the moderators from various angles.

The cold moderator can operate in two modes: 1) moderator mode using room-temperature water (thermal neutron experiments), where the cold moderator chamber must be empty and its temperature equals the ambient temperature; 2) cold moderator mode (cold neutron experiments), where the cold moderator chamber is loaded with the operating substance — mesitylene mixed with metaxylene (m-xylene) — in a total volume of approximately 1 liter and the operating temperature is no higher than 20–30 K.

The cyclic mode of the moderator operation is ensured by loading its chamber with pre-calibrated solid frozen pellets of a mixture of mesitylene and m-xylene with a diameter of 3.5–3.9 mm in the amount of 30 000 pieces (Fig. 10).

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[12] *Cher L.* Organic Compounds for Cold Moderators // Proc. of the 14th Intern. Conf. on Advanced Neutron Sources. Starved Rock, Illinois, 1998. V. 2. P. 241–244.

[13] *Shabalin E. P., Kulikov S. A.* Complex of Neutron Moderators for the IBR-2M Reactor // Proc. of the 17th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-XVII). New Mexico, 2005;

Bulavin M. V. et al. Pelletized Cold Neutron Moderator. RF Patent 2492538, IPC G 21 K 001/00. Applicant and Patent Holder: Joint Institute for Nuclear Research. RU Bull. "Inventions. Utility Models" No. 35, 10.09.2013. P. 2.

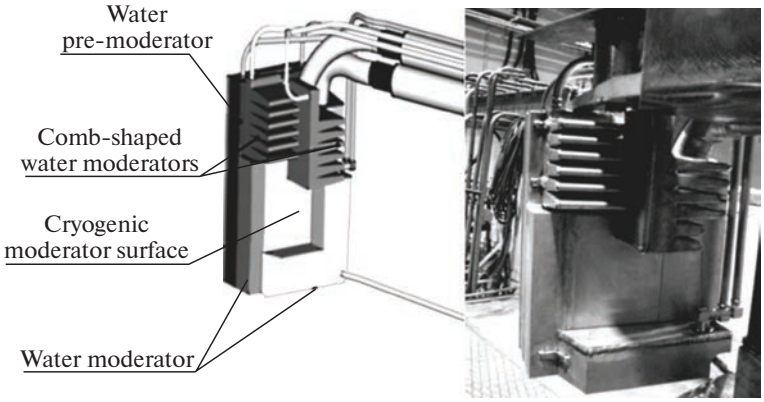


Fig. 9. The CM-202 bispectral neutron moderator at the IBR-2 reactor



Fig. 10. Solid pellets of a mixture of mesitylene and m-xylene frozen in liquid nitrogen

The pelletized method of moderator chamber loading allows for the easy removal of energy released from the moderation of fast neutrons, as well as the rapid loading and unloading of the moderator substance, making the moderator's operating life virtually unlimited. Importantly, the pelletized structure, unlike a solid frozen piece of material, enables radiolytic hydrogen formed as a result of irradiation to freely exit the moderator chamber without creating excess pressure.

Mesitylene and metaxylene pellets are loaded into the moderator chamber by pneumatic transport using a flow of cold helium with a temperature of approximately 80 K through a pipeline of complex configuration (Fig. 11). This operation principle of the moderator is to a certain degree similar to known proposals for pelletized solid methane moderator designs[14].

The pelletized cold neutron moderator has a primary and secondary cooling circuits. The primary circuit includes a cold moderator chamber, a pneumatic transport pipeline, motion sensors for frozen pellets in the pipe, a helium flow sensor connected to a Pitot tube, a dosing device, a gas blower, and a pipeline for helium removal from the moderator chamber. The secondary cooling circuit consists

[14] *Bauer G. S., Lucas A. T., Sulfredge C. D.* A Pelletized Solid Methane Moderator for a Medium-to-High Power Neutron Source // Proc. of the 13th Meeting of the International Collaboration on Advanced Neutron Sources / Ed. by G. S. Bauer et al. Villigen, 1995. V. 2. P. 644–652.

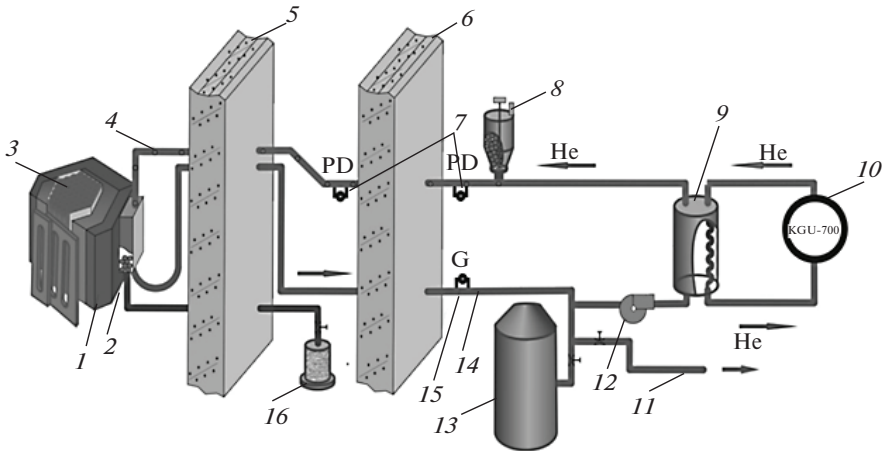


Fig. 11. The pelletized cold neutron moderator at the IBR-2 reactor: 1 — water moderator; 2 — cold moderator chamber; 3 — IBR-2 core; 4 — pneumatic transport pipeline (primary cooling circuit); 5, 6 — biological shielding; 7 — motion sensors for frozen pellets in the pipe; 8 — dosing device; 9 — heat exchanger; 10 — KGU-700 cryogenic helium unit and the secondary cooling circuit; 11 — pipeline for emergency hydrogen removal; 12 — gas blower; 13 — gas holder; 14 — pipeline for helium removal from the moderator chamber; 15 — helium flow sensors (Pitot tube); 16 — tank for draining waste mesitylene and m-xylene

of a cryogenic helium unit and helium supply and removal pipelines to and from the KGU. The heat exchanger is designed to transfer low temperatures from the helium in the secondary cooling circuit to the helium circulating in the primary cooling circuit.

The minimum operating temperature of the moderator is 20 K. At this temperature, the moderator can operate for the entire IBR-2 reactor cycle at a power of 2 MW (12 days).

After the reactor is shut down, the melted operating substance is removed to a special tank for drainage and disposal, whereafter the moderator is prepared for a new cycle.

Routine operation of the pelletized cryogenic moderator complex at IBR-2 and future plans

In the period from 2012 to 2025, the complex of pelletized cryogenic moderators with a cryogenic system and an industrial-grade control and monitoring system successfully and safely operated for physics experiments during the IBR-2 operation at power for more than 5000 h. This unique result was presented in papers[15] and reflected in numerous other scientific publications and reports at international conferences.

[15] *Bulavin M. et al.* The World's First Pelletized Cold Neutron Moderator Began Its Operation // Neutron News. 2013. V. 24, No. 3. P. 27;

Bulavin M. et al. Pelletized Cold Moderator of the IBR-2 Reactor: Current Status and Future Development // J. Phys.: Conf. Ser. 2016. V. 746. 012031.

On the whole, the analysis of the obtained results shows that, compared to a thermal moderator based on room-temperature water, a cold moderator at 20 K produces up to 14 times more cold neutrons, greatly reducing the exposure time of the studied objects and significantly improving the quality of the obtained results. The commissioning of the new cryogenic system, which operates using two Linde helium cryogenic units with a total capacity of 3000 W, made it possible to reduce the mesitylene temperature in the moderator chambers from 32 to 20 K, increasing the cold neutron flux density by another 15–20%.

Figure 12 shows some of the qualitative improvements provided by the use of cold moderators when conducting neutron studies on the IBR-2 spectrometers[16].

The Laboratory is currently developing promising new devices and technologies for cryogenic moderators, including for the new high-flux neutron source being developed at FLNP.

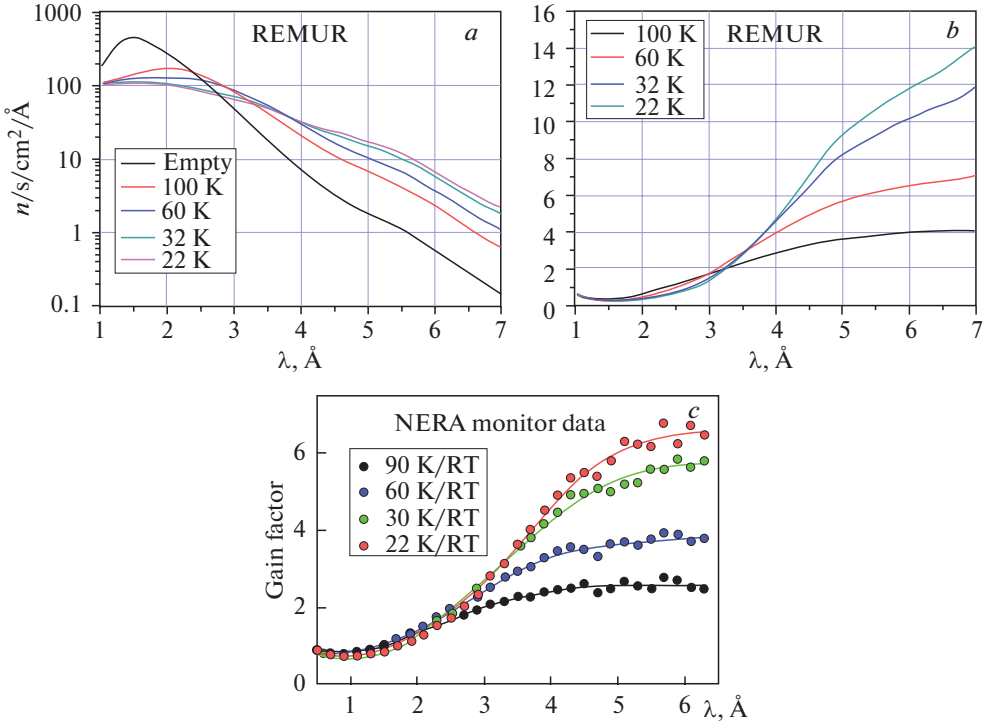
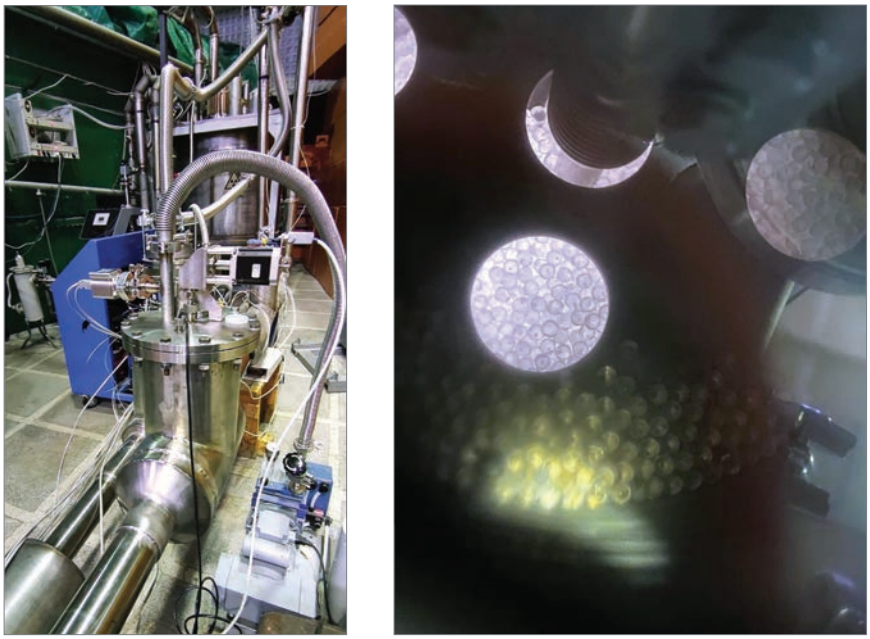


Fig. 12. Neutron spectrum (a) and gain factor (b, c) in the cold neutron flux density from the surface of a cold moderator at different temperatures relative to the cold neutron flux density from the surface of a thermal moderator based on room-temperature water

[16] *Bulavin M. V., Kozhevnikov S. V., Zhaketov V. D., Petrenko A. V., Verkhoglyadov A. E., Kulikov S. A., Shabalin E. P.* The Use of the Cryogenic Moderator on the REMUR Neutron Reflectometer // J. Surf. Invest.: X-Ray, Synchrotron Neutron Tech. 2016. No. 1. P. 5–14;

Bulavin M. V., Vasin R. N., Kulikov S. A., Lokaichek T., Levin D. M. The Use of the Combined Moderator at the IBR-2 Reactor: Advantages for Neutron Diffraction Texture Analysis of Rocks // J. Surf. Invest.: X-Ray, Synchrotron Neutron Tech. 2016. No. 5. P. 1–10.



A new type of dosing device with an increased internal volume. Left: general view of the device on the CM-201 test bench. Right: frozen mesitylene pellets inside the dosing device (viewed through a special inspection window)



The prototype of a high-performance dropper for producing solid frozen mesitylene pellets

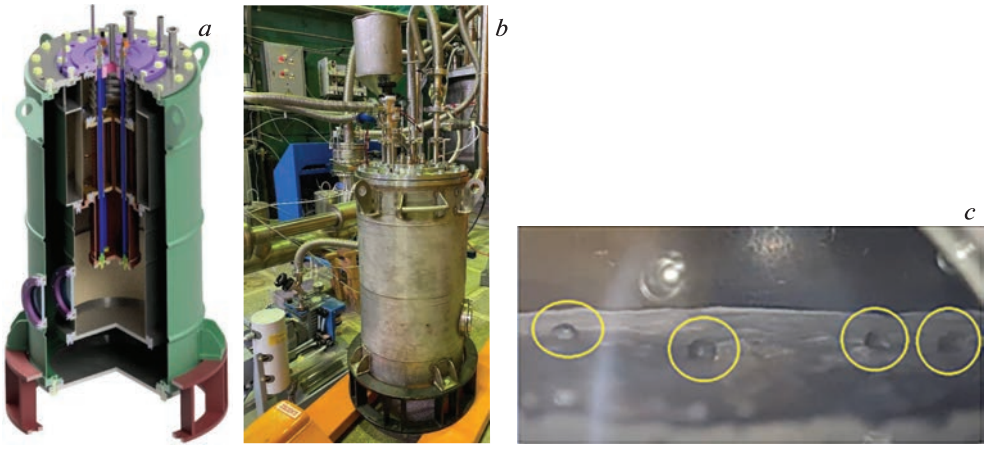


Fig. 13. a, b) The facility for producing solid frozen pellets of regular shape from methane in liquid nitrogen/argon (dropper for methane pellets); c) supercooled drops of solid methane obtained during the experiment

A new dosing device with an increased internal volume was developed and implemented during operation of the cryogenic moderator complex. Testing revealed that the use of this new type of dosing device significantly (by a factor of four) reduced the time for loading pellets into the cryogenic moderator chamber. The introduction of this new dosing device into trial operation allowed the cryogenic moderator chamber to be loaded in just 2 h (instead of 6 to 7 h with the previous dosing device), which had a positive impact on the operation of the entire cryogenic moderator complex during the operation of the IBR-2 reactor for physics experiments[17].

A prototype of a high-performance dropper was made for producing solid frozen pellets (similar to Rupert's drops) from mesitylene[18]. This prototype is being used to develop an industrial model with a capacity of 1.3 l/h, with integrated control electronics, as well as a machine vision-based counting and rejection system for finished pellets.

The industrial prototype of the facility will ensure uninterrupted loading of pellets into the IBR-2 cryogenic moderator complex during reactor operation for physics experiments. The operating principle of the facility itself will form the basis for the development of a promising line of production of solid methane pellets for the use in cryogenic moderators at any neutron source worldwide.

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[17] *Bulavin M. V., Litvak I. L.* Using Frozen Beads from a Mixture of Mesitylene and Meta-Xylene with Rupert's Drop Properties in Cryogenic Neutron Moderators // J. Nucl. Eng. 2025. V. 6(2). P. 9; https://doi.org/10.3390/jne6020009;

Galushko A. V. et al. Use of Frozen Beads of Mesitylene and Meta-Xylene Mixture with Rupert's Drop Properties in Cryogenic Neutron Moderators // Part. Nucl., Lett. 2025. V. 22, No. 2(259). P. 305–314 (in Russian).

[18] *Litvak I. L., Bulavin M. V., Chepurchenko R. V., Galushko A. V.* Operating Principles of a Device for Producing Dispersed Moderating Material in the Form of Balls for Cryogenic Neutron Moderators. JINR Commun. P-18-2024-60. Dubna, 2024. 20 p. (in Russian).

FLNP has also made some progress in this area. A prototype of a so-called methane dropper — a facility for producing solid methane pellets — was developed. The first experiments to produce frozen methane droplets in liquid nitrogen (argon) have now been conducted using the experimental facility.

The experimental facility will be further modified and equipped with a two-stage cryocooler for producing large quantities of solid methane pellets in various coolants, such as liquid helium, hydrogen, or neon. A draft design for such a facility is being developed.

Currently, FLNP has developed and successfully operated a unique, world's only complex of pelletized cryogenic moderators based on aromatic hydrocarbons, using extensive experience and groundwork in neutron moderator development. This has made it possible to bring neutron research at the IBR-2 reactor to a qualitatively new world-class level.

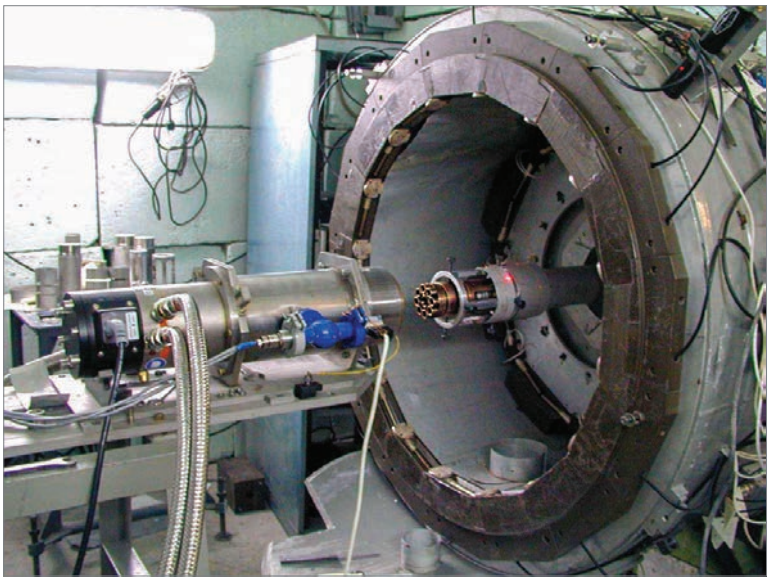
Further development of cryogenic moderators at FLNP, including for the purpose of their use at the new advanced neutron source at FLNP JINR, is moving towards creating a universal pelletized cryogenic moderator based on promising hydrogen-containing materials (mesitylene, methane) with a system for quickly changing the working material in the moderator chamber for use at neutron sources of any power and intensity.

NEUTRON STUDIES OF CONDENSED MATTER UNDER HIGH PRESSURE

In the last two decades of the 20th century, the world's leading neutron centers focused on the active development of experimental methods for studying condensed matter at high pressures and the creation of experimental infrastructure for their implementation. The reason for the significant scientific and practical interest in such research is that the exposure to high pressure leads to the emergence of new, often unique, physical phenomena in the studied materials, enabling the development of new structural modifications of substances with unique physical properties. For example, diamond is a modification of carbon that crystallizes at high pressure.

It should be noted that the unique nature of neutron interactions with matter determines several advantages of neutron diffraction over X-ray and other methods in structural studies. These include high penetrating power, high sensitivity to the positions of light atoms in the structure (hydrogen, oxygen, etc.), which is especially important in the presence of heavy atoms or structural disorder, and the ability to simultaneously study the atomic and magnetic structures of materials.

The low fluxes of neutron sources, many orders of magnitude lower than those of synchrotron radiation sources, naturally imposed significant limitations on the development of high-pressure research, which remained unresolved for a long time. Such neutron experiments required a comparatively large volume of test material, and the achievable pressures were typically limited to a narrow range of 1–2 GPa (10 000–20 000 bar). Despite this, the development of multidetector systems, modern reflector neutron guides, including focusing ones, specialized high-pressure



The DN-12 neutron spectrometer

chambers, and the provision of low-background experimental conditions have enabled significant progress in this field.

Between 1993 and 1997, first the basic configuration (in collaboration with the staff of the NRC "Kurchatov Institute") and then (with the participation of the PNPI staff) the final configuration of the DN-12 spectrometer was developed at the IBR-2 high-flux reactor, one of the most intense pulsed neutron sources in the world, for studying the atomic and magnetic structures and dynamics of microsamples under high pressure using the methods of neutron diffraction and inelastic incoherent neutron scattering (V. L. Aksenov, A. M. Balagurov, B. N. Savenko, D. P. Kozlenko, S. L. Platonov (FLNP JINR), V. A. Somenkov, V. P. Glazkov, I. V. Naumov, G. F. Syrykh (NRC "Kurchatov Institute"), V. A. Trunov, A. P. Bulkin, V. A. Kudryashev (PNPI)). The main elements of the spectrometer were a curved neutron guide on supermirrors ($m = 2$), a detector system in a protective casing consisting of two rings containing 16 independent point neutron ^{3}He gas counters each, an electronic system for control, acquisition and processing of neutron data. The experiments utilized specialized high-pressure cells with sapphire anvils, developed by staff of the NRC "Kurchatov Institute" and the Institute for High Pressure Physics of RAS (IHPP RAS) and previously successfully used in experiments on the DISK neutron diffractometer at the IR-8 stationary reactor of the NRC "Kurchatov Institute". The spectrometer was also equipped with a closed-cycle cryocooler to generate low temperatures in the range of 10–300 K in the high-pressure cell. Successful neutron diffraction experiments were conducted on the DN-12 in the high-pressure range of up to 10 GPa (100 000 bar) using a very small sample volume of 0.5–1 mm^3. For comparison, the standard sample volume in neutron scattering experiments is about 1 cm^3.



High-pressure cells with diamond anvils



High-pressure cells with sapphire anvils

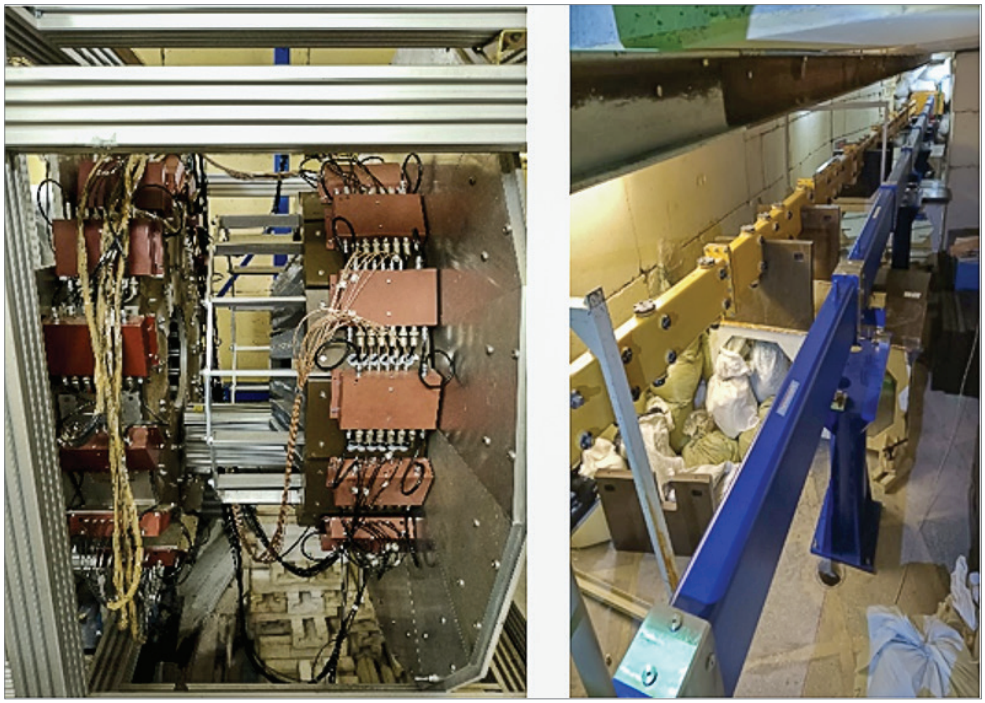
The development of the DN-12 spectrometer initiated a new, original research area that has become an important part of FLNP JINR research program. It involves systematically studying the relationship between changes in the crystal and magnetic structures and properties of entire classes of functional materials. This experimental approach allows the identification of the microscopic mechanisms of various physical phenomena in the studied materials that arise as a result of changes in structural parameters during crystal lattice compression. Among the most important results obtained over the past quarter century in research at the DN-12 spectrometer using high-pressure neutron diffraction are:

- detection of a number of pressure-induced magnetic phase transitions in $R_{1-x}A_xMnO_3$ (R = La, Pr, A = Ca, Sr) manganites with the colossal magnetoresistance effect and determination of the structural and magnetic P–T phase diagrams of these compounds (D. P. Kozlenko, S. E. Kichanov, E. V. Lukin, B. N. Savenko (FLNP JINR), V. I. Voronin (IMP UB RAS), Z. Jirák (Institute of Physics, CAS, Czech Republic), N. T. Dang (Duy Tan University, Vietnam));
- analysis of the influence of spin crossover effects on the magnetic and structural properties of complex cobalt oxides $R_{1-x}A_xCoO_3$ (R = La, A = Ca, Sr), $LaSrCoO_4$ (N. O. Golosova, D. P. Kozlenko, S. E. Kichanov, E. V. Lukin, B. N. Savenko, O. V. Lis (FLNP JINR), V. I. Voronin (IMP UB RAS), Z. Jirák (Institute of Physics, CAS, Czech Republic));
- establishment of microscopic mechanisms of pressure-induced magnetic collapse of the Co sublattice in RCo_2 intermetallides (R = Tb, Dy, Ho) and violation of the concept of band electron metamagnetism in $ErCo_2$ (D. P. Kozlenko, A. V. Rutkauskas, S. E. Kichanov, B. N. Savenko (FLNP JINR), E. Burzo, P. Vlaic (Babes-Bolyai University, Romania));
- detection of a pressure-induced state of spin liquid in the quasi-two-dimensional multiferroic $YMnO_3$ (D. P. Kozlenko, S. E. Kichanov, B. N. Savenko (FLNP JINR), J.-G. Park (Seoul National University, Republic of Korea));

- detection of new pressure-induced structural and magnetic states in quasi-two-dimensional van der Waals magnetic materials MPS_3 (M = Mn, Fe) (D. P. Kozlenko, S. E. Kichanov, B. N. Savenko (FLNP JINR), J.-G. Park (Seoul National University, Republic of Korea), S. S. Saxena (University of Cambridge, UK), M. J. Coak (University of Birmingham, UK), N. T. Dang (Duy Tan University, Vietnam)).

The DN-12 spectrometer was also the first to demonstrate the feasibility of conducting experiments to study the dynamics of hydrogen-containing materials at pressures of up to 10 GPa using inelastic incoherent neutron scattering. The baric dependences of the transverse optical and librational modes in ammonium halides were determined based on an analysis of the experimentally measured generalized phonon state density. Hybridization of these modes under pressure was detected in ammonium iodide near the order–disorder orientational phase transition (D. P. Kozlenko, B. N. Savenko (FLNP JINR), V. A. Somenkov, V. P. Glazkov, G. F. Syrykh (NRC "Kurchatov Institute"), A. S. Telepnev (IHPP RAS)).

Many years of successful research experience at the DN-12 spectrometer formed the basis for the development of a new high-intensity diffractometer, the DN-6, which began operating in its basic configuration in 2013 (D. P. Kozlenko, S. E. Kichanov, E. V. Lukin, B. N. Savenko, Ts. Panteleev, V. Milkov (FLNP JINR)). The DN-6 is located on the experimental beamline with a significantly high neutron flux; its main elements are the supermirror neutron guide with a parabolic vertical focusing section and the multidetector system with a scattered



The main components of the DN-6 diffractometer, the detector system, and the curved supermirror neutron guide

neutron collection area six times larger than that of the DN-12. A significant increase in the diffractometer's luminosity made it possible to use high-pressure cells with diamond anvils and significantly expand the available pressure range to 40 GPa (400 000 bar). Moreover, the experiments utilize extremely small sample volumes, down to 0.01–0.02 mm^3. The DN-6 is also equipped with a cryostat for conducting experiments with high-pressure cells in the temperature range of 5–300 K (A. N. Chernikov (FLNP JINR)).

Over the past decade, using the DN-6 diffractometer, a number of unique results have been achieved, including:

- determination of the magnetic structure of the high-pressure phase of the mineral magnetite Fe_3O_4, widely distributed in the Earth's crust;
- detection of pressure-induced antiferromagnetic–paramagnetic transition in the classical Jahn–Teller system $LaMnO_3$;
- the effect of a significant (sixfold) increase in the magnetic ordering temperature, suppression of intermediate antiferromagnetic phases and stabilization of the Yafet–Kittel ferrimagnetic phase in geometrically frustrated Mn_3O_4 material under high pressure.

In recent years, the DN-6 diffractometer has undergone an additional upgrade with the replacement of the previously installed central section of the neutron guide (supermirror index $m = 2$) with a new one featuring supermirrors with a more efficient neutron reflection ($m = 3$). As a result, the incident neutron flux has increased approximately by a factor of two on average, which in the long run enables a further expansion of the available pressure range to 50 GPa (500 000 bar).

THEORETICAL PHYSICS

In the 21st century, the Bogoliubov Laboratory of Theoretical Physics (BLTP) continued to develop its traditional research areas and explore new ones, responding to the current challenges of modern physics and remaining closely linked to the JINR experimental program. The achievements of BLTP over these years cover a wide range of fundamental physics research and intensive educational activities. Research has been focused on developing the theoretical foundations and mathematical methods that shape our understanding of nature at all scales – from the structure of nucleons to astrophysics and the dynamics of the early Universe. Laboratory staff develop and refine models in quantum chromodynamics, electroweak interactions, neutrino physics, nuclear structure, and condensed matter. Significant efforts are devoted to the study of quantum gravity, supersymmetry, and cosmological scenarios. These conceptual studies deepen our theoretical knowledge and facilitate the interpretation of complex experimental data. A large part of the research extends beyond its specific subject areas and is interdisciplinary in nature.

The Laboratory of Theoretical Physics brings together over 200 long-term researchers, more than a quarter of whom are non-Russian. This team is complemented by a dynamic program of short-term visits for scientists from JINR Member States and international partner organizations. The Laboratory of Theoretical Physics maintains an exceptional level of scientific productivity; in the 21st century, laboratory staff have published over 10 000 scientific papers in leading peer-reviewed journals and a significant number of monographs and chapters in scientific collections. Laboratory researchers also serve on editorial boards and international advisory committees, further enhancing its global scientific authority.

The laboratory actively collaborates with research organizations in many countries and plays a key role in international scientific initiatives. BLTP promotes global integration in theoretical physics and supports the development of collaborative research between countries through its commitment to open scientific exchange. Since 2000, BLTP staff have organized over 250 international conferences and workshops, as well as 80 research schools for students and young scientists from around the world, covering all areas present at BLTP. These events have attracted over 20 000

participants, including both thematic conferences with a wide range of participants and meetings aimed at deepening collaboration between BLTP and scientific organizations in specific countries. Among the latter, a series of joint meetings, held regularly for many years, are noteworthy. The 13th Workshop on Physics of Strong Interacting Systems, organized jointly with institutes in China, was held in 2025. Since 2007, joint meetings with the Asia Pacific Center for Theoretical Physics have been held annually. Also, since 2007, joint meetings with theorists from South Africa have been held every two years. Several joint meetings and roundtables have been held with theorists from Italy, Germany, France, and other countries.

The following can be distinguished among the cycles of thematic events: conferences on high-energy spin physics, regularly held since 1981; the Baldin seminar on problems of high energy physics, organized jointly with the Laboratory of High Energy Physics; seminars on high-energy physics ("Quarks"); workshops on the physics of finite and infinite nuclear matter; workshops on nuclear structure and related topics, as well as schools on nuclear theory and astrophysical applications; schools and workshops on few-body systems; conferences on symmetry methods in physics; the Dubna-Nano conference cycle; workshops on nucleation theory and its applications; workshops and conferences on classical and quantum integrable systems, integrable systems and quantum symmetries, supersymmetries and quantum symmetries; schools on integrable and stochastic systems, and others. In addition to regular events, numerous conferences and meetings were organized on other pressing scientific issues of interest to BLTP staff. Representative conferences were held to commemorate the birthdays of BLTP founders and distinguished staff members, including conferences dedicated to the 100th anniversary of the birth of D. I. Blokhintsev and the 100th and 110th anniversaries of the birth of N. N. Bogoliubov. BLTP twice hosted scientific sessions of the Nuclear Physics Section of the Physical Sciences Division of the Russian Academy of Sciences, and in 2024, the Laboratory hosted the Russian Conference on Nuclear Physics "Nucleus-2024". Regular seminars, international conferences, and workshops create an active environment for scientific exchange and fruitful collaboration.

The synthesis of theory, experiment and technology at JINR is provided by an active interlaboratory interaction. BLTP plays a key role in developing the theoretical foundations and research programs for major JINR experiments, such as the NICA complex, the Superheavy Element Factory, the Baikal Neutrino Telescope, the IBR-2 reactor, and others. The use of modern computing resources is an integral component of cutting-edge research. The Laboratory actively develops computational



The BLTP staff during the seminar dedicated to the 60th anniversary of the Laboratory. May 2016



BLTP Directors of different years V. G. Kadyshevsky, A. N. Sissakian, A. T. Filippov, and D. V. Shirkov against the background of images of the first directors N. N. Bogoliubov and D. I. Blokhintsev



BLTP Director V. V. Voronov (second from left) and a group of researchers from Slovakia. 2015



The BLTP Directorate: A. V. Andreev, D. I. Kazakov, O. V. Teryaev, E.-M. Anitas, and N. V. Antonenko. 2026

methods for theoretical research, making extensive use of the JINR Multifunctional Information and Computing Complex (MICC), which includes the high-performance Govorun supercomputer. Its development was crucially driven by BLTP's need for a platform for complex computations. These resources are currently used for large-scale numerical modeling and data-intensive theoretical studies, particularly in the fields of lattice gauge theories, quantum chromodynamics, statistical physics, and condensed matter models.

In addition to scientific research, BLTP plays a crucial role in training a new generation of theoretical physicists. Laboratory staff actively participate in teaching at university branches and departments located primarily in Dubna and Moscow, including Dubna State University, Moscow Institute of Physics and Technology, Moscow State University, Moscow Engineering Physics Institute, and the Higher School of Economics, as well as in other universities and cities across Russia, strengthening ties between science and education. These educational programs are implemented in collaboration with the JINR University Centre. The Dubna International Advanced School of Theoretical Physics (DIAS-TH), a project launched at BLTP in 2003, provides systematic and advanced training for undergraduate and graduate students, and young scientists from JINR Member States. The project includes seminars and lectures by leading JINR scientists. Every year, with the support of DIAS-TH, three to four intensive thematic schools for young scientists in modern areas of theoretical physics are organized, bringing together leading specialists from JINR Member States and other global research centers. The Laboratory promotes the development of highly qualified personnel in the fields of theoretical and mathematical physics through mentoring, joint research, and organized academic events.

It is worth noting the financial support of international collaborations on the Laboratory research topics from JINR Member States and other countries. Throughout the 21st century, programs have been established and funded for international collaboration between BLTP and scientists from Germany (the Heisenberg–Landau program), Poland (the Bogoliubov–Infeld program), the Czech Republic (the Votruba–Blokhintsev program), Romania (the Ţiţeica–Markov program), Bulgaria (the Soloviev–Hristov program), Armenia (the Smorodinsky–Ter-Antonyan program), China, Vietnam, and India, as well as from organizations such as the International Center for Theoretical Physics (ICTP, Italy), the National Institute for Nuclear Physics (INFN, Italy), and CERN. A large number of international student schools at BLTP were organized under the auspices and with the support of the Helmholtz Association of German Research Centers.

BLTP demonstrates dynamic development, adapting its research to the latest advances in physics and technology.

The Laboratory is constantly expanding its research areas, and its scientific results serve as the foundation for the development of not only JINR's experimental programs but also applied technologies. Maintaining a strong position in the educational sphere guarantees an influx of young and talented specialists, ensuring the future of the Laboratory.

The following sections list only a portion of the most important achievements of the Bogoliubov Laboratory of Theoretical Physics over the past 20–25 years in the theory of fundamental interactions and elementary particle physics, theoretical nuclear physics, condensed matter theory, and modern mathematical physics. These results demonstrate the high scientific potential of the BLTP staff, the Laboratory's involvement in the global scientific agenda, and the relevance of its research. It is impossible to cite the vast number of scientific papers published by the Laboratory's staff over these years. The references to articles cited in this book represent only a small portion of BLTP's contribution to modern global science.

THEORY OF FUNDAMENTAL INTERACTIONS

Research into fundamental interactions of fields and particles in the 21st century has included the development of the general foundations and mathematical methods of quantum field theory (QFT) and their application to important specific problems, including the description of various experiments with special attention to the NICA complex.

RENORMALIZATION GROUP AND ITS VARIOUS APPLICATIONS

The application of the renormalization group method, proposed at BLTP in the classic works of N. N. Bogoliubov and D. V. Shirkov, is the basis of all areas of QFT. In the 1980s and 1990s, interest in renormalization theory and the R-operation returned, which had been lost for some time. This was due to the rapid development of multiloop calculations in various models of quantum field theory, particularly in non-Abelian gauge theories such as quantum chromodynamics (QCD). This work is still underway, and the JINR Laboratory of Theoretical Physics has made a significant contribution to this field, achieving many record-breaking results.

Methods have been proposed and algorithms have been developed for calculating Feynman diagrams. Thus, in the 2010s, A. V. Bednyakov and A. F. Pikelner obtained three-loop renormalization group functions for all parameters of the Standard Model (SM), taking into account mixing in the quark sector[1], as well as the leading four-loop contributions to the beta function of the strong coupling constant[2]. The discovery of the Higgs boson at the LHC made it possible to use the obtained expressions to study the problem of the stability of the SM vacuum at a new level of accuracy[3].

In the early 2020s, the question arose of whether the two-loop expressions for the beta functions of the most general renormalizable theory, obtained in the mid-1980s, could be generalized to the case of three or more loops. The most general formulas for the gauge and Yukawa coupling constants in four and three loops, respectively, were obtained by combining existing literature results and direct cal-

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[1] *Bednyakov A. V., Pikelner A. F., Velizhanin V. N.* // JHEP. 2013. V. 01. P. 017; Nucl. Phys. B. 2014. V. 879. P. 256; Phys. Lett. B. 2014. V. 737. P. 129.

[2] *Bednyakov A. V., Pikelner A. F.* // Phys. Lett. B. 2016. V. 762. P. 151.

[3] *Bednyakov A. V., Kniehl B. A., Pikelner A. F., Veretin O. L.* // Phys. Rev. Lett. 2015. V. 115. P. 201802.

culations in "toy" models[4]. These formulas made it possible to perform renormalization group (RG) analysis of arbitrary New Physics models without the need for explicit diagrammatic calculations or renormalization procedures.

S. V. Mikhailov introduced the β-expansion, which represents each order of the conventional QCD perturbation theory for RG-invariant quantities as an expansion in admissible coefficients of the β-function expansion (and their products)[5]. This double expansion provides the most complete information on internal charge renormalizations; in particular, it allows detailed control over the values of the corresponding approximations when shifting the renormalization scale. D. Kotlorz and S. V. Mikhailov proposed an application for optimizing the perturbation theory series[6], leading to a decrease in the estimate of observed RG-invariant quantities to 10%.

The dependence of the effective charge of QCD on the scale is modified by accounting the interactions of the Standard Model. A. V. Bednyakov and A. F. Pikelner considered 3-loop and leading 4-loop contributions to the β function within the framework of the Standard Model [1, 2]. It was shown that the latter significantly exceed the 5-loop contributions in pure QCD at the scale of hundreds of gigaelectronvolts and above. Two-loop electroweak corrections are taken into account in a modified minimal subtraction scheme in the expressions defining the parameters of effective QCD with five quark flavors as functions of the effective charges of the Standard Model[7]. A. V. Kotikov and A. I. Onishchenko found in analytical form[8] the acceptance criteria for the effective charge of QCD at the thresholds of heavy quark production at the 4-loop level in a modified minimal subtraction scheme.

In the works of A. V. Bednyakov and A. F. Pikelner[9], 3-loop relations were found that link non-perturbative lattice calculations with key QCD parameters (effective charge and quark masses) used in calculating observables in collider experiments. A complex analytical calculation of 3-loop vertex functions in symmetric kinematics was carried out[10]. The relevance of the calculation is confirmed by the fact that the obtained result was immediately used by the HPQCD collaboration to improve the accuracy of the lattice calculation of the *c*-quark mass.

For the first time, six-loop RG functions of both dimensionless and dimensional parameters were derived for the general ϕ^4 theory, advancing RG applications in condensed matter[11]. One of the possible applications of this result is the

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[4] *Bednyakov A., Pikelner A.* // Phys. Rev. Lett. 2021. V. 127. P. 041801.

[5] *Mikhailov S. V.* // JHEP. 2007. V. 06. P. 009.

[6] *Kotlorz D., Mikhailov S. V.* // Phys. Rev. D. 2019. V. 100. P. 056007; *Bednyakov A. V.* // Phys. Lett. B. 2015. V. 741. P. 262; *Bednyakov A. V., Kniehl B. A., Pikelner A. F., Veretin O. L.* // Nucl. Phys. B. 2017. V. 916. P. 463.

[7] *Bednyakov A. V.* // Phys. Lett. B. 2015. V. 741. P. 262; *Bednyakov A. V., Kniehl B. A., Pikelner A. F., Veretin O. L.* // Nucl. Phys. B. 2017. V. 916. P. 463.

[8] *Kniehl B. A., Kotikov A. V., Onishchenko A. I., Veretin O. L.* // Phys. Rev. Lett. 2006. V. 97. P. 042001.

[9] *Bednyakov A., Pikelner A.* // Phys. Rev. D. 2020. V. 101. P. 071502; Phys. Rev. D. 2020. V. 101. P. 091501.

[10] *Pikelner A.* // JHEP. 2021. V. 06. P. 083.

[11] *Bednyakov A., Pikelner A.* // JHEP. 2021. V. 04. P. 233.

study of universality classes in the theory of critical behavior corresponding to different symmetries and different order parameters.

The works related to perturbative verification of the results obtained within the large-charge expansion stand out. The calculation of a six-loop expression[12] for anomalous dimensions of fixed-charge operators within the $O(N)$-symmetric ϕ^4, as well as three-loop calculations in scalar electrodynamics[13] and the Standard Model[14], confirmed the adequacy of using the large-charge expansion in gauge theories.

A new direction that has emerged in the last decade is D. I. Kazakov's development of renormalization theory and the renormalization group as applied to so-called non-renormalizable interactions. Such theories include gauge and supersymmetric theories in higher spatial dimensions, scalar theories with strongly nonlinear and non-polynomial interactions, four-fermion interactions, etc.

As follows from the general theory of the R-operation, after subtracting all divergent subgraphs in the lower orders of perturbation theory, the resulting ultraviolet divergences are always local in nature. This statement, known as the Bogoliubov–Parasyuk theorem, is valid in any local quantum field theory. This implies recurrence relations for counterterms in subsequent orders of perturbation theory, which lead to renormalization group equations. It is noteworthy that such generalized renormalization group equations are valid for non-renormalizable interactions and perform the same role as in renormalizable ones; i.e., they sum up infinite series of radiative corrections for the leading and subleading asymptotics. This formalism is applicable to scattering amplitudes, Green's functions, and the effective action in any local theory. The works of D. I. Kazakov, A. T. Borlakov, D. Tolkachev, and R. M. Iakhibbaev consider specific examples of the application of this formalism to scattering amplitudes in maximally supersymmetric theories in higher dimensions, which are a simplified model of quantum gravity, as well as to calculating the effective potential in non-polynomial scalar theories used in inflationary cosmology[15]. A separate unique example is the four-fermion V–A interaction in four dimensions, where it is shown that proper inclusion of radiative corrections restores unitarity and leads to an asymptotically free theory.

QUANTUM ELECTRODYNAMICS

In quantum electrodynamics (QED), the primary focus of theorists is to support experimental research conducted at existing and future facilities. This requires constructing theoretical predictions that can be tested experimentally, both to extract detailed information about known physical phenomena and to search for so-called new physics beyond the Standard Model of particle physics and general rela-

[12] *Bednyakov A., Pikelner A.* // Phys. Rev. D. 2022. V. 106. P. 7.

[13] *Antipin O., Bednyakov A., Bersini J., Panopoulos P., Pikelner A.* // Phys. Rev. Lett. 2023. V. 130. P. 021602.

[14] *Bednyakov A. V.* // Phys. Lett. B. 2024. V. 852. P. 138615.

[15] *Kazakov D., Borlakov A., Tolkachev D., Iakhibbaev R. et al.* // JHEP. 2015. V. 11. P. 059; JHEP. 2016. V. 12. P. 154; JHEP. 2023. V. 04. P. 128; JCAP 09. 2023. V. 049; Eur. Phys. J. 2025. V. 85. P. 1000.

tivity. The constant advancement of experimental techniques and methods requires a corresponding increase in the accuracy of theoretical predictions, which in turn requires taking into account various effects in perturbative and non-perturbative calculations. The resulting theoretical predictions must be made with reference to experimental conditions and implemented in computer programs that can be directly used in simulations and analysis of experimental data.

Since the early 2000s, BLTP staff, together with colleagues from other laboratories and research centers, have made significant contributions to the development of methods for calculating electromagnetic and electroweak radiative corrections. They applied these methods to obtain highly accurate theoretical predictions of the phenomena observed in the interactions of elementary particles studied in modern experiments. In particular, E. A. Kuraev with his students (A. B. Arbuzov, Yu. M. Bystritskiy, V. V. Bytev) and colleagues developed and applied the method of structure functions in quantum electrodynamics (QED). This method allows for effective consideration of the radiative corrections of higher orders of perturbation theory, amplified by large logarithms of the ratio of the characteristic scale of the process energy to the electron mass. It was shown that the application of this method helps in solving the problem of interpreting data from various experiments measuring the ratio of the electric and magnetic form factors of the proton[16]. Radiative corrections were also calculated for the radiative decay of a charged pion, which at that time attracted great interest due to the possible detection of a tensor contribution to the decay amplitude[17].

The structure function method served as the basis for the Monte Carlo event generator MCGPJ, developed jointly with colleagues from INP SB RAS[18]. The use of this generator at the VEPP-2M and VEPP-2000 electron–positron colliders was important for improving the accuracy of experimental data analysis. E. A. Kuraev and A. B. Arbuzov made a significant contribution to the success of the international group of Radio Monte Carlo theorists in an effort to improve the accuracy of theoretical predictions for processes studied at electron–positron colliders[19].

An example of another successful application of the QED structure function method is the calculation of the most important higher-order radiative corrections to the decay spectrum of a polarized muon[20]. The use of this method also proved important for resolving the mystery of the proton charge radius when measuring it in elastic electron–proton scattering[21]. Combining methods for taking into account strong and QED interactions allowed A. E. Dorokhov and M. A. Ivanov to make significant progress in the accuracy of the theoretical description of the decay of neutral pions and η mesons into an electron–positron pair[22].

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[17] *Kuraev E. A., Bystritsky Yu. M., Velicheva E. P.* // Phys. Rev. D. 2004. V. 69. P. 114004.

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[22] *Dorokhov A. E., Kuraev E. A., Bystritskiy Yu. M., Secansky M.* // Eur. Phys. J. C. 2008. V. 55. P. 193.

A. B. Arbuzov and S. G. Bondarenko actively participated in the work of the group led by D. Yu. Bardin and L. V. Kalinovskaya from DLNP JINR on the calculations of electroweak radiative corrections to the processes studied at modern and future high-energy colliders, including LEP, HERA, LHC, FCC-ee, CEPC, etc. This group developed the SANC computer system[23], with the use of which Monte Carlo integrators and event generators[24], relevant for applications in experimental high-energy physics[25], were implemented.

Yu. M. Bystritskiy and V. A. Zykunov carried out extensive work on taking into account electromagnetic and electroweak corrections of higher orders for the basic processes of Möller[26] and Bhabha scattering[27], which were carried out jointly with a group of theorists from Canada and serve as an important tool for the precision measurement of the parameters of the Standard Model, as well as for the calibration and testing of accelerator complexes around the world.

Another area of QED application actively developing at BLTP is the precision spectroscopy of light atoms and molecules. Modern methods of sympathetic cooling of atoms, molecules, and ions in traps, as well as quantum logic and quantum information methods, create unique opportunities for ultra-precise measurements of their spectra (with a relative accuracy of 10^{-12} and higher). From a theoretical perspective, the most suitable platform for such precise spectral calculations is nonrelativistic quantum electrodynamics (NRQED). BLTP staff members V. I. Korobov, D. Aznabaev, and A. Bekbaev performed the most accurate calculations[28] of vibrational transitions for molecular hydrogen ions H_2^+ and HD^+. Comparison with the experiment allowed refining the values of fundamental physical constants, such as the Rydberg constant, the proton-to-electron mass ratio, the proton charge radius, etc. The results obtained from precision spectroscopy of the HD^+ ion[29] were taken into account in the corrections of the fundamental constants by the CODATA group, which made it possible to improve the accuracy of determining the proton-to-electron mass ratio several times. Precision spectroscopy allows measuring the masses of negatively charged pions, kaons, and antiprotons with

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Patra S., Germann M., Karr J.-Ph., Haidar M., Hilico L., Korobov V. I., Cozijn F. M. J., Eikema K. S. E., Ubachs W., Koelemeij J. C. J. // Science. 2020. V. 369. P. 1238.

high accuracy[30], and obtaining constraints on the possible manifestations of new interactions and on the hypothetical "fifth force"[31].

NEUTRINO PHYSICS

During the first quarter of the 21st century BLTP conducted diverse research in the field of neutrino physics and its astrophysical and cosmological applications. The main directions included the development of quantum-mechanical and quantum-field theories of neutrino oscillations in vacuum, matter and external fields[32, 33, 34, 35] and the phenomenology of neutrino interactions with nucleons and nuclei (including polarization effects) at energies from intermediate to ultra-high[36, 37,]. Numerous works were related to the development of mechanisms for generating neutrino masses, the study of the effects of the possible presence of non-standard particles and interactions, as well as deep theoretical studies of low-energy nuclear-physical processes in one way or another related to neutrino physics and the theory of electroweak interactions, such as nuclear beta decay, double two-neutrino ($2\nu\beta\beta$) and neutrinoless ($0\nu\beta\beta$) beta decays, electron capture[38] .

In the covariant quantum field theory of neutrino oscillations[32], developed by V. A. Naumov together with D. V. Naumov (DLNP) and D. S. Shkirmanov, the technique of so-called macroscopic Feynman diagrams is used, the outer lines of which are wave packets — localized covariant superpositions of Fock states with certain momenta, and the vertices are connected by a neutrino propagator. The phenomenon of "flavor oscillations" in this concept results from the interference of macroscopic diagrams with neutrinos of different masses in intermediate states. A so-called factorization theorem has been proven, which allowed separating the calculations of the amplitudes of processes at macroscopically distant vertices of the diagram ("source" and "detector") from the calculation of the "flavor evolution" process. The duality in the behavior of a "dressed" (i.e., modified by external wave packets) neutrino propagator and the effective neutrino wave packet has been studied. The theory resolves all known paradoxes of the standard quantum-mechanical theory of neutrino oscillations and predicts numerous effects absent in the quantum-mechanical approach. These are primarily decoherence and dispersion effects associated with the spreading and spatial divergence of the effective neutrino wave

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Šimkovic F., Krivoruchenko M. I., Kovalenko S. // Phys. Part. Nucl. 2017. V. 48. P. 1023.

packets. In particular, it has been shown that "flavor oscillations" disappear at large distances between the "source" and the "detector". One of the most impressive predictions of the theory is the violation of the classical inverse-square law at small (but macroscopic) distances between the source and the detector[33]. This prediction was verified using a detailed statistical analysis of data from reactor experiments with short and long baselines, as well as data from Ga–Ge solar neutrino detectors (GALLEX and SAGE) with artificial radioactive sources. It has been shown that the measured event count rates in reactor experiments do not contradict the prediction of the theory, although the data are still insufficient for a reliable test of the effect. Experiments with stopped kaons have been proposed, which may allow studying the possible violation of the inverse-square law at ultra-short distances.

The studies related to the implementation and optimization of modern models of neutrino–matter interactions in the Monte Carlo neutrino generator GENIE, the most popular software product today, combining theory and experiment in neutrino physics and underlying the processing and interpretation of data from virtually all modern experiments with accelerator, atmospheric and astrophysical neutrinos, can be mentioned as an example of the development of the theory and phenomenology of neutrino–matter interactions[36, 37]. In particular, the so-called KLN model was developed at BLTP, which is a generalization of the well-known Rein-Seghal model based on the relativistic quark $SU(6)$ Feynman–Kissinger–Ravndal model. The KLN model is implemented in GENIE and is intended for calculating the processes of resonant production of single pions in neutrino–nucleon interactions. The model operates with 18 families of nucleon and baryon resonances and interfering nonresonance contributions. The KLN generalization involves taking into account the final lepton mass and its polarization, which allows the model to be used to study reactions involving τ-lepton production and to calculate the latter's polarization vector. The GENIE project also studied in detail recent improvements to the KLN model, which allow for the calculation of angular and momentum distributions of secondary pions, i.e., the computation of 5-dimensional differential cross sections. All this is necessary for modeling and processing data from current and future neutrino experiments (Hyper-Kamiokande, DUNE, JUNO, IceCube/DeepCore/PINGU, KM3NeT/ORCA/P2O) with accelerator, atmospheric, and astrophysical neutrinos. Work is underway to fine-tune the parameters of meson neutrinoproduction models, modify and modernize nucleon transition form factors, etc. The problem of correctly combining the modeling of single-pion neutrinoproduction with other processes (quasielastic, diffraction, deep-inelastic scattering, etc.) is being addressed, taking into account intranuclear cascades, polarization effects, and final-state hadron interactions.

In the works of V. A. Matveev and his co-authors, various rare processes beyond the Standard Model were considered. In the work of S. N. Gninenko, N. V. Krasnikov, and V. A. Matveev[39], the invisible decay of muonium into two neutrinos was studied, which in the SM has a branching ratio Br $(M \to \nu_e \bar{\nu}_\mu) = 6.6 \cdot 10^{-12}$. Using the reported experimental results of precision measurements of the muon lifetime carried out by the MuLan Collaboration, it was established that the upper limit

[39] *Gninenko S. N., Krasnikov N. V., Matveev V. A.* // Phys. Rev. D. 2013. V. 87. 015016.

on the branching ratio Br ($M \to$ invisible) $< 5.7 \cdot 10^{-6}$, which leaves a large gap of approximately six orders of magnitude between this limit and the predictions. In order to improve substantially this limit, an experiment was proposed dedicated to the sensitive search for this invisible decay. The feasibility study of the experimental setup shows that the sensitivity of the search for this decay mode in branching fraction Br ($M \to$ invisible) at the level of 10^{-12} could be achieved.

The $K_{S,L} \to$ invisible decays, which have never been investigated experimentally, were studied[40]. In the Standard Model, their branching ratios for the decay into two neutrinos were predicted to be extremely small, Br ($K_{S,L} \to \nu\bar{\nu}$) $\approx 10^{-16}$. Several natural extensions of the SM were considered such as two-Higgs-doublet (2HDM), 2HDM and light scalar, and dark mirror sector models, which allow one to enhance the Br ($K_{S,L} \to$ invisible) up to a measurable level. The possible search for $K_{S,L} \to$ invisible decays and $K_{S,L}$ oscillations into the dark sector at the NA64 experiment at CERN with the sensitivity to Br ($K_{S,L} \to$ invisible) $\lesssim 10^{-7}$–10^{-5} was discussed.

A large amount of research is based on the use of atomic nuclei as a laboratory for studying the electroweak interaction and the fundamental properties of neutrinos. This activity unites the fields of atomic and nuclear physics, particle physics (including physics beyond the Standard Model, related to the Grand Unification problem), astrophysics, and cosmology. One of the most important processes linking all of these areas is the neutrinoless double beta decay of nuclei ($0\nu\beta\beta$), which has not yet been observed but is of great interest to the scientific community[41] as a kind of litmus test – an indicator of the possible Majorana nature of neutrinos.



V. A. Matveev, N. V. Krasnikov, D. I. Kazakov, K. G. Chetyrkin (INP RAS), and A. F. Vladimirov

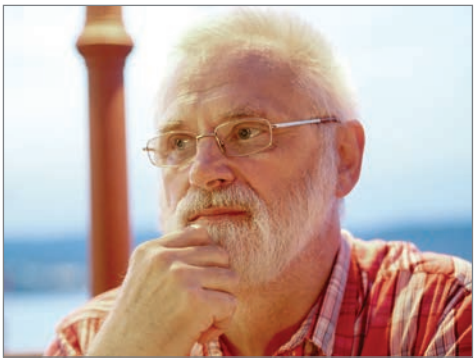
[40] *Gninenko S. N., Krasnikov N. V., Matveev V. A.* // Natural. Sci. Rev. 2024. 1. 5.
[41] *Vergados J. D., Ejiri H., Simkovic F.* // Rep. Prog. Phys. 2012. V. 75. P. 106301.



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Participants of the 2nd International Workshop "Theory of Hadronic Matter under Extreme Conditions". BLTP JINR, September 16–19, 2019



V. I. Korobov



S. G. Bondarenko and A. V. Gladyshev



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S. V. Mikhailov, G. P. Korchemsky, A. P. Bakulev, A. V. Efremov, and A. V. Radyushkin



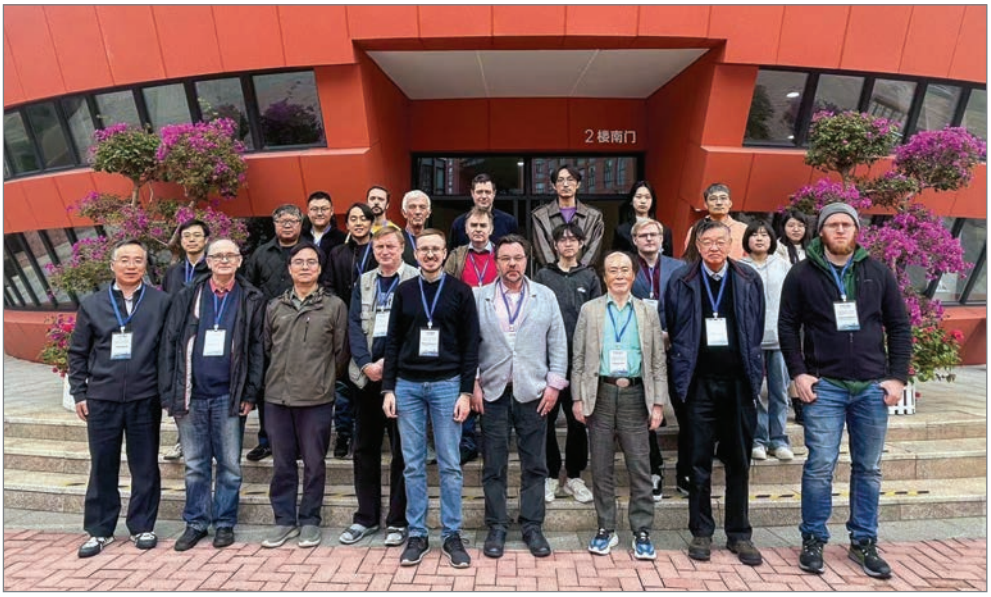
M. A. Ivanov, G. V. Efimov, G. Ganbold, and S. N. Nedelko



F. Šimkovic, I. D. Kakorin, V. A. Naumov, D. V. Naumov, S. M. Bilenky, and A. G. Olshevsky



Participants of the seminar in memory of E. A. Kuraev



BLTP researchers O. V. Teryaev, N. I. Volchansky, A. V. Kotikov, I. V. Anikin, N. S. Tsegelnik, and G. Yu. Prokhorov at the 2nd International Workshop on QCD and Hadron Structure

F. Šimkovic and his colleagues have obtained many important results in a comprehensive study of this process. In particular, detailed self-consistent calculations of the nuclear matrix elements of $0\nu\beta\beta$ decays of ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, and ^{130}Xe were performed within both the standard quasiparticle random phase approximation (QRPA) and the renormalized QRPA (RQRPA). Pairwise and residual nucleon interactions, as well as two-nucleon short-range correlations, were derived for the first time from realistic nucleon–nucleon potentials, namely, the charge-dependent Bonn potential and the Argonne potential. The sensitivity of the matrix elements to the dynamics of short-range and high-momentum particles in the nucleus was studied[42, 43].

In addition to purely theoretical research, BLTP staff participated in cutting-edge neutrino experiments, such as NEMO3/SuperNEMO, Baikal-GVD, JUNO, and NOvA. They made significant contributions to the formation of physics programs and the development of software for processing and interpreting experimental data.

QUANTUM CHROMODYNAMICS

Quantum chromodynamics, a traditional field for BLTP, was actively developing at the Laboratory in the 21st century. QCD has been a part of the Laboratory's work since its formation, and its origin was inseparably associated with the work of A. V. Efremov, A. V. Radyushkin, and their students and colleagues. Research was conducted both within the field of QCD perturbation theory and beyond it.

The fractal analytical perturbation theory ((F)APT) of QCD has been greatly developed. The analytical perturbation theory proposed by D. V. Shirkov and I. L. Solovtsov[44] is based on the synthesis of analyticity and the renormalization group for a running charge. The approach leads to a non-power PT with new charges for momentum regions that do not have Landau singularities, are small, and are defined up to $q^2 \sim 0$. In development of the APT, A. P. Bakulev and S. V. Mikhailov proposed FAPT[45], where the results of the APT were extended to any, including complex, powers of the effective charge. FAPT extends the analyticity condition to the results of the renormalization group summation, leading to fractal powers of the charge, which is very important for calculating hard processes within the QCD factorization.

Within QCD APT, D. V. Shirkov, O. V. Teryaev, R. S. Pasechnik, and O. P. Solovtsova analyzed experimental data on spin nucleon sum rules[46], and the

[42] *Šimkovic F., Faessler A., Muther H., Rodin V., Stauf M.* // Phys. Rev. C. 2009. V. 79. P. 055501.

[43] *Šimkovic F., Rodin V., Faessler A., Vogel P.* // Phys. Rev. C. 2013. V. 87. P. 045501.

[44] *Shirkov D. V., Solovtsov I. L.* // Phys. Rev. Lett. 1997. V. 79. P. 1209; Theor. Math. Phys. 2007. V. 150. P. 132.

[45] *Bakulev A. P., Mikhailov S. V., Stefanis N. G.* // Phys. Rev. D. 2005. V. 72. P. 074014; Phys. Rev. D. 2007. V. 75. P. 056005; JHEP. 2010. V. 06. P. 085.

[46] *Pasechnik R. S., Shirkov D. V., Teryaev O. V.* // Phys. Rev. D. 2008. V. 78. P. 071902;

Pasechnik R. S., Shirkov D. V., Teryaev O. V., Solovtsova O. P., Khandramai V. L. // Phys. Rev. D. 2010. V. 81. P. 016010.

Bjorken sum rule[47] was investigated in the region of small momentum transfers up to the 4-loop contribution of conventional PT and QCD APT. It was shown that APT shifts the applicability limit of QCD to very low momentum transfers of approximately 300 MeV (and even to $q^2 = 0$ after some modification of the operator development[48]), which provided more accurate information on the non-perturbative contributions of high twists.

An analysis of experimental data within QCD APT was performed by A. V. Kotikov, O. P. Solovtsova, and A. S. Sidorov for non-singlet structure functions[49, 50]: the QCD scale values were extracted, and the dependence of the higher twist contributions and the corresponding parton distributions on the parton momentum fraction was found. A similar analysis within the standard QCD was performed by A. V. Kotikov[51]. Parameterizations of parton distributions were constructed based on their asymptotics for large and small values of the parton momentum fractions[52].

QUANTUM CHROMODYNAMICS SUM RULES

In the field of QCD applications, the study of exclusive processes at large/medium momentum transfers is noteworthy. Among them, the transition (electromagnetic) form factors of light mesons — pions and η mesons — are distinguished by the high measurement accuracy and interest of the community. Their calculations, following the QCD factorization and light-cone sum rules, include the coefficient function of perturbation theory and nonperturbatively described amplitudes of the hadron distribution. Both of these components were obtained, the results of the early CLEO experiments (1998) were explained, and the contradiction between the data of the BaBar (2008) and Belle (2012) collaborations was resolved in the works of A. P. Bakulev, S. V. Mikhailov and A. V. Pimikov[53]. Technical advances in the study of QCD corrections to the two-point correlator of two composite operators[54] are related to this problem. A justified application of the FAPT to the calculation of

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[47] *Khandramai V. L., Pasechnik R. S., Shirkov D. V., Solovtsova O. P., Teryaev O. V.* // Phys. Lett. B. 2012. V. 706. P. 340;
Ayala C., Cvetic G., Kotikov A. V., Shaikhatdenov B. G. // Int. J. Mod. Phys. A. 2018. V. 33. P. 1850112; Eur. Phys. J. C. 2018. V. 78. P. 1002.

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[49] *Sidorov A. V., Solovtsova O. P.* // Mod. Phys. Lett. A. 2014. V. 29. P. 1450194.

[50] *Kotikov A. V., Krivokhizhin V. G., Shaikhatdenov B. G.* // Phys. Atom. Nucl. 2012. V. 75. P. 507.

[51] *Shaikhatdenov B. G., Kotikov A. V., Krivokhizhin V. G., Parente G.* // Phys. Rev. D. 2010. V. 81. P. 034008;
Kotikov A. V., Krivokhizhin V. G., Shaikhatdenov B. G. // J. Phys. G. 2015. V. 42. P. 095004.

[52] *Illarionov A. Yu., Kotikov A. V., Parzycki S. S., Peshekhonov D. V.* // Phys. Rev. D. 2011. V. 83. P. 034014; *Kotikov A. V., Lipatov A. V.* // Phys. Rev. D. 2025. V. 111. P. 094009.

[53] *Bakulev A. P., Mikhailov S. V., Stefanis N. G.* // Phys. Lett. B. 2004. V. 578. P. 91; *Mikhailov S. V., Stefanis N. G.* // Nucl. Phys. B. 2009. V. 821. P. 291;
Mikhailov S. V., Pimikov A. V., Stefanis N. G. // Phys. Rev. D. 2016. V. 93. P. 114018.

[54] *Mikhailov S. V., Volchanskiy N.* // JHEP. 2019. V. 01. P. 202; JHEP. 2020. V. 21. P. 197; Phys. Rev. D. 2023. V. 108. P. 096015.

the perturbative part of pion form factors[55] advanced the QCD predictions of pion form factors to low transfers $q^2 \sim 0.5$ GeV^2 in good agreement with experimental data. Using similar light-cone sum rules, I. V. Anikin also calculated the electromagnetic form factors of nucleons and isobars[56] taking into account twists 3 and 4.

ANOMALIES IN THE PHYSICS OF HADRONS AND HEAVY IONS

Another approach to transition form factors, combining perturbation theory and going beyond it, is related to the axial anomaly, a fundamental property of quantum field theory. Generalizing this concept to the case of virtual photons allowed A. G. Oganesian, Ya. Klopot, and O. V. Teryaev to obtain exact sum rules, which, along with the use of quark-hadron duality, led to the description of the form factors of pseudoscalar mesons in various kinematic regions[57]. It was shown that the anomaly-based approach is complementary (dual) to the use of light-cone sum rules[58].

Anomalies play a significant role in a wide range of issues in hadron physics. The gluon $U(1)_A$ anomaly leads to non-conservation of the $U(1)_A$ charge, resulting in a theory that contains neither a conserved $U(1)^A$ quantum number nor an additional Goldstone boson. It is also responsible for suppressing isospin violation effects in the spectrum of pseudo-Goldstone states. The Wess–Zumino effective Lagrangian summarizes the effects of the chiral $SU(3)_L \times SU(3)_R$ anomaly in the current algebra and ultimately binds the $\pi 0 \to \gamma\gamma$ decay amplitude to other amplitudes such as $\gamma \to 3\pi$, $\gamma\gamma \to 3\pi$, and also gives rise to vertices describing strong interactions with an odd number of pseudoscalars, which are absent in the chiral-symmetric theory. Thus, anomalies impose strict constraints on the amplitudes of the associated processes, and therefore the results of such calculations are highly accurate. This is a consequence of the Adler–Bardeen theorem, which states that the chiral anomaly does not change when higher-order corrections are taken into account. Despite the clarity achieved in fundamental matters, equally important questions remain concerning the various manifestations of anomalies in processes where they are only part of a more complex dynamics associated with the accounting of strong interactions. For example, questions regarding the magnitude of the contribution of anomalous vertices to amplitudes containing hadronic resonance states of spin 1 require detailed study. It is possible to include resonances in the effective Lagrangian, but in this case, it does not lead to constraints on the strong interaction constants, significantly reducing the predictive power of such calculations.

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[55] *Ayala C., Mikhailov S. V., Stefanis N. G.* // Phys. Rev. D. 2018. V. 98. P. 096017; *Ayala C., Mikhailov S. V., Pimikov A. V., Stefanis N. G.* // EPJ Web Conf. 2019. V. 222. P. 03017; *Mikhailov S. V., Pimikov A. V., Stefanis N. G.* // Phys. Rev. D. 2021. V. 103. P. 096003.

[56] *Anikin I. V., Braun V. M., Offen N.* // Phys. Rev. D. 2013. V. 88. P. 114021; 2015. V. 92. P. 014018; 2016. V. 94. P. 034011.

[57] *Klopot Y. N., Oganesian A. G., Teryaev O. V.* // Phys. Lett. B. 2011. V. 695. P. 130; Phys. Rev. D. 2011. V. 84. P. 051901; *Khlebtsov S., Klopot Y. N., Oganesian A. G., Teryaev O. V.* // Phys. Rev. D. 2019. V. 99. P. 016008; 2021. V. 104. P. 016011.

[58] *Oganesian A. G., Pimikov A. V., Stefanis N. G., Teryaev O. V.* // Phys. Rev. D. 2016. V. 93. P. 054040.

M. K. Volkov, A. A. Osipov, and A. A. Pivovarov[59] showed that the amplitude of the radiative decay of the axial-vector resonant state $f_1(1285) \to \rho^0\gamma$ is non-trivially related to the non-Abelian axial anomaly. The non-triviality lies in the fact that the surface terms of the quark triangular diagram describing this process, by virtue of the vector Ward identity and Bose statistics, lead to a complete cancellation of the linear dependence on external momenta. As a result, the expansion of the amplitude begins with a cubic term in momenta, and the corresponding coupling constant within the Nambu–Jona-Lasinio model is expressed in terms of the decay constant $\rho \to 2\pi$ and the quark masses. The part of the amplitude under consideration is consistent with QCD calculations of the triangular quark diagram performed in the perturbative region. This agreement (by virtue of the Adler–Bardeen theorem) indicates a deep connection between the obtained result and fundamental ideas about the nature of the anomaly and, in turn, sheds light on the details of its manifestation at the level of non-perturbative dynamics of hadronic states.

A more complex manifestation of the Adler–Bardeen anomaly was studied[60]. It was shown that the theoretical description of the $f_1(1285) \to \pi^+\pi^-\gamma$ decay includes three types of anomalous vertices: triangular AVV, AAA, and quadrangular $AAAV$. The main conclusion is the dominance of the ρ-resonance in the process amplitude, while the quadrangular anomaly is important due to its positive interference with the ρ-exchange channel. This is, in fact, the first theoretical study of this process in which the AVV anomaly is used in the analysis. Since experimental data for this decay are absent, the width of the $f_1(1285) \to \rho^0\pi^-\gamma$ decay was calculated, the amplitude of which is related to the amplitude of $f_1(1285) \to \pi^+\pi^-\gamma$ through the hypothesis of vector dominance[61]. The obtained agreement with experimental data is a significant and nontrivial argument in favor of the quark–antiquark nature of the $f_1(1285)$ meson, due to which the anomaly begins to play a major role in the chiral dynamics of this state.

The problem of taking into account $\pi - a_1$ mixing, important for describing the physics of axial-vector mesons (in the presence of a non-Abelian anomaly), was studied by A. A. Osipov and colleagues[62,63,64,65,66]. It is well known that a naive accounting for $\pi - a_1$ mixing effects in the presence of electromagnetic interactions leads to a violation of low-energy theorems following from the anomalous Ward identities. The covariant diagonalization procedure developed by the authors eliminates the problem, but leads to a deviation from the vector dominance hypothesis. Another important result is related to the study of the mechanism of isospin symmetry restoration by the gluon anomaly in the spectrum of pseudoscalar states. A mechanism was considered[67] by which the $U(1)$ anomaly at the second step of

[59] *Osipov A. A., Pivovarov A. A., Volkov M. K.* // Phys. Rev. D. 2017. V. 96. P. 054012.
[60] *Osipov A. A., Volkov M. K.* // Phys. Rev. D. 2018. V. 97. P. 074020.
[61] *Osipov A. A., Pivovarov A. A., Volkov M. K.* // Phys. Rev. D. 2018. V. 98. P. 014037.
[62] *Morais J., Hiller B., Osipov A. A.* // Phys. Lett. B. 2017. V. 773. P. 277.
[63] *Osipov A. A., Khalifa M. M.* // Phys. Rev. D. 2018. V. 98. P. 036023.
[64] *Osipov A. A., Hiller B., Zhang P. M.* // Phys. Rev. D. 2018. V. 98. P. 113007.
[65] *Osipov A. A., Khalifa M. M., Hiller B.* // Phys. Rev. D. 2020. V. 101. P. 034012.
[66] *Osipov A. A., Pivovarov A. A., Volkov M. K., Khalifa M. M.* // Phys. Rev. D. 2020. V. 101. P. 094031.
[67] *Osipov A. A.* // JETP Lett. 2023. V. 117, No. 12. P. 898–904.

the $1/N_c$ expansion induces effective vertices that violate the Zweig rules. They appear only when there is a clear violation of isospin and $SU(3)$ symmetries by the masses of light quarks and suppress the effect caused by the breaking of these symmetries in the leading order.

The axial anomaly also manifests itself in the effective hydrodynamic theory of quark–gluon plasma (QGP)[68], which made it possible, in particular, to predict a decrease in the global polarization of hyperons with energy[69] and to estimate its value at the energies of the NICA complex several years before the experimental confirmation of these results in the STAR experiment[70]. The method used became a natural generalization of the so-called anomalous gluon contribution[71], first discovered at BLTP by A. V. Efremov and O. V. Teryaev, in which the role of the gluon field is played by the four-dimensional velocity of the dense quark–gluon medium. Subsequently, V. I. Zakharov, G. Yu. Prokhorov, and O. V. Teryaev discovered manifestations of a gravitational anomaly in QGP[72] and an analogue of the Unruh effect[73], which can lead to additional hadronization mechanisms. New objects of study in QCD — gravitational form factors of the energy-momentum tensor — are also related to the gravitational anomaly. One of these, associated with the generalization of the concept of pressure for elementary particles, can be extracted from data on deep inelastic Compton scattering at JLab using holographic sum rules for generalized parton distributions obtained at BLTP by O. V. Teryaev[74]. These form factors connect QCD with gravitational interactions of particles and generalizations of the equivalence principle[75], and can be extracted from experimental data and models of generalized parton distributions. I. V. Anikin performed similar calculations within the framework of light-cone sum rules[76].

EFFECTIVE THEORIES FOR HEAVY AND LIGHT QUARKS

The Laboratory developed non-renormalizable field theories based on the nonlocal nature of interactions. Various models of nonlocal field theory, developed in the groups of G. V. Efimov and M. K. Volkov, are still very popular among theorists, as they allow for numerical calculations in the strong coupling regime, a problem that remains unsolved. These calculations are in demand by various international experimental collaborations. In particular, studies of heavy quark physics were also carried out using non-perturbative approaches, as well as the nonlocal quark model proposed and developed at BLTP. Interest in heavy quark physics, i.e., the physics of *b* (bottom) and *c* (charm) quarks, arose in the 1990s and has experienced rapid

[68] *Sadofyev A. V., Shevchenko V. I., Zakharov V. I.* // Phys. Rev. D. 2011. V. 83. P. 105025.
[69] *Rogachevsky O., Sorin A., Teryaev O.* // Phys. Rev. C. 2010. V. 82. P. 054910.
[70] *Baznat M., Gudima K., Teryaev O.* // Phys. Rev. C. 2013. V. 88. P. 061901.
[71] *Efremov A. V., Teryaev O. V.* JINR Preprint E2-88-287. Dubna, 1988.
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[75] *Teryaev O. V.* // Front. Phys. Beijing. 2016. V. 11. P. 111207.
[76] *Anikin I. V.* // Phys. Rev. D. 2019. V. 99. P. 094026.

development at many global research centers, including BLTP. The main impetus was the observation that a new spin-flavor symmetry emerges in the limit of large quark masses, giving rise to relations that significantly reduce the number of independent physical observables. For example, in the semileptonic weak decays of heavy mesons via the b–c transition, all form factors are expressed in terms of a single function, called the Isgur–Weiss function. The large quark mass limit, performed in the QCD Lagrangian, leads to a theory called the effective heavy quark theory, whose Lagrangian is independent of quark masses, but only dependent on their four velocities.

A significant number of studies of exclusive decays of heavy hadrons, both mesons and baryons, have been carried out at the Laboratory within the various quark models satisfying all the requirements of the effective theory of heavy quarks. The studies into the weak decays of the B_c meson, consisting of two heavy b and c quarks with different flavors, are particularly noteworthy. These studies have found a fairly good response and citation rate. In addition, calculations of the dipole polarizability of light pseudoscalar mesons have been carried out within the mean-field approach to the QCD vacuum model and QCD bosonization. These calculations are based on a statistical ensemble of almost everywhere homogeneous Abelian (anti) self-dual gluons in the domain model. In this approach, a nonlocal effective action of meson fields has been derived, describing all possible strong, weak and electromagnetic interactions of meson fields, including their excited states[77].

Calculations of the branching ratios of the axial-vector decays of mesons $f_1 \to a_0\pi$, $\pi\pi\eta$, $f_1 \to \rho\pi$, $\pi\pi\pi$ and $f_1 \to KK\pi$ in the standard Nambu–Jona-Lasinio quark model $U(3) \times U(3)$ have received deserved attention from experimenters. In this case, intermediate channels with the states $a_0(980)\pi$ and $f_0(500)\eta$ are taken into account in the $f_1 \to \pi\pi\eta$ decay. It has been shown that the decays $f_1 \to \rho\pi$ and $f_1 \to 3\pi$ arise due to the difference in the masses of the u and d quarks. All results were obtained without using any additional arbitrary parameters and are in satisfactory agreement with known experimental data[78].

Regular international conferences on heavy quark physics were organized in Dubna (1993, 1996, 2000, 2003), Bad Honnef (Germany, 1994), and Rostock (Germany, 1997). These conferences were later transformed into international schools on heavy quark physics (Dubna, 2008, 2013, 2016, and 2019).

Effective theories also allow studying light quark masses, which are fundamental parameters of quantum chromodynamics, reflect the laws of weak and electromagnetic gauge symmetry breaking, and, furthermore, contain information about the structure of flavors in physics beyond the Standard Model. Therefore, it is important to know these parameters for both phenomenological and theoretical applications. Quarks are bound within hadrons, which makes it impossible to directly measure the mass of an isolated quark. Nature has assigned a special role to the light u, d, and s quarks, whose masses determine the degree of explicit violation of $SU(3)_L \to SU(3)_R$ chiral symmetry in quantum chromodynamics. Since the masses of light quarks are small compared to characteristic hadronic scales, their

[77] *Nedelko S., Voronin V.* // Phys. Rev. D. 2023. V. 107. P. 094027.
[78] *Volkov M. K., Pivovarov A. A., Nurlan K.* // Natural Sci. Rev. 2025. V. 2. P. 100403.

influence on hadronic observables is negligible. The flavor independence of strong interactions further complicates the experimental study of quark masses. Determining the masses of light quarks at a fundamental level is a challenge facing quantum field theory. The difficulty lies in the fact that its application to calculation of hadronic observables requires non-perturbative methods. One such tool is lattice calculations. Currently, the most reliable results on the masses of light quarks have been obtained using this method.

The quark mass problem was studied by A. A. Osipov within the $1/N_c$-chiral perturbation theory[79]. The starting point of the study was the formulas for the squares of the pseudoscalar meson masses obtained in the NLO approximation. It is known that in this approximation the ratios m_u/m_d and m_s/m_d are interrelated and belong to an ellipse. An alternative approach was proposed, which also leads to a functional dependence between m_u/m_d and m_s/m_d, but the result is not an ellipse, but an algebraic curve of the third order. It was shown that, unlike an ellipse, this curve has a number of remarkable properties. It is universal; i.e., its shape is uniquely determined by the requirement that the mass formulas (after taking into account electromagnetic corrections) correspond to the phenomenological values of the meson masses at each point of the curve. It is stable; i.e., taking into account higher corrections does not affect its shape. Furthermore, the position on the curve is controlled by a renormalization group invariant: the product of the quark mass and the quark condensate mass, which allows, given the known value of the condensate, for determining the absolute values of the quark masses. These properties allow the cubic to be used for joint analysis with lattice calculations[80]. As a result, the obtained estimates for both the quark mass ratios and their absolute values have an accuracy comparable to that of lattice calculations and are generally consistent with the data presented by PDG (2024) and FLAG (2022).

PARTON DISTRIBUTIONS IN EXCLUSIVE AND INCLUSIVE PROCESSES

In the 21st century, the application of QCD factorization was marked by a significant expansion of the types of its non-perturbative ingredients — parton distributions, among which the above-mentioned generalized parton distributions, as well as those dependent on the transverse momentum (TMD), should be particularly noted. In the field of studying generalized parton distributions, O. V. Teryaev substantiated the application of the standard Radon transform method[81], which served as a justification for holographic sum rules, verified, in particular, for photon generalized parton distributions. S. V. Goloskokov proposed and developed a theoretical description of the exclusive hard electroproduction of mesons using generalized parton distributions, which made it possible to describe a wide range of experimental data[82].

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[79] *Osipov A. A.* // JETP Lett. 2024. V. 119. P. 897.
[80] *Osipov A. A.* // Phys. Rev. D. 2024. V. 110. P. 014044.
[81] *Teryaev O. V.* // Phys. Lett. B. 2001. V. 510. P. 125.
[82] *Goloskokov S. V.*, *Kroll P.* // Eur. Phys. J. C. 2008. V. 53. P. 367.

The Laboratory conducted studies of inclusive processes at large/medium momentum transfers. D. Kotlorz and S. V. Mikhailov developed and applied to the data analysis an approach to GLAPD evolution that explicitly takes into account the inevitable experimental constraints on the Bjorken variable fractions. From the convolution property of parton distributions, A. V. Kotikov obtained neutrino-nucleon scattering cross sections at ultrahigh energies[83], as well as a modification of parton distributions in nuclei[84], and non-perturbative ingredients of semi-inclusive processes — fragmentation functions in the region of small fractions of hadron momentum and the associated average parton multiplicities in jets[85].

A detailed study of various k_t-dependent parton functions and approximations for them was carried out under the supervision of A. V. Efremov[86]. The analysis of such distributions is based on the work carried out at the Laboratory of Theoretical Physics on higher-twist contributions[87], which laid the recognized foundations for the subsequent application of QCD to spin effects. In a similar manner, I. V. Anikin and O. V. Teryaev analyzed higher-twist contributions in exclusive processes[88]. These issues, along with other problems of spin physics in QCD, were discussed at regular International Dubna Seminars on High-Energy Spin Physics, held in odd years.

HADRONIC MATTER UNDER EXTREME CONDITIONS

The study of critical phenomena in hadronic matter under extreme baryon density, temperature, electromagnetic field strength, relativistic rotation, and acceleration has been a key area of experimental and theoretical research in relativistic nuclear physics and elementary particle physics. Due to the particular complexity of the subject matter, the theory of hadronic matter requires the integrated use of a wide range of theoretical physics methods, from numerical calculations within the lattice QCD to phenomenological statistical and thermodynamic models. Such methods have been developed over several decades at BLTP. In recent years, in conjunction with the active development of the physics program for the JINR flagship experimental project, the NICA accelerator complex, BLTP's expertise in this area has been consolidated into a single project, "Theory of hadronic matter under extreme conditions". This has created favorable conditions for obtaining a number

[83] *Fiore R., Jenkovszky Laszlo L., Kotikov A. V., Paccanoni F., Papa A., Predazzi E.* // Phys. Rev. D. 2005. V. 71. P. 033002; *Fiore R., Jenkovszky Laszlo L., Kotikov A. V., Paccanoni F., Papa A.* // Phys. Rev. D. 2006. V. 73. P. 053012; *Illarionov A. Yu., Kniehl B. A., Kotikov A. V.* // Phys. Rev. Lett. 2011. V. 106. P. 231802.

[84] *Kotikov A. V., Shaikhatdenov B. G., Pengming Zh.* // Phys. Rev. D. 2017. V. 96. P. 114002.

[85] *Bolzoni P., Kniehl B. A., Kotikov A. V.* // Phys. Rev. Lett. 2012. V. 109. P. 242002; Nucl. Phys. B. 2013. V. 875. P. 18; *Kotikov A. V., Teryaev O. V.* // Phys. Rev. D. 2021. V. 103. P. 034002.

[86] *Avakian H., Efremov A. V., Schweitzer P., Yuan F.* // Phys. Rev. 2010. D. V. 81. P. 074035; *Efremov A. V., Schweitzer P., Teryaev O. V., Zavada P.* // Phys. Rev. D. 2009. V. 80. P. 014021; *Avakian H., Efremov A. V., Schweitzer P., Yuan F.* // Phys. Rev. D. 2008. V. 78. 114024.

[87] *Efremov A. V., Teryaev O. V.* // Sov. J. Nucl. Phys. 1984. V. 39. 962; Phys. Lett. B. 1985. V. 150. P. 383.

[88] *Anikin I. V., Pire B., Teryaev O. V.* // Phys. Rev. D. 2000. V. 62. P. 071501; *Anikin I. V., Ivanov D. Yu., Pire B., Szymanowski L., Wallon S.* // Nucl. Phys. B. 2010. V. 828. P. 1; Phys. Lett. B. 2010. V. 682. P. 413.

of important physical results, as well as for organizing periodic international conferences and schools for young scientists.

Lattice calculations in QCD and the physics of quark–gluon plasma

The non-perturbative aspects of QCD are of particular interest, making it one of the most fascinating and complex theories in modern theoretical physics. This complexity of QCD comes from the strong interaction between elementary excitations (quarks and gluons), which cannot be studied analytically using first principles. Therefore, the method of numerical calculations in lattice QCD, which is widely recognized in science and is one of the most successful in studying the properties of QCD, has become a key focus in the study of the non-perturbative properties of the theory of strong interactions. The success of lattice QCD is based on several factors. First, the method is based on first principles of quantum field theory. Second, its inaccuracies are well understood, controlled, and can be systematically improved. Finally, thanks to advances in computing technology and the increased efficiency of algorithms, it is now possible to study lattice QCD with parameters as close to reality as possible (with dynamical quarks, physical masses of π mesons, large physical lattice dimensions, and a large momentum cutoff (small spacing of the lattice)). Research using the lattice QCD modeling method has been conducted at JINR since the 1980s. The pioneering work in this area was carried out by V. P. Gerdt, V. K. Mitryushkin, I. K. Sobolev, and A. M. Zadorozhny. Among the important results obtained at JINR using the lattice QCD modeling method, it is worth mentioning the following.

V. K. Mitrjushkin and E. M. Ilgenfritz studied gluon and ghost propagators in the infrared region[89,90,91,92]. V. V. Braguta, E. M. Ilgenfritz, A. Yu. Kotov, and A. A. Roenko studied the influence of a magnetic field on the properties of QCD. In particular, they examined the impact of a magnetic field on phase transitions[93,94], the conductivity of electric current in quark–gluon plasma[95,96], and the QCD equation of state at nonzero magnetic field and baryon density[97].

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[91] *Bornyakov V. G., Mitrjushkin V. K., Muller-Preussker M.* // Phys. Rev. D. 2010. V. 81. P. 054503.

[92] *Bogolubsky I. L., Burgio G., Muller-Preussker M., Mitrjushkin V. K.* // Phys. Rev. D. 2006. V. 74. P. 034503.

[93] *Ilgenfritz E.-M., Kalinowski M., Muller-Preussker M., Petersson B., Schreiber A.* // Phys. Rev. D. 2012. V. 85. P. 114504.

[94] *Ilgenfritz E.-M., Muller-Preussker M., Petersson B., Schreiber A.* // Phys. Rev. D. 2014. V. 89. P. 054512.

[95] *Astrakhantsev N., Braguta V., D'Elia M., Kotov A. Yu., Nikolaev A. A.* // Phys. Rev. D. 2020. V. 102. P. 054516.

[96] *Almirante G., Astrakhantsev N., Braguta V. V., D'Elia M., Maio L.* // Phys. Rev. D. 2025. V. 111. P. 034505.

[97] *Astrakhantsev N., Braguta V. V., Kotov A. Yu., Roenko A. A.* // Phys. Rev. D. 2024. V. 109. P. 094511.

Detailed calculations of super-strong magnetic fields generated by spectators in collisions of relativistic heavy ions were first performed at BLTP in the work of V. D. Toneev, V. V. Skokov, and A. Yu. Illarionov[98]. The phenomenon of chiral magnetic catalysis predicts that a magnetic field should increase the chiral condensate and consequently the critical temperature of the chiral transition. The overwhelming majority of theoretical work confirmed the existence of chiral catalysis in QCD. However, lattice calculations performed on the physical mass of a quark using the Regensburg lattice group showed that inverse chiral magnetic catalysis does indeed occur in QCD: the critical temperature of the chiral phase transition decreases with increasing magnetic field strength. Inverse chiral catalysis in QCD, simultaneously with magnetic catalysis of the deconfinement transition, was first studied at non-zero baryon density at BLTP by V. V. Braguta and A. Yu. Kotov[99]. An indication of the possibility of a catalytic influence of a magnetic field on deconfinement was first obtained within the mean-field approach to the QCD vacuum being developed at BLTP[100]. These results are now generally accepted.

The BLTP Lattice Group is one of the leaders in the investigation of the properties of two-color QCD at high baryon density. The following important studies have been carried out in this area: the study of phase transitions at non-zero baryon density[101], the calculation of the interaction potential of heavy quarks in dense baryonic matter[102], the study of the gluon propagator[103], and the calculation of the equation of state in dense two-color QCD[104].

The study of the influence of rotation on the properties of hadronic matter using lattice QCD methods is another area in which the BLTP Lattice Group is a leader. V. V. Braguta, A. Yu. Kotov, and A. A. Roenko examined the influence of relativistic rotation on the critical temperature in QCD[105, 106]. Contrary to most theoretical studies, it was shown that the critical temperatures of the confinement/deconfinement transitions and the chiral transition increase with increasing angular velocity. Another important result is the calculation of the moment of inertia of quark–gluon plasma[107, 108]. The results show that in a certain temperature range

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[98] *Skokov V., Illarionov A. Y., Toneev V.* // Int. J. Mod. Phys. A. 2009. V. 24. P. 5925.

[99] *Braguta V. V., Chernodub M. N., Kotov A. Yu., Molochkov A. V., Nikolaev A. A.* // Phys. Rev. D. 2019. V. 100. P. 114503.

[100] *Galilo B. V., Nedelko S. N.* // Phys. Rev. D. 2011. V. 84. P. 094017.

[101] *Braguta V. V., Ilgenfritz E.-M., Kotov A. Yu., Molochkov A. V., Nikolaev A. A.* // Phys. Rev. D. 2016. V. 94. P. 114510.

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[103] *Bornyakov V. G., Braguta V. V., Nikolaev A. A., Rogalyov R. N.* // Phys. Rev. D. 2020. V. 102. P. 114511.

[104] *Astrakhantsev N., Braguta V. V., Ilgenfritz E. M., Kotov A. Yu., Nikolaev A. A.* // Phys. Rev. D. 2020. V. 102. P. 074507.

[105] *Braguta V. V., Kotov A. Yu., Kuznedelev D. D., Roenko A. A.* // Phys.Rev. D. 2021. V. 103. P. 094515.

[106] *Braguta V. V., Kotov A., Roenko A., Sychev D.* // PoS LATTICE2022. 2023. V. 190.

[107] *Braguta V. V., Chernodub M. N., Roenko A. A., Sychev D. A.* // Phys. Lett. B. 2024. V. 852. P. 138604.

[108] *Braguta V. V., Chernodub M. N., Kudrov I. E., Roenko A. A., Sychev D. A.* // Phys. Rev. D. 2024. V. 110. P. 014511.

the moment of inertia is negative. Another striking result is the detection of a spatially inhomogeneous confinement/deconfinement phase transition[109]. Calculations show that at non-zero angular velocity in a certain temperature range, the appearance of a mixed phase is possible, in which the confinement and deconfinement phases are spatially separated: the system is in the deconfinement phase near the axis of rotation, and, in the confinement phase, it is at the periphery. Interestingly, the effect of acceleration, as established by V. I. Zakharov, G. Yu. Prokhorov, O. V. Teryaev, N. S. Tsegelnik, and D. A. Shokhonov, may be opposite and promote hadronization[73].

Mean-field methods and QCD quantum effective action

In a series of papers[100, 110, 111, 112, 113, 114, 115, 116], in continuation of earlier studies (G. V. Efimov and S. N. Nedelko), V. E. Voronin and S. N. Nedelko with co-authors formulated a mean-field approach to the QCD vacuum description and the derivation of quantum effective meson action based on the statistical ensemble of almost everywhere homogenious Abelian (anti-)self-dual gluon fields.

Calculations of the QCD quantum effective action in one-loop approximation (*Leutwyler H.* // Phys. Lett. B. 1980. V. 96; Nucl. Phys. B. 1981. V. 179) and within the functional renormalization group method (*Eichhorn A., Gies H., Pawlowski J. M.* // Phys. Rev. D. 2011. V. 83), as well as modeling of the effective action in line with the Ginzburg–Landau Lagrangian[111, 112], show that almost everywhere homogenious Abelian (anti)self-dual gluon field corresponds to a global minimum of the QCD quantum effective action. The properties of the statistical ensemble of mean fields corresponding to the dominant fluctuations of gluon fields in the vacuum, and the analytic structure of quark and gluon propagators in this mean field provide the area law for the Wilson loop and, simultaneously, the confinement of dynamical quarks and gluons, as well as predetermine the mechanism for dynamical chiral symmetry breaking $SU_L(N_f)XSU_R(N_f)$ and $U_A(1)$ without strong CP violation. In this approach, the vacuum acts as a medium in which the infrared regime of QCD is radically modified, the wave modes of color fields are suppressed, so that excitations of color-charged fields correspond not to elementary particles, but to field fluctuations localized in time and space. In addition, the standard parton picture is preserved in the large-momentum regime of Euclidean kinematics — the short distance mode of QCD is not modified by the mean field.

The transition from confined quark and gluon fields to color-neutral composed fields describing collective excitations allowed the derivation of an effective non-

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[109] *Braguta V. V., Chernodub M. N., Roenko A. A.* // Phys. Lett. B. 2024. V. 855. P. 138783.

[110] *Kalloniatis A. C., Nedelko S. N.* // Phys. Rev. D. 2001. 64; Phys. Rev. D. 2004. 69; Phys. Rev. D. 2005. 71; Phys. Rev. D. 2006. V. 73.

[111] *Galilo B. V., Nedelko S. N.* // Phys. Part. Nucl. Lett. 2011. V. 8. P. 67.

[112] *Nedelko S. N., Voronin V. E.* // Eur. Phys. J. A. 2015. V. 51. 45; Phys. Rev. D. 2021. V. 103(11). 114021.

[113] *Nedelko S. N., Voronin V. E.* // Phys. Rev. D. 2016. V. 93(9). 094010; Phys. Rev. D. 2017. V. 95(7). 074038; Phys. Rev. D. 2023. V. 107(9). 094027.

[114] *Voronin V.* // Phys. Rev. D. 2024. V. 110. 014040.

[115] *Nedelko S. N., Nikolskii A., Voronin V. E.* // J. Phys. G. 2022. V. 49 3. 035003.

[116] *Nedelko S. N., Nikolskii A.* // Eur. Phys. J. A. 2023. V. 59. P. 4.

local action for all possible meson fields, including radially and orbitally excited mesons. The strong, electromagnetic, and weak interactions of mesons are represented in the effective action in terms of explicitly calculable nonlocal n-point interaction vertices.

A systematic calculation of the masses of light, heavy-light mesons and heavy quarkonia, including the spectrum of excited states, was carried out within this approach and electromagnetic form factors; strong and semileptonic decays of all kinds of mesons, the polarizability of pseudoscalar mesons, etc. were studied. This mean-field approach describes, under the conditions of a minimal set of parameters (strong coupling constant and quark masses in the infrared limit, scalar gluon condensate and topological susceptibility of the gluodynamics vacuum), a wide range of diverse phenomena of hadron physics from the pion to the bottomonium, with good accuracy, without additional tuning the formalism. The values of the parameters are fixed by the values of the basic mesons masses and further used in all calculations.

An indication of a catalytic effect of the electromagnetic field on deconfinement was obtained in this approach[100, 112]. It was shown that an extremely strong electromagnetic field generated in relativistic heavy-ion collisions[98, 117] can polarize the QCD vacuum, locally changing the character of the mean field from (anti-) self-dual to purely chromomagnetic, thereby catalyzing deconfinement. The phenomenon of a catalytic effect of the magnetic field on the deconfinement phase transition was later confirmed in lattice QCD calculations (*D'Elia M. et al.* // Phys. Rev. Lett. 2013. V. 110; *Bali G. S. et al.* // JHEP. 2013. V. 1304), and was studied at non-zero baryon density in detail in[99]. In the mean-field approach, such a catalytic effect leads to the presence of strong background chromomagnetic fields in the quark–gluon phase, which provides an additional mechanism for the production of direct photons in collisions of relativistic heavy ions[116].

Statistical and transport models of hadronic matter

Along with calculating the equation of state "from first principles", the laboratory developed phenomenological equations of state for dense and hot hadronic matter, used to describe heavy-ion collisions and the properties of neutron stars.

For example, Yu. B. Ivanov, V. V. Skokov, and V. D. Toneev proposed a simple quasiparticle model based on low-order perturbative QCD[118]. Unlike existing quasiparticle models, this model is formulated in dynamic, rather than thermodynamic, terms and is easily applicable to a system with a finite baryon density. The model allows for a good reproduction of lattice calculations at zero and finite values of the baryon chemical potential. The resulting quark–gluon equation of state, consistent with realistic hadronic equations of state, predicts a phase transition to the quark phase at higher densities than those achievable in the inner regions of neutron stars[119]. In particular, this brings into question the possibility of the existence of hybrid (hadron–quark) stars.

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[117] *Ivanov Yu. B., Russkikh V. N., Toneev V. D.* // Phys. Rev. C. 2006. V. 73. 044904.

[118] *Ivanov Yu. B., Skokov V. V., Toneev V. D.* // Phys. Rev. D. 2005. V. 71. 014005.

[119] *Ivanov Yu. B., Khvorostukhin A. S., Kolomeitsev E. E., Skokov V. V., Toneev V. D., Voskresensky D. N.* // Phys. Rev. C. 2005. V. 72. 025804.

In development of earlier works by D. N. Voskresensky and E. E. Kolomeitsev, a relativistic mean-field model was proposed in which the hadron masses and coupling constants depend on a scalar field. All hadron masses are subject to universal scaling, while the coupling constants scale differently. In works with A. S. Khvorostukhin and V. D. Toneev[120, 121], this model was generalized to finite temperatures, and high-lying baryon resonances and meson excitations were also taken into account. For applications to neutron stars, the appearance of hyperons and Δ(1232) baryons in the inner regions of dense neutron stars was taken into account[122, 123]. It is shown that the effect of decreasing hadron masses in the medium allows constructing the equation of state so that it satisfies most of the known empirical constraints, including constraints on the pressure of nuclear matter, a constraint on the maximum mass of neutron stars, and constraints following from the cooling dynamics of neutron stars.

Developing the hypothesis put forward in the work of D. N. Voskresensky[124] that ultra-strong magnetic fields can be formed in heavy-ion collisions, the first detailed calculations of magnetic fields arising in ultra-relativistic collisions were performed at BLTP by V. D. Toneev, V. V. Skokov, and A. Yu. Illarionov[98]. The magnetic fields created in non-central collisions of heavy ions, calculated within the microscopic transport model, turned out to be equal to $0.1-1\ m_\pi^2 \sim 0.4-4 \cdot 10^{24}$ Gauss in the energy range from SPS to the highest energies accessible to RHIC.

Electric fields, as well as the collective influence of magnetic and electric fields on the propagation of quasiparticles, were analyzed in detail in subsequent works by V. D. Toneev and co-authors[125].

Along with microscopic transport models at BLTP, Yu. B. Ivanov and V. D. Toneev developed a three-fluid hydrodynamic model for simulating relativistic heavy-ion collisions[117]. Besides two baryon-rich fluids, this model also considers the evolution of a third, baryon-free (i.e., with zero total baryon charge) fluid from newly formed particles. Within this model, a systematic analysis of various observable quantities was carried out at collision energies from 1 to approximately 160 *A* GeV for various equations of state. In particular, it is proved that the onset of deconfinement, which occurs at the compression stage of a nuclear collision, manifests itself as an irregularity in the characteristic of the baryon stop in the collision[126]. This is the softest point effect inherent in the equation of state with the deconfinement transition. This irregularity is claimed to be a very robust signal of a first-order phase transition, which is also preserved under the conditions of the

[120] *Khvorostukhin A. S., Toneev V. D., Voskresensky D. N.* // Nucl. Phys. A. 2007. V. 791. P. 180–221.

[121] *Khvorostukhin A. S., Toneev V. D., Voskresensky D. N.* // Nucl. Phys. A. 2008. V. 813. P. 313–346.

[122] *Maslov K. A., Kolomeitsev E. E., Voskresensky D. N.* // Phys. Lett. B. 2015. V. 748. P. 369–375.

[123] *Kolomeitsev E. E., Maslov K. A., Voskresensky D. N.* // Nucl. Phys. A. 2017. V. 961. P. 106–141.

[124] *Voskresensky D. N., Anisimov N. Yu.* // Sov. Phys. JETP V. 51. P. 13–22

[125] *Voronyuk V., Toneev V. D., Cassing W., Bratkovskaya E. L., Konchakovski V. P., Voloshin S. A.* // Phys. Rev. C. 2011. V. 83. P. 054911.

[126] *Ivanov Yu. B., Blaschke D.* // Eur. Phys. J. A. 2016. V. 52. P. 237.

NICA MPD experiment. Recently, the hydrodynamic model was supplemented with a function for calculating the yield of light nuclei and the interaction of particles in the final state, described within the ultrarelativistic quantum molecular dynamics (UrQMD) model[127]. The updated model allows for a quite adequate reproduction of the data on the main observable quantities of light nuclei, especially their functional dependence on the collision energy and the mass of the light nucleus.

One of the most important discoveries of the RHIC experiment is the detection of significant hyperon polarization, which may be related to the vorticity of the nuclear matter formed as a result of the non-central collision. It turned out that this rotation occurs with such an angular velocity that plasma particles at distances of 10–20 fm move at considerably relativistic velocities. Clearly, such rapid rotation can affect the properties of QCD. Numerous theoretical studies have examined the influence of relativistic rotation on the properties of QCD.

Rotation effects were studied by K. K. Gudima, M. I. Baznat, A. S. Sorin, and O. V. Teryaev using kinetic models[69, 70], as a result of which vortex layers were found, the separation of regions with different hydrodynamic helicity was discovered and investigated, and the qualitative features and quantitative characteristics of hyperon polarization were predicted and explained. Vortex rings were discovered by Yu. B. Ivanov within a three-fluid hydrodynamic model, in which polarization calculations were also performed[128]. Polarization, phase transitions, and transport phenomena in rotating hadron and quark–gluon matter were considered by G. Yu. Prokhorov, V. I. Zakharov, and O. V. Teryaev[72,73].

NUCLEAR THEORY

Nuclear physics focuses on the study of the structure and dynamics of complex particle systems that form hadrons and nuclei. Research conducted by the nuclear physics community at BLTP covers most modern topics. The goals of nuclear theory research are to develop new effective methods for describing finite Fermi systems, predict interesting effects for experimental observation, and provide theoretical justification for planned experiments. Many papers are devoted to the theory of nuclear structure from the stability valley to the drip lines and beyond. New theoretical methods and models have been proposed for describing the structure of exotic and superheavy nuclei, the characteristics of low-lying excitations, and isomeric states.

The most promising areas of future research in nuclear theory are the structure of the nucleus far from the stability valley and clustering phenomena, reactions with heavy ions and the structure of superheavy elements, the dynamics of resonance phenomena in systems with a small number of bodies, relativistic nuclear dynamics and exotic properties of nuclear matter.

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[127] *Kozhevnikova M., Ivanov Yu. B.* // Phys. Rev. C. 2023. V. 107. 024903.
[128] *Ivanov Yu. B., Soldatov A. A.* // Phys. Rev. C. 2018. V. 97. P. 044915.

NUCLEAR STRUCTURE

Over the past two decades, nuclear structure has been studied along several lines. First of all, there has been further development of the quasiparticle–phonon model (QPM), created at BLTP JINR by Prof. V. G. Soloviev and his students (L. A. Malov, V. V. Voronov, A. I. Vdovin, Ch. Stoyanov) and which has proven itself in studies of both low-energy states of nuclei and the properties of giant resonances. The nature of an unexpectedly large number of low-lying 0^+ levels in deformed ^{158}Gd was established within the QPM[129]. It was shown that a significant fraction of 0^+ states have large two-phonon components, mainly built from collective octupole phonons, which is consistent with previous predictions of the interacting boson model (IBM) developed by Prof. R. V. Jolos and colleagues. The obtained results indicate that deviations from the Alaga rules for $M1$ transitions from 1^+ states to the states of the ground band can be observed in Gd isotopes[130]. Within the Q-phonon approach[131], the properties of low-lying dipole states in chains of various isotopes were investigated.

The generalization of the QPM was achieved through the use of realistic effective nucleon–nucleon interactions in the energy density functional (EDF) approach. This enhanced the predictive power of the model and ensured its complete self-consistency. Simultaneously, based on the analysis of the fine structure of low-energy excitation spectra and giant resonances, various forms and parameterizations of the EDF were tested for their ability to describe a wide range of experimental data. To explain and predict various spectral and beta decay characteristics of spherical neutron-rich nuclei, V. V. Voronov and A. P. Severyukhin, using the separable approximation method, generalized the QPM equations describing the coupling between the one- and two-phonon components of the wave function to the case of the effective nucleon–nucleon Skyrme interaction[132, 133]. Subsequently, N. N. Arsenyev and I. N. Borzov made important contributions to the research. It was shown that changing the effective mass of a nucleon on the surface of a nucleus and taking into account the tensor component of the residual nucleon–nucleon interaction significantly improved the description of beta decay rates[134, 135]. A strong influence of the coupling with two-phonon components on the distribution of the strength of $E1$ transitions in the low-energy region and an increase in the width of the pygmy-dipole resonance in neutron-rich nuclei were established[136]. Using the QPM, the characteristics of double gamma decay of the lowest quadrupole state in

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[129] *Lo Iudice N., Sushkov A. V., Shirikova N. Yu.* // Phys. Rev. C. 2004. V. 70. P. 064316

[130] *Shirikova N. Yu., Sushkov A. V., Jolos R. V.* // Eur. Phys. J. A. 2022. V. 58. P. 98.

[131] *Jolos R. V., Shirikova N. Yu., Voronov V. V.* // Phys. Rev. C. 2004. V. 70. P. 054303.

[132] *Severyukhin A. P., Stoyanov Ch., Voronov V. V., Van Giai N.* // Phys. Rev. C. 2002. V. 66. P. 034304.

[133] *Severyukhin A. P., Voronov V. V., Van Giai N.* // Eur. Phys. J. A. 2004. V. 22. P. 397.

[134] *Severyukhin A. P., Margueron J., Borzov I. N., Van Giai N.* // Phys. Rev. C. 2015. V. 91. P. 034322.

[135] *Severyukhin A. P., Voronov V. V., Borzov I. N., Arsenyev N. N., Van Giai N.* // Phys. Rev. C. 2014. V. 90. P. 044320.

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^{48}Ca were calculated for the first time and it was found that the width of the gamma decay is sensitive to the strength of mixing of simple and complex configurations in the region of the giant dipole resonance (GDR)[137].

Increasing the configuration space in QPM requires the calculation of a huge number of matrix elements of the interaction of simple and complex configurations. To overcome this difficulty, a general approach to describing the gross structure of giant resonances in heavy and superheavy spherical nuclei has been proposed. This approach is based on the use of a random matrix method to describe the coupling of one- and two-phonon configurations. Calculations based on this approach have shown that anharmonic effects have a weak influence on the GDR width, while these effects are decisive when describing the widths of isoscalar giant monopole and quadrupole resonances[138]. Furthermore, it has been demonstrated that the GDR width can be described through an effective mechanism when one-phonon states are obtained within a microscopic approach, and two-phonon states are generated using Gaussian orthogonal ensembles[139].

Completely self-consistent methods were developed in the works of V. O. Nesterenko and his colleagues to describe the structure and dynamics of spherical and deformed nuclei within the quasiparticle random phase approximation (QRPA) with Skyrme forces. Using QRPA calculations, the mechanisms underlying the fine structure of various resonances were revealed: deformation splitting in $E1$ resonances[140], deformation-induced $E2/E0$ coupling in $E0$ resonances[141], spin-orbit splitting and Landau fragmentation in $M1$ excitations[142]. In addition, important features of single-particle spectra in $^{250-262}$No were revealed, and new excited levels were predicted[143]. It is important that nobelium isotopes precede superheavy nuclei, and the description of their properties is a necessary test for models claiming to make predictions in the superheavy nuclei region.

Toroidal dipole resonance (TDR) is a unique example of internal vortex motion of the electric type in atomic nuclei. In fact, this resonance is a realization in the nuclei of Hill's vortex, which is well known in the hydrodynamics of liquids and gases. It was shown[144] that TDR should exist in all nuclei, regardless of their shape and mass number. TDR is unique in that, being a vortex excitation, it does not contribute to the continuity equation; i.e., it is a representative of an extremely poorly studied type of nuclear dynamics. Moreover, TDR can be the primary cause

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[140] *Kleinig W., Nesterenko V. O., Kvasil J., Reinhard P.-G., Vesely P.* // Phys. Rev. C. 2008. V. 78. P. 044313.

[141] *Kvasil J., Nesterenko V. O., Repko A., Kleinig W., Reinhard P.-G.* // Phys. Rev. C. 2016. V. 94. P. 064302.

[142] *Nesterenko V. O., Vishnevskiy P. I., Kvasil J., Repko A., Kleinig W.* // Phys. Rev. C. 2021. V. 103. P. 064313.

[143] *Nesterenko V. O., Mardyban M. A., Repko A., Jolos R. V., Reinhard P.-G., Dzhioev A. A.* // Phys. Rev. C. 2025. V. 111. P. 064322.

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of the $E1$ pygmy resonance, which is important for astrophysical applications and the construction of the equation of state. Individual toroidal states were predicted in light, strongly deformed nuclei[145] such as ^{24}Mg. The problem of unambiguous experimental identification of TDR has long been discussed. In this regard, a scheme for identifying TDR in the reaction of inelastic scattering of electrons at large angles was developed[146].

The success in applying the Wigner function moments (WFM) method to the description of dipole magnetic excited states of a collective nature was achieved by taking into account the spin degrees of freedom of nucleons, which led to the discovery of new types of scissor mode states in deformed nuclei. As part of the WFM method, E. B. Balbutsev and I. V. Molodtsova developed a method for solving the time-dependent Hartree–Fock equations taking into account the spin degrees of freedom and predicted a new type of nuclear collective motion — the "spin" scissor mode[147]. A generalization of the WFM method, which takes into account simultaneously the spin and isospin degrees of freedom of the nucleus and superfluid pairing correlations, was made[148]. The "antiferromagnetic" properties of nuclei, which manifest themselves as a response of the dynamic mean field to an external perturbation, were also investigated. It was found that the antiferromagnetic properties of nuclei lead to a splitting of the energy levels at zero deformation (the Zeeman effect)[149].

In a study of collective effects in rare-earth nuclei, R. G. Nazmitdinov and co-authors discovered that the backbending phenomenon occurs when the positive signature of γ-vibrational excitations disappears in a rotating reference frame[150] . As a result, the average nuclear field spontaneously breaks axial symmetry and leads to the emergence of non-axiality in the rotating internal frame, which enhances the scissor-like $M1$ excitations[151].

In the last decade, H. G. Ganev has been actively developing a new microscopic algebraic approach based on the use of symplectic dynamical groups and spectrum-generating algebras. New algebraic models of nuclear structure were created and developed within this approach[152, 153, 154]. Using them, it was possible to successfully describe the low-lying collective states of the main, β-, and γ-bands. The possibility of describing low-lying rotational bands in multi-cluster nuclear sys-

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[146] *Von Neumann-Cosel P., Nesterenko V. O., Brandherm I., Vishnevskiy P. I., Reinhard P.-G., Kvasil J., Matsubara H., Repko A., Richter A., Scheck M., Tamii A.* // Phys. Rev. Lett. 2024. V. 133. P. 232502

[147] *Balbutsev E. B., Molodtsova I. V., Schuck P.* // Nucl. Phys. A. 2011. V. 872. P. 42.

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[151] *Kvasil J., Lo Iudice N., Nazmitdinov R. G., Porrino A., Knapp F.* // Phys. Rev. C. 2004. V. 69. P. 064308.

[152] *Ganev H. G.* // Eur. Phys. J. A. 2014. V. 50. P. 183.

[153] *Ganev H. G.* // Eur. Phys. J. A. 2021. V. 57. P. 181; Chin. Phys. C. 2023. V. 47. P. 104101.

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tems was demonstrated. In contrast to other phenomenological approaches and the standard shell model, the probabilities of $E2$ transitions are well described without the use of effective charges in the developed algebraic models.

In connection with intensive experimental studies of superheavy nuclei, R. V. Jolos and E. A. Kolganova with colleagues carried out a number of pioneering works on the microscopic description and prediction of the properties of these nuclei. The relationship between the excitation energy and the probability of the $E2$ transition to the first 2^+ state was found[155]. The energies of the lowest 2^+ states in even-even superheavy nuclei were predicted. These energies are maximum in the Fl and Og isotopes, which indicates their almost spherical shape[156]. The structure of the kinetic energy operator in the nuclear collective Hamiltonian was investigated. Higher-order terms in the collective momentum have a significant effect on the excitation energies and matrix elements of the $E2$ transitions[157]. Based on the energy density functional, L. A. Malov and colleagues predicted the ^{288}Fl nucleus as the next doubly magic nucleus after ^{208}Pb, and ^{304}120 was identified as the most likely candidate for the next doubly magic nucleus[158]. Systematic calculations of the excitation spectra, wave function structure, and γ-transition probabilities were performed in odd-proton nuclei with $Z = 97–109$. It was shown that the structure of low-lying nuclear states in these nuclei is mainly determined by single-particle components[159]. The excitation spectra of nuclei belonging to the α-decay chain of ^{288}Mc were calculated using two different single-particle potentials: a modified two-center potential and a potential based on the Skyrme functional. In addition to the $E1$ transitions[160], strong $M1$ and $M2$ transitions are predicted in ^{276}Mt.

Deviations of the moments of inertia from their solid-state values have been studied in detail and given a qualitative interpretation within the quasiclassical theory of periodic orbits, which relates the shell structure to classical periodic orbits in the nuclear potential[161].

Calculating the lifetimes of isomeric states remains a complex problem, requiring a solution due to the intensive experimental study of these states. For heavy nuclei with $N = 153$, T. M. Shneidman and colleagues investigated the effect of Coriolis mixing on the γ decay of single-quasiparticle isomeric states. It was shown that the mixing of states increases sharply if the isomeric state closely approaches a rotational state with the same angular momentum, but built on a different quasiparticle state. The increase in the decay rate of the isomeric state $K^\pi = 7/2^+$ in ^{251}Cf

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[155] *Jolos R. V., Kolganova E. A.* // Phys. Lett. B. 2021. V. 820. P. 136581.

[156] *Shirikova N. Yu., Sushkov A. V., Malov L. A., Kolganova E. A., Jolos R. V.* // Phys. Rev. C. 2022. V. 105. P. 024309.

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by three orders of magnitude compared to the decay of a similar state in ^{249}Cm was explained[162].

NUCLEAR ASTROPHYSICS

Research into the properties of hot nuclei has focused primarily on developing a thermodynamically consistent method for calculating the characteristics of lepton–nucleus weak reactions (electron capture, neutrino scattering and absorption by nuclei, etc.) under extreme astrophysical conditions. A. I. Vdovin and A. A. Dzhioev developed a statistical method for calculating the spectral densities of multipole operators of the weak nucleon current in hot nuclei, based on the superoperator formalism[163]. They modified the standard definition of fermion superoperators, which guaranteed the fulfillment of the principle of detailed balance for spectral densities and made it possible to apply the equations-of-motion method to describe excitations in hot nuclei.

Using a statistical method for iron-group nuclei and neutron-rich nuclei with $N \approx 50$, it was shown that the abandonment of the Brink–Axel hypothesis and the application of the principle of detailed balance significantly increases the contribution of thermally excited nuclear states to the rates and cross sections of lepton–nucleus processes in comparison with the predictions of the shell model. This leads to a more rapid increase in cross sections with temperature at low lepton energies, which, in turn, increases the neutronization rate of stellar matter and increases its opacity to neutrinos. Furthermore, the temperature-induced weakening of nucleon pairing correlations increases the temperature dependence of the energy and strength of Gamow–Teller $p \to n$ transitions in neutron-rich nuclei. It was shown that thermal effects, rather than configurational mixing, as previously believed, are the primary mechanism unblocking low-energy transitions. Due to this, the process of electron capture by nuclei and neutronization of the stellar matter does not stop at neutron-rich nuclei with $N \approx 50$.

The study of the influence of temperature on charge-neutral neutrino-nuclear processes has shown that heating nuclei leads to a significant broadening of the energy spectrum of neutrinos propagating in stellar matter. Furthermore, it was found that the combined consideration of nuclear deexcitation and neutrino oscillations significantly enhances the contribution of nuclear processes to the formation of the electron antineutrino flux arising during the pre-supernova stage of stellar evolution. This, in turn, increases the probability of detecting such antineutrinos by ground-based detectors[164].

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[162] *Shneidman T. M., Minkov N., Adamian G. G., Antonenko N. V.* // Phys. Rev. C. 2022. V. 106. P. 014310.

[163] *Dzhioev A. A., Vdovin A. I.* // Phys. Part. Nucl. 2022. V. 53. P. 885; Phys. Part. Nucl. 2022. V. 53. P. 939; Phys. Part. Nucl. 2022. V. 53. P. 1051.

[164] *Dzhioev A. A., Yudin A. V., Dunina-Barkovskaya N. V., Vdovin A. I.* // MNRAS. 2024. V. 527. P. 7701.

NUCLEAR REACTIONS

G. G. Adamian, N. V. Antonenko and colleagues proposed new approaches to the description of low-energy nuclear reactions and nuclear excitations[165, 166]. The manifestation of a dinuclear system in the structure of the nucleus and nuclear reactions was considered[167]. It was shown that hyperdeformed states can be considered as resonance states associated with the formation of binary nuclear systems in reactions with heavy ions[168]. The structure of collective bands of variable parity in actinides and nuclei of rare earth elements was described in the model of a dinuclear system[169]. The model is based on the assumption that cluster-type states are present with a certain probability in each state of the nucleus due to the motion of the nuclear system along the mass asymmetry coordinate. The calculated parity splittings and electric multipole transitions are in good agreement with experimental data[170]. The cluster model was applied to describe the phenomenon of superdeformed states decay[171].

The dinuclear system model was applied to analyze the isotopic dependence of the cross sections for the production of superheavy nuclei in cold and hot fusion reactions. Optimal excitation energies and combinations of colliding nuclei were proposed for experimental studies. It was found that the use of projectile nuclei with a large number of neutrons does not always lead to an increase in the production cross section of nuclei with $Z = 110, 112$, and 114 in cold fusion[172, 173]. The survival probabilities of an excited compound nucleus and the fusion cross sections calculated within the dinuclear system model were applied to describe the excitation functions of No isotopes in the reactions $^{48}Ca + {}^{204,206,208}Pb$ and the production cross sections of superheavy nuclei with $Z > 102$ in cold and hot fusion reactions[174, 175].

Excitation functions for the production of new, heaviest isotopes of superheavy nuclei in the evaporation channels of charged particles and neutrons in hot fusion

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[167] *Shneidman T. M., Adamian G. G., Antonenko N. V., Ivanova S. P., Jolos R. V., Scheid W.* // Phys. Rev. C. 2002. V. 65. P. 064302.

[168] *Adamian G. G., Antonenko N. V., Nenoff N., Scheid W.* // Phys. Rev. C. 2001. V. 64. P. 014306.

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[171] *Adamian G. G., Antonenko N. V., Jolos R. V., Palchikov Yu. V., Scheid W.* // Phys. Rev. C. 2004. V. 69. P. 054310.

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[173] *Adamian G. G., Antonenko N. V.* // Phys. Rev. C. 2005. V. 72. P. 064617.

[174] *Adamian G. G., Antonenko N. V., Zubov A. S.* // Phys. Rev. C. 2005. V. 71. P. 034603.

[175] *Zubov A. S., Adamian G. G., Antonenko N. V., Ivanova S. P., Scheid W.* // Eur. Phys. J. A. 2005. V. 23. P. 249.

reactions with ^{48}Ca were predicted for the first time[176, 177]. The possibility of direct production of unknown isotopes of superheavy nuclei in various evaporation channels was demonstrated[178]. The production cross sections of superheavy nuclei with charge numbers 114–117 were predicted[179, 180] in the evaporation channels of (5–9)*n* complete fusion reactions with ^{48}Ca. The calculated production cross sections clearly indicate that Ds is a boundary nucleus between the island of stability of superheavy nuclei and the continent of nuclei with a relatively large number of neutrons.

The production cross section of ^{277}Cn was calculated in the reactions ^{48}Ca + ^{233}U and ^{70}Zn + ^{208}Pb to study the difference in fusion probabilities in cold and hot fusion reactions. A strong correlation was found between the fusion probability and the asymmetry in the reaction input channel. The possibility of filling the gap between the isotopes of superheavy nuclei with $Z = 112$ formed in cold and hot fusion reactions was indicated[181]. An analytical formula for estimating the average kinetic energy of emitted particles in multi-step evaporation processes was obtained[182], which significantly simplifies the calculation of the production cross sections of evaporation residues.

A. K. Nasirov and colleagues investigated the influence of the input channel on the de-excitation of a compound nucleus in reactions with different mass and charge asymmetries, but leading to the production of the same compound nucleus ^{220}Th with the same excitation energy. The strong difference in the observed cross sections is due to their dependence on the characteristics of the input channel and the participating partial waves[183]. It was shown that the sharp decrease in the cross section in the ^{54}Cr + ^{243}Am reaction compared to the ^{48}Ca+^{243}Am reaction is caused by strong competition between fusion and quasi-fission[184].

In addition to problems related to the fusion of heavy nuclei, reactions that can produce previously unknown isotopes are of interest. The decay of dinuclear systems from configurations more asymmetric than the initial one can lead to the production of unknown isotopes of heavy nuclei. It is possible to obtain new isotopes of superheavy nuclei with $Z = 104–108$ in the reactions ^{48}Ca + ^{238}U, ^{243}Am and $^{244;246;248}$Cm, which cannot be obtained in complete fusion reactions. The methods developed at BLTP for describing quasifission reactions from asymmetric

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[181] *Hong J., Adamian G. G., Antonenko N. V., Jachimowicz P., Kowal M.* // Eur. Phys. J. A. 2022. V. 58. P. 180.

[182] *Rahmatinejad A., Shneidman T. M., Adamian G. G., Antonenko N. V., Jachimowicz P., Kowal M.* // Phys. Lett. B. 2023. V. 844. P. 138099.

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[184] *Kaumov B. M., Ganiev O. K., Nasirov A. K., Yuldasheva G. A.* // Phys. Rev. C. 2022. V. 105. P. 014618.

configurations are suitable for analyzing the production of various exotic nuclei, for example, light nuclei with a large number of neutrons[185, 186]. The production cross sections of various neutron-rich isotopes in multinucleon transfer reactions with stable and radioactive beams have been predicted[187, 188].

It was shown that the appearance of some nuclei in fusion reactions cannot be explained without taking into account the emission of light nuclei from the primary products. The production cross sections of evaporation residues in the light particle emission channels were calculated within the dinuclear system model[189]. The mass and angular distributions of quasi-fission fragments were studied in the reaction ^{78}Kr(10A MeV) + ^{40}Ca. The analysis shows[190] the possibility of rotation of the resulting binary nuclear system by 180°.

To study the interaction of nuclei in the entrance channel of reactions, V. V. Sargsyan and colleagues proposed a new method for extracting the probabilities of transferring a certain number of neutrons from experimental data on transfer and capture (fusion). For the ^{40}Ca + ^{96}Zr system, a nearly exponential dependence of the probabilities of transferring one and two neutrons at a reverse angle on the distance of closest approach of the nuclei was demonstrated. At an energy slightly below the Coulomb barrier, the ratio of the probabilities of transferring one and two neutrons becomes close to unity[191].

A quantum diffusion approach was proposed to describe nuclear reactions at energies below the Coulomb barrier. In this approach, the relative motion of nuclei is associated with internal degrees of freedom and is considered as an open quantum system. The astrophysical S-factor was analyzed within this approach for reactions of astrophysical interest. The S-factor demonstrates a clear maximum at collision energies 20–40% below the Coulomb barrier. An analytical expression was proposed to predict the dependence of the S-factor maximum on the choice of colliding nuclei. It was shown that at low collision energies, a strong dependence of the S-factor on $E_{\text{c.m.}}$ leads to a significant decrease in the stellar burning rate[192].

It was found that accounting for the nondiagonal matrix elements of the coupling matrix, which are usually neglected in coupled-channel approaches, makes it possible to explain the difficulties that arise in various models when interpreting experimental data for the S-factor of the fusion reaction of two nuclei[193].

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[193] *Wen P. W., Lin C. L., Nazmitdinov R. G., Vinitsky S. I., Chuluunbaatar O., Gusev A. A., Nasirov A. K., Jia H. M., Gózdz A.* // Phys. Rev. C. 2021. V. 103. P. 054601.

The cluster approach was used by A. V. Andreev and H. Pasca with colleagues to successfully describe various characteristics of fission. In this approach, the fissile nucleus at the moment of scission is considered as a dinuclear system. It was shown that the bimodality or multimodality of fission can be associated with variations in the charge and mass distribution over a small range of charge and mass numbers[194]. A ternary fission model was proposed based on statistical analysis and calculations of the potential energy of ternary systems at the moment of scission[195]. The formation of a ternary system was considered as the second stage after the formation of a dinuclear system through the release of one or more α particles and neutrons from one or both fragments in the region of their interaction. Mass distributions have been calculated for induced fission of even mercury isotopes with mass numbers from $A = 174$ to 196. With increasing A, the mass distribution of the products changes from symmetric for ^{174}Hg to asymmetric for isotopes close to ^{180}Hg, and back to more symmetric for ^{192,194,196}Hg. In ^{180,184}Hg, the mass distribution of fission fragments remains asymmetric even at high excitation energies[196]. A change in the shape of the mass/charge distribution with increasing excitation energy was predicted[197]. The coexistence of a symmetric mass distribution and an asymmetric charge distribution of fission fragments was studied[198], and it was shown that the average number of neutrons per proton in the fission fragments is not the same and is not equal to that in the fissile nucleus[199].

It is necessary to know the survival probability of an excited compound nucleus with respect to fission to calculate the production cross sections of superheavy nuclei. The competition between channels associated with particle evaporation and fission is determined by the corresponding energy thresholds and level densities. A. Rahmatinejad and colleagues calculated the nuclear level densities in the isotopic chains of superheavy nuclei with $Z = 112–120$, as well as in their residues after the emission of neutrons, protons, and α particles. The influence of shell effects on the energy dependence of the ratios of level density parameters in various channels was studied[200].

The cluster approach has proven useful in describing spontaneous fission, which is assumed to occur through cluster states. Calculations by I. S. Rogov and colleagues demonstrated an excellent description of the half-lives of cluster decay

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[199] *Pasca H., Andreev A. V., Adamian G. G., Antonenko N. V.* // Phys. Rev. C. 2023. V. 107. P. 024603.

[200] *Rahmatinejad A., Shneidman T. M., Adamian G. G., Antonenko N. V., Jachimowicz P., Kowal M.* // Phys. Rev. C. 2022. V. 105. P. 044328.

and spontaneous fission[201]. A number of predictions for superheavy nuclei were confirmed experimentally. The dependence of the prohibition coefficient on the spin of the parent nucleus was determined, and an analytical formula for an approximate estimate of the prohibition coefficient for the spontaneous fission of an odd nucleus was proposed[202].

HALO NUCLEI

The study of halo nuclei has received considerable attention because they are believed to have a compact core and several valence nucleons surrounding the nucleus. The characteristic features demonstrated by halo nuclei include weak valence nucleon binding energy, narrow momentum distributions of reaction products due to fragmentation, and an anomalously large interaction cross section. Mixing of bound or bound and unbound levels becomes especially important when studying halo nuclei[203].

S. N. Ershov and his co-authors developed a microscopic four-particle theory for the decay reactions of a two-neutron halo. The importance of taking into account both elastic and inelastic fragmentation, leading to low-lying halo excitations, was demonstrated. Inelastic scattering calculations showed[204, 205] the accumulation of dipole and monopole excitations of ^{11}Li near the three-body threshold and provided a good description of the observed peak in the experimental energy spectrum of ^{11}Li. A theory of electron scattering by nuclei on a Borromean two-neutron halo was proposed with full accounting for final-state interactions[206] . The properties, geometry, and structure of the main-state continuum were studied, and a soft dipole mode in ^{22}C was predicted[207].

D. Valiolda and co-authors proposed a quantum-classical method for studying the decay of halo nuclei. This approach was used to calculate for the first time the cross sections of the decay of ^{11}Be into Pb at energies up to 5 MeV/nucleon, including low-lying resonances[208].

S. A. Rakityansky and S. N. Ershov discovered that long-range ($\sim 1/r^2$) potential tails and the Coulomb potential ($1/r$) cause an unusual behavior of the S-matrix poles. The Coulomb tail not only changes the topology of the Riemann energy surface, but also destroys the so-called mirror symmetry of the poles in both single-channel and two-channel problems[209]. V. K. Lukyanov and co-authors conducted a theoretical analysis of elastic scattering and momentum distributions of

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clusters in decay reactions of exotic halo nuclei. The decisive role of the periphery of these nuclei for their scattering and decay into clusters was established[210].

THEORY OF FEW-BODY SYSTEMS

The theory of few-body systems studies quantum systems that can be viewed as consisting of several (say, two, three or four) elementary constituents. Depending on the specific situation and the energy range under consideration, these constituents can be quarks, mesons, individual nucleons, nuclei or even atoms and molecules. The small number of elementary constituents in a system allows for the development and elaboration of mathematically rigorous and precise methods for studying it, without requiring further physical approximations. Due to their universality, approaches based on few-body theory are interdisciplinary in nature, paving the way to solving various problems in nuclear physics, atomic and molecular physics, quantum chemistry, and other fields.

The list of BLTP's results on few-body topics in the 21st century opens with a solution found by V. V. Pupyshev to Faddeev differential equations, corresponding to the collapse of a system of three identical bosons, the interaction potentials between which are proportional to the inverse square of the interparticle distance[211]. A procedure for extrapolating the triplet phases of proton–proton scattering in the region of very low energies was proposed[212]. Two-dimensional scattering of a quantum particle in the field of a central long-range potential, decreasing at large distances r as a power function $r^{-\beta}$ with $\beta > 2$, was studied. In this case, explicit low-energy forms were established for all scattering phase shifts[213].

Peaks were revealed in the energy dependence of the total cross section of η-meson photoproduction in a numerical study of the photoproduction of η meson on deuteron based on the Alt–Grassberger–Sandhas formalism for various parameters of the ηN interaction[214].

Based on the kinematic description of a system of three non-interacting particles in hyperspherical coordinates, two new infinite series of matrix identities were obtained, relating the angles of the triangle formed by the particles, the masses of the particles, and the internal hyperspherical angles[215]. New algorithms for an explicit construction of multichannel quantum-mechanical Hamiltonians with specified spectral properties were developed[216]. A two-pole pair T-matrix model[217] was used in studying three-boson systems with $r_0/a_0 \ll 1$. The position of the second pole on the unphysical sheet was considered as a parameter of the integral Faddeev

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equation. Values of previously uncalculated interaction parameters in a system of three bosons were predicted.

Quantum-mechanical calculations of the partial cross sections leading to different final states of the antiprotonic helium atom were performed[218]. Adiabatic approximations were used for the four-particle scattering wave function corresponding to the initial state, as well as for the antiprotonic helium wave function arising in the final state.

E. A. Kolganova and A. K. Motovilov with co-authors calculated the bound states of the $^4He_3$ system and the ultracold scattering of the ^4He atom on the $^4He_2$ dimer[219, 220]. These calculations were based on the version of differential Faddeev equations corresponding to the hard-core model. The method used, unlike some other competing approaches, is accurate and is ideally suited for calculations in triatomic systems, where two-particle interactions have a strong repulsive component at small distances between atoms. The scattering phase shifts and the scattering length of $^3He-{}^4He_2$ were also calculated[221]. It was shown that the excited state of the $^4He_3$ trimer is of Efimov nature. In order to obtain the full-scale Efimov effect[222] in the $^4He_3$ system, it is sufficient to weaken the He–He interatomic potential by approximately 3%. For the first time, the binding energies of the $^6Li–He_2$ and $^7Li–He_2$ systems, as well as the scattering length of the ^4He atom on the $^4He^7Li$ dimer, were calculated. It was shown that the excited states in both of these systems are of Efimov nature[223].

Three-body dynamics in ultracold binary mixtures of Fermi and Fermi–Bose particles was studied. The existence of universal properties was established in this dynamics. A new class of universal bound states (now called Kartavtsev–Malykh states or Kartavtsev–Malykh trimers) was discovered[224]. A condition on the ratio of the masses of particles of different types was established, guaranteeing the non-binding of a three-particle system[225].

The effect of perturbation of the spectral band of a lattice quantum system by a nearby resonance was investigated. A rather general model of a Hamiltonian was considered, consisting of a "nuclear" part, a "molecular" part with eigenvalues embedded in the continuous spectrum of the nuclear part, and a weak coupling operator between channels, which transforms these unperturbed eigenvalues into molecular resonances. If the nuclear channel itself has a narrow resonance with a position close to the molecular energy, then the width of the resulting molecular resonance turns out to be inversely proportional to the nuclear width[226]. The evolution of (possibly infinite-dimensional) subspace of states of a quantum system

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evolving according to the non-stationary Schrödinger equation was investigated. Based on the concept of maximal angle between subspaces, several optimal bounds on the rate of this evolution were obtained. One of these bounds can be considered as a natural generalization of the Mandelstam–Tamm estimate to the case of quantum subspaces[227]. A completely new sharp estimate for the variation of the spectral subspace of a Hermitian operator (the a priori tanΘ theorem) under off-diagonal perturbations was found and proved[228, 229]. The distribution of bound-state energies of a system of two identical spinless fermions on a two-dimensional lattice was investigated under the assumption that these fermions interact with each other only at adjacent and immediately following adjacent lattice sites[230].

E. A. Soloviev and co-authors developed a concept of dynamic adiabatic states to describe collisions of single-electron atoms and ions. The corresponding dynamic adiabatic potential curves were investigated for the entire range of internuclear distances[231]. A dynamic approach was developed for the first time for calculating charge exchange in $H^+ + He^+(1s)$ collisions over a wide energy range up to the cross section maximum[232].

A new approach to the study of a system of three charged particles in a continuum was used to investigate a number of three-particle reactions of astrophysical interest[233]. The proposed scheme is applicable to the three-particle systems in which two particles have masses significantly exceeding the mass of the third particle.

A time-dependent grid method was developed for the numerical study of the dynamics of few-body systems without using conventional partial-wave expansions[234]. The approach has a particular advantage for breakup processes: no asymptotic boundary conditions involving the decay channel are required for a time-dependent few-body wave function[235, 236, 237]. It was found that atom–atom interactions or electron scattering on a fixed impurity can be actually switched off using geometric confinement. This effect is useful for increasing the sensitivity of controlled atomic interferometers, for managing the properties of quasi-1D quantum gases, and for improving the cooling of microelectronic devices[238].

V. S. Melezhik and co-authors developed a nonperturbative approach to calculating particle collisions in the case of anisotropic interactions in quasi-one-dimensional geometries in order to overcome the limitations of pseudopotential theory and accurately take into account long-range anisotropic interactions[239]. The tunneling velocities of two interacting ultracold atoms placed in an anharmonic

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trap were calculated. It was found that the alternate tunneling of atoms is the only possible tunneling scenario[240]. A new efficient method for sympathetic cooling of ions was proposed: for this purpose, cold buffer atoms should be used at energies near the atom–ion resonance generated by confinement[241]. It was found that the micromotion of the ion does not prevent the occurrence of resonance, the position of which can be controlled by radio-frequency fields. This circumstance provides additional opportunities for fine adjustment of atom–ion interactions in low spatial dimensions[242].

A calculation of the lowest 0^+ states of the ^{12}C nucleus was carried out in order to establish the role of three-particle forces in the α-cluster model. The ^{12}C nucleus was considered as a system composed of three α particles[243].

S. S. Kamalov and co-authors well described the data on the photo- and electroproduction of π^0 near the threshold in the meson-exchange dynamic model, which describes most of the existing data on electromagnetic pion production up to the region of the second resonance[244, 245]. The meson-exchange model of the πN system in the S_{11} channel was extended to 2 GeV by explicitly including a set of S_{11} resonances. Calculations based on this model indicate the presence of a third and fourth S_{11} resonance with masses of (1846 ± 47) and (2113 ± 70) MeV, respectively[246].

V. N. Kondratiev studied the influence of a strong magnetic field on the synthesis of chemical elements under conditions of nuclear statistical equilibrium. It was shown that for iron-group nuclides, magnetic modification of the nuclear structure shifts the maximum mass of nucleosynthesis products toward lower mass numbers, approaching the mass of titanium[247].

RELATIVISTIC NUCLEAR PHYSICS

The study of nucleon resonance decays into a nucleon and a ω meson is closely related to the problem of estimating changes in the properties of a vector meson in the experimental environment at the Thomas Jefferson National Accelerator Facility (USA), ELSA-SAPHIR in Bonn (Germany), GRAAL in Grenoble (France), and LEPS in SPring-8 (Japan). A. I. Titov and co-authors considered the electromagnetic production of vector mesons within the effective Lagrangian approach and the vector dominance model taking into account the $F15(1680)$ and $D13(1520)$ resonances. Single- and double-polarization characteristics and parity violation

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asymmetries were obtained[248, 249], which were used to determine the π-meson exchange coupling constant at high energies. The possible production of Θ^+ was shown, manifested by a distinct peak in the missing mass distribution[250, 251]. A comparative analysis of the scattering length of vector meson (ω, φ, J/ψ)-proton interactions was carried out for the first time. A nontrivial exponentially strong dependence of the scattering length on the quark composition of the interacting hadrons was discovered[252].

An important goal of current and future heavy-ion collision experiments (RHIC, NICA) is to understand the nature of phase transitions in hot and dense nuclear matter. These transitions are considered within the effective Nambu–Jona-Lasinio model with a Polyakov loop, one of the few that describes the properties of the chiral phase transition and the confinement–deconfinement transition. This model also provides a schematic description of the chiral phase transition and the properties of mesons at finite temperature and density. V. D. Toneev, Yu. L. Kalinovsky, and A. V. Friesen investigated the influence of meson correlations on the thermodynamic properties of the quark–meson system[253]. It was shown that the splitting of the multiplet mass of positive and negative mesons in dense matter is responsible for the different behavior of the K^+/π^+ and K^-/π^- ratios, and the "peak" structure was interpreted as a sequence of the chiral symmetry restoration effect and the subsequent deconfinement effect[254].

The Tsallis power law distribution describes experimental data very well both in high-energy physics (LHC and RHIC) and in astrophysics. A. S. Parvan showed that the Tsallis statistics in the grand canonical ensemble satisfies the requirements of equilibrium thermodynamics in the thermodynamic limit if the thermodynamic potential is a homogeneous first-order function in the extensive state variables of the system, and the entropy variable is an extensive state variable[255]. The correctness of the Planck and Ott formalisms of the relativistic thermodynamics of a moving body was investigated. The Lorentz transformations of thermodynamic quantities belong to the Planck formalism in the case where the momentum is an independent variable in the Hamiltonian. Moreover, in Planck's description, the first law of thermodynamics is covariant and the Lagrangian is preserved under the Legendre transformation. However, in Ott's description, the first law of thermodynamics is not covariant. Thus, only Planck's formulation of the relativistic thermodynamics of a moving body is correctly defined, while Ott's formalism should be discarded[256].

The search for manifestations of the color transparency effect began about four decades ago. A. B. Larionov studied the possible manifestations of this effect in

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the reaction of hard proton–proton knockout from a deuteron $d(p,pp)n$ at relativistic energies, where the incident proton and both outgoing protons are fast and can undergo soft elastic rescattering by a slow neutron. Calculations are performed within the generalized eikonal approximation, supplemented by a quantum diffusion model. Nuclear transparency and tensor analyzing power of the deuteron are calculated in the incident proton momentum range of 6–75 GeV/c. An estimate of the event rate for NICA is given[257].

Current and future experiments on elastic electron scattering on few-nucleon systems (D, ^{3}He, T) are conducted at large momentum transfer squares, which requires the use of relativistic research methods. S. G. Bondarenko, V. V. Burov, and S. A. Yurev solved the Bethe–Salpeter–Faddeev equation for a multi-rank separable kernel of nucleon–nucleon interaction. The obtained covariant amplitudes of $3N$ systems were used to calculate the electromagnetic form factors of three-nucleon systems. Relativistic corrections were investigated for the first time, the contribution of which turned out to be significant at large momentum transfers[258, 259].

L. P. Kaptar and co-authors performed a relativistic treatment of the deuteron in the Bethe–Salpeter formalism for the meson–nucleon interaction. It allows analyzing relativistic effects in reactions with the deuteron. Calculations were performed for the reactions $pd \to d\varphi p$ (experiment at COSY)[260], $pD \to (pp)n$ with the fast direct pair[261] pp, and the exclusive charge exchange reaction[262] $pD \to n(pp)$.

The description of mesons as quark–antiquark bound states within the Bethe–Salpeter equation with momentum-dependent quark mass functions determined by the Dyson–Schwinger equation can successfully explain many spectroscopic data, such as meson masses, the electromagnetic properties of pseudoscalar mesons and their radial excitations, and other observables. It was proposed to use rigorous mathematical methods to find the exact positions of the poles and the corresponding residues when solving the Bethe–Salpeter equation for mesons in the presence of singularities[263]. With a set of parameters that provides a good description of the lattice data within the Dyson–Schwinger approach, solutions of the Bethe–Salpeter equation for pseudoscalar glueballs demonstrate a rich mass spectrum that includes the ground and excited states predicted by lattice calculations. The resulting mass spectrum also contains several intermediate excitations[264].

V. D. Toneev and co-authors conducted research on the global effects of strange particle production in hot and dense nuclear matter within a collective thermodynamic approach. The consequences of strangeness separation (the effect of strangeness distillation) and softening were discussed[265]. A hybrid model for describing

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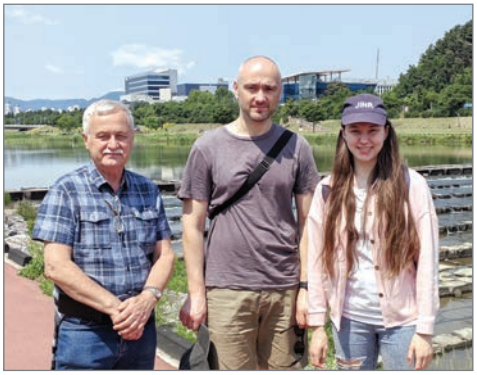
Sector No. 1 of the BLTP Department of Atomic Nucleus Theory



The Helmholtz International Summer School "Nuclear Theory and Astrophysical Applications". Dubna, 2005



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The 13th BLTP JINR – ITP CAS Workshop on Physics of Strong Interacting Systems. Almaty, Kazakhstan, 2025



R. V. Jolos, N. V. Antonenko, and V. V. Voronov



V. K. Lukyanov and V. A. Matveev



E. A. Solov'ev, A. A. Korobitsyn, P. M. Krasovitsky, E. A. Koval, E. A. Kolganova, D. Janseytov, E. V. Mardyban, and V. S. Melezhik



V. V. Burov



W. M. S. Hammouda and G. G. Adamyan



N. K. Skobelev, S. N. Ershov, and L. A. Malov

collisions of relativistic heavy ions was proposed[266]. The early stage of interaction, responsible for the creation of entropy, is calculated within the quark–gluon string transport model, leading to the initial state. The transition to the subsequent isentropic expansion occurs with exact accounting of all conservation laws. Relativistic three-dimensional hydrodynamics of the state is applied to this stage of expansion. The model reproduces the global characteristics of nuclear interactions over a wide range of collision energies.

Magnetic fields generated in non-central heavy-ion collisions were studied using ultrarelativistic quantum molecular dynamics model. The simulations were performed for various impact parameters in the SPS energy range ($E_{\text{lab}} = 10158A$ GeV) and for the highest energies available at RHIC[267]. The generated magnetic field was shown to be highly non-uniform, but in the central region of the overlapping nuclei, it varies relatively weakly in the transverse direction. Electromagnetic fields generated in heavy-ion collisions have little effect on the electric charge separation relative to the reaction plane[268].

RESEARCH IN RELATED FIELDS

The planned LUXE experiments at DESY and E-320 at FACET-II are aimed at studying fundamental QED processes in strong laser fields. A. I. Titov and colleagues developed a theory of nonlinear quantum processes in strong electromagnetic fields. It was first used to predict the probabilities of the production of hard Compton photons and electron–positron pairs during the interaction of ultrarelativistic electrons with intense laser pulses over a wide range of electron energies and laser beam intensities[269]. A significant enhancement of the cross sections of multiphoton (subthreshold) processes was predicted during the interaction of photons and electrons with short electromagnetic (laser) pulses[270].

Nuclear theory methods were applied to the study of metallic clusters. V. O. Nesterenko and colleagues proposed a method for describing multipole oscillations of valence electrons in deformed alkali metal clusters. Both the deformed mean field and the residual interaction were obtained in a consistent way from the Kohn–Sham functional. The origin and main characteristics of electron infrared quadrupole modes in sodium clusters were described within the time-dependent local density approximation[271, 272].

Electromagnetic fields of simple non-stationary sources are used to analyze the Lorentz and Feld–Tai lemmas, which have wide application in electrodynamics, optics, radiophysics, and electronics. These lemmas are valid for more general time

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dependences of electromagnetic field sources than originally assumed[273]. A careful analysis of the kinematic relations for the two-photon Cherenkov process indicates the existence of angles with maximum radiation intensity. This helps in experiments aimed at detection of the two-photon Cherenkov effect[274].

Methods of nuclear theory were used to describe statistical processes. Analytical expressions for the occupation numbers were obtained within the non-Markovian quantum Langevin approach for a fermionic or bosonic oscillator fully coupled to several thermal reservoirs with mixed statistics. Full coupling of a quantum system to a thermal reservoir usually leads to its evolution toward asymptotic equilibrium. It was shown that such equilibrium may not be achieved if the system is simultaneously connected to bosonic and fermionic thermal reservoirs, and these reservoirs are not coupled to each other[275].

THEORY OF CONDENSED MATTER

At the very end of the last century, significant changes occurred in theoretical research on condensed matter at BLTP. Traditional research areas, such as theory of solids, nonlinear many-body problems, condensed matter models, and quantum statistics of radiation and matter, were replaced by new, modern topics: strongly correlated systems (headed by N. M. Plakida and G. Röpke); dynamical systems: chaos, integrability, and self-organization (headed by V. B. Priezzhev); disordered structures: glasses, topological defects, nanostructures, and Josephson junctions (headed by V. A. Osipov); and mesoscopic and coherent phenomena in quantum systems (headed by M. A. Smondyrev and V. S. Yarunin). This restructuring was not accidental. On the one hand, these areas corresponded to new global trends in condensed matter physics. On the other hand, the leaders of these areas and leading researchers in the topic already had significant results in these fields. As recent years have shown, this reorganization has proven to be both timely and fruitful, leading to competitive results that have received global recognition. Below they will be described in more detail.

HIGH-TEMPERATURE SUPERCONDUCTORS AND CUPRATES

High-temperature superconductors remain one of the most interesting and actively studied topics in condensed matter physics. These materials, primarily copper oxide (cuprate) superconductors, show superconducting properties at temperatures significantly higher than predicted by traditional BCS theory. The discovery of high-temperature superconductors revolutionized the field by demonstrating

[273] *Afanasiev G. N.* // J. Phys. D. 2001. V. 34. P. 539.

[274] *Afanasiev G. N.* Vavilov–Cherenkov and Synchrotron Radiation. Kluwer Publishers, 2004. P. 124; *Afanasiev G. N., Kartavenko V. G., Zrelov V. P.* // Phys. Rev. E. 2003. V. 68. P. 066501.

[275] *Hovhannisyan A. A., Sargsyan V. V., Adamian G. G., Antonenko N. V., Lacroix D.* // Physica A. 2020. V. 545. P. 123653; Phys. Rev. E. 2020. V. 101. P. 062115; Phys. Rev. A. 2020. V. 102. P. 022209.

that superconductivity can occur at temperatures above the boiling point of liquid nitrogen, opening up practical and technological advantages.

The fundamental mechanism of high-temperature superconductivity is complex and still not fully understood. It involves strong electron correlations, spin fluctuations, and unconventional pairing mechanisms. Unlike conventional superconductors, where electron pairing occurs through lattice vibrations (phonons), cuprates show a more complex interaction between charge, spin, and lattice degrees of freedom. The unique layered structure of cuprates, in which CuO_2 planes act as superconducting layers, further complicates their theoretical description.

A combination of theoretical modeling and experimental confirmation is required to understand the microscopic origins of high-temperature superconductivity. Theoretical approaches often incorporate systems of strongly correlated electrons, such as the t–J model and the extended Hubbard model, which take into account electron–electron interactions and magnetic correlations. Experimental methods, including neutron scattering and optical conductivity measurements, play a key role in verifying theoretical predictions and clarifying the underlying mechanisms.

High-temperature cuprate superconductors have been the subject of numerous theoretical studies due to their complex physical nature. N. M. Plakida made an important contribution to these studies[276]. He conducted a detailed analysis of this problem, focusing on the study of the role of electron–phonon interaction and spin fluctuations in superconductivity using the extended Hubbard model. The study emphasized the crucial role of strong electron correlations in stabilizing the superconducting phase. Continuing this study, N. M. Plakida and his student V. S. Udovenko[277] presented a microscopic theory of superconductivity that takes into account interstitial Coulomb repulsion and electron–phonon interaction. The work showed that pairing due to spin fluctuations significantly increases the temperature of transition to superconducting state (T_c), providing important information about pairing mechanisms in high T_c materials.

Another line of research was proposed by E. A. Kochetov and colleagues. Using the Kondo–Heisenberg model of strongly correlated electrons, they investigated the properties of the normal state of high-temperature superconductors in the lightly doped phase. In general, superconductivity manifests itself as an instability of the normal state, and understanding the nature of the normal state from which superconductivity arises is of exceptional importance. There is a huge amount of experimental evidence pointing to the rich and unusual physics of lightly doped cuprates. E. A. Kochetov et al. showed that the unusual physics of lightly doped cuprates is based on the effects generated by strong electron correlations, such as the destruction of long-range antiferromagnetic order at a critical doping of about 6%, which is in very good agreement with experiment[278], and the abrupt reconstruction of the large hole Fermi surface into small electron pockets in the pseudogap

[276] *Plakida N. M.* High-Temperature Cuprate Superconductors (Experiment. Theory, and Applications) // Springer Ser. Solid-State Sci. 2010. V. 166. P. 570.

[277] *Plakida N. M., Oudovenko V. S.* // Eur. Phys. J. B. 2013. V. 86. P. 115.

[278] *Ivantsov I., Ferraz A., Kochetov E.* // Phys. Rev. B. 2016. V. 94. P. 005100.

phase. This means that the standard Fermi liquid theory in the pseudogap phase does not work. The observed Fermi surface reconstruction can be explained directly within the microscopic Kondo–Heisenberg model, provided that strong electron correlations are fully taken into account[279]. It has been shown that the Fermi surface reconstruction leads to the emergence of a nodal electron pocket and two accompanying hole pockets, as was recently confirmed experimentally. All these properties indicate that the normal state of lightly doped cuprates shows essentially non-Fermi liquid behavior, generated by strong electron correlations.

Using computer simulation, A. A. Vladimirov et al.[280] developed a theory of relaxation functions for the dynamic spin susceptibility within the t–J model. The generalized mean-field approximation was used to calculate the spin correlation functions, which allowed good agreement to be achieved with neutron scattering experiments on $LaSrCuO_4$. Continuing the study of spin dynamics, Vladimirov et al.[281] presented a microscopic theory of the magnetic resonance mode in the superconducting state. The resonance mode, observed as a sharp magnetic peak at the antiferromagnetic wave vector, is an important characteristic of high-temperature superconductivity, and the theoretical predictions are in good agreement with experimental data for YBa_2Cu_3Oy compounds.

BOSE–EINSTEIN CONDENSATION AND QUANTUM SYSTEMS

Bose–Einstein condensation (BEC) is a macroscopic quantum phenomenon in which a large fraction of bosons occupies the same quantum state, leading to coherent collective behavior. This phenomenon plays a central role in understanding fundamental quantum-statistical effects and phase transitions in various physical systems. The theoretical description of BEC is based on quantum field theory, where spontaneous symmetry violation and long-range coherence arise naturally during the condensation process.

V. I. Yukalov[282] considered the features of BEC in systems with conserved and non-conserved numbers of particles, emphasizing the role of gauge symmetry violation in the possibility of implementing BEC. The study covered various systems, including cold atomic gases and magnons, taking into account the differences between equilibrium and nonequilibrium condensates. The features of symmetry violation in finite quantum systems, in particular, in the case of BEC, were studied[283]. The analysis touched upon the key issues of stability and the absence of an energy gap in states with Bose condensation. A detailed review[284] on the physics of cold atoms was published, where current mathematical methods allowing for increasing the accuracy of the theoretical description were presented.

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[280] *Vladimirov A. A., Ihle D., Plakida N. M.* // Phys. Rev. B. 2009. V. 80. P. 104425.
[281] *Vladimirov A. A., Ihle D., Plakida N. M.* // Phys. Rev. B. 2011. V. 83. P. 024411.
[282] *Yukalov V. I.* // Laser Phys. 2012. V. 22. P. 1145.
[283] *Birman J. L., Nazmitdinov R. G., Yukalov V. I.* // Phys. Rep. 2013. V. 526. P. 1.
[284] *Yukalov V. I.* // Laser Phys. 2013. V. 23. P. 062001.

FRACTALS AND SMALL-ANGLE SCATTERING

Fractal structures are widespread in nature and condensed matter physics. They are characterized by self-similarity and scale invariance. These structures often arise from complex dynamic processes, resulting in hierarchical patterns that repeat at different spatial scales. Understanding the structural properties of fractals is essential for analyzing materials with non-standard (non-Euclidean) geometries, such as porous media, polymer networks, and aggregated particles. Small-angle neutron, X-ray, and light scattering techniques offer powerful tools for investigating the internal structure of fractal systems at the nanoscale. Small-angle scattering provides information on the size, shape, and spatial arrangement of scattering centers, making it indispensable for characterizing both bulk and surface fractals.

E. Anitas[285] conducted a comprehensive analysis of small-angle scattering from complex fractal structures, distinguishing between mass and surface fractals. The study emphasized the importance of accurately modeling the scattering intensity for the reliable determination of structural characteristics. In fractal systems, the scattering intensity follows a characteristic power law, reflecting the self-similar nature of the main structure. A. Yu. Cherny et al.[286, 287] presented theoretical models of generalized Cantor fractals, investigating how changes in fractal dimension affect scattering profiles. These models help to distinguish deterministic fractal patterns from random ones, which provides a deeper understanding of the geometric complexity of real systems.

A. Yu. Cherny et al.[288] developed promising analytical methods for studying data on small-angle scattering from deterministic mass and surface fractals. The study showed that deterministic structures exhibit important scattering features compared to random fractals. It was noted that the periodicity of the scattering curves on a logarithmic scale indicates a self-similar structure of deterministic fractals. Furthermore, Cherny et al.[289] focused on extracting detailed structural information from the scattering intensity curves of deterministic mass fractals. They identified logarithmic periodicity in momentum space as a characteristic feature, relating it to pair correlation functions in real space. The proposed approach has found a wide response among specialists, since it allows for more accurate modeling of systems where fractal geometry determines the scattering behavior.

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[285] *Anitas E. M.* Small-Angle Scattering (Neutrons, X-Rays, Light) from Complex Systems // Springer Briefs in Physics. Springer International Publishing: Cham, Switzerland, 2019. 116 p.

[286] *Cherny A. Yu., Anitas E. M., Kuklin A. I., Balasoiu M., Osipov V. A.* // J. Appl. Cryst. 2010. V. 43. P. 790.

[287] *Cherny A. Yu., Anitas E. M., Osipov V. A., Kuklin A. I.* // Phys. Chem. Chem. Phys. 2017. V. 19. P. 2261.

[288] *Cherny A. Yu., Anitas E. M., Osipov V. A., Kuklin A. I.* // Phys. Chem. Chem. Phys. 2019. V. 21. P. 12748.

[289] *Cherny A. Yu., Anitas E. M., Osipov V. A., Kuklin A. I.* // Phys. Rev. E. 2011. V. 84. P. 036203.

THEORY OF SELF-ORGANIZED CRITICALITY AND EXACTLY SOLVABLE MODELS OF STATISTICAL PHYSICS

By the early 1990s, the theory of phase transitions and critical phenomena in equilibrium systems was a mature, well-developed field. Progress in studying similar phenomena far from thermodynamic equilibrium was incomparably more modest due to the lack of a general approach that would provide an analogue to the Boltzmann–Gibbs theory applicable to equilibrium systems. An important step in this direction was the theory of self-organized criticality proposed by Buck, Tang, and Weisenfeld. It provided a unified understanding of the mechanisms responsible for the formation of large-scale self-similar structures and the development of giant avalanche-like fluctuations in systems with a large number of degrees of freedom and nonlinear threshold dynamics. The range of phenomena described by self-similar statistical laws is extremely broad: from earthquakes and forest fires to stock markets and noise in electronic devices.

Due to the complexity of the approximate description of such systems, exactly solvable models with avalanche dynamics, such as the sandpile model and related models, turned out to be the most effective means of studying them. In the 1990s and 2000s, a group led by V. B. Priezzhev became a world leader in the field of exact solutions of self-organized criticality models. The starting point of this activity can be considered the pioneering calculation by V. B. Priezzhev of the height probabilities of in the Abelian sandpile model on a plane square lattice[290]. Finally completed fifteen years later[291], it was followed by several works by competing groups that reproduced the result using alternative approaches. This research required the development of substantially new combinatorial methods, which subsequently became an important part of mathematical and statistical physics. Using them, V. B. Priezzhev's group also obtained many striking results on the structure of avalanches and correlation functions in the sandpile model[292, 293, 294, 295], which, in particular, provide one of the few examples of an exact calculation of the correlation functions predicted by the recently constructed logarithmic conformal field theory. Also, as part of the search for models demonstrating self-organized criticality, V. B. Priezzhev, together with an Indian group, proposed a new model of Eulerian walks[296], a simplification of the sandpile model, which subsequently found many applications and was widely studied by both Priezzhev's group and other groups.

The interest of the scientific community in this topic and the international significance of the obtained results motivated the holding of such international workshops at BLTP as "Self-Similar Systems" (1998) and "Logarithmic Conformal

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[290] *Priezzhev V. B.* // J. Stat. Phys. 1994. V. 74. P. 955.

[291] *Poghosyan V. S., Priezzhev V. B., Ruelle P.* // J. Stat. Mech. 2011. P10004.

[292] *Ivashkevich E. V., Ktitarev D. V., Priezzhev V. B.* // Physica A. 1994. V. 209. P. 347.

[293] *Ivashkevich E. V.* // J. Phys. A: Math. Gen. 1994. V. 27. P. 3643.

[294] *Priezzhev V. B.* // J. Stat. Phys. 2000. V. 98. P. 667.

[295] *Poghosyan V. S., Grigorev S. Yu., Priezzhev V. B., Ruelle P.* // Phys. Lett. B. 2008. V. 659. P. 768.

[296] *Priezzhev V. B., Dhar D., Dhar A., Krishnamurthy S.* // Phys. Rev. Lett. 1996. V. 77. P. 5079.

Field Theories and Statistical Mechanics" (2011), which brought together leading experts in these fields.

INTERACTING PARTICLE MODELS AND THE KARDAR–PARISI–ZHANG UNIVERSALITY

In recent years, integrable interacting particle models have been widely used as a research laboratory for studying universal statistical laws describing the random evolution of nonequilibrium systems under the action of random forces. Examples of such systems include random fronts and interfaces, such as combustion, wetting, sedimentation, and bacterial colony growth fronts, traffic flows with random dynamics, and polymers in random media. Large classes of such systems are characterized by identical statistical behavior on large spatiotemporal scales, defined by power laws with universal exponents. An example is the Kardar–Parisi–Zhang class, first discovered in the study of random surface growth and exhibiting an exceptionally broad range of applicability.

The conducted study of interacting particle systems was aimed at obtaining new results for known models, as well as at constructing new models that, on the one hand, would preserve the integrability property, ensuring the possibility of an exact solution, and on the other hand, would include new interactions that make it possible to test the universality of the Kardar–Parisi–Zhang class, and to describe the mechanisms of its violation and find examples of changes in the type of large-scale behavior. In this direction, several new integrable models with different types of interparticle interactions were proposed and investigated, such as the asymmetric avalanche process[297], the zero range process[298], and the generalized totally asymmetric simple exclusion process[299]. Among the important results, it is necessary to note the first explicit solution of the equation for the transition probabilities between particle configurations in an asymmetric simple exclusion process on a periodic lattice, obtained by V. B. Priezzhev[300], and the construction by A. M. Povolotsky of the most general three-parameter family of exactly solvable particle models with multiparticle jumping and a factorized steady state, including many well-known models as special cases[301]. These results received wide international recognition and formed the basis for further studies of the Kardar–Parisi–Zhang universality class, stochastic vertex models, polymers in random environments, etc.

QUANTUM INTEGRABLE SYSTEMS AND SUPERCONFORMAL INDICES

A fundamentally new class of special functions in mathematical physics — elliptic hypergeometric functions — was discovered in a series of papers writ-

[297] *Priezzhev V. B., Ivashkevich E. V., Povolotsky A. M., Hu C. K.* // Phys. Rev. Lett. 2001. V. 87. P. 084301.

[298] *Povolotsky A. M.* // Phys. Rev. E. 2004. V. 69. P. 061109.

[299] *Derbyshev A. E., Povolotsky A. M., Priezzhev V. B.* // Phys. Rev. E. 2015. V. 91. P. 022125.

[300] *Priezzhev V. B.* // Phys. Rev. Lett. 2003. V. 91. P. 050601.

[301] *Povolotsky A. M.* // J. Phys. A. 2013. V. 46. P. 465205.

ten by V. P. Spiridonov between 2000 and 2025. The results obtained generalize many classical achievements in the theory of special functions with new applications in quantum field theory, statistical mechanics, and quantum integrable systems[302].

In a pioneering paper published in 2000, discrete elliptic biorthogonal rational functions of the classical type were constructed, and later the most general functions of this type were found, possessing two-index biorthogonality — a new type of orthogonality relation. A key result was the evalulation of the elliptic beta integral, the most complex known exactly calculated integral, defining a general universal relation in mathematical physics. A theory of transcendental elliptic hypergeometric functions was formulated, and many exact relations for multidimensional integrals on root systems were proposed. An elliptic analog of the Euler–Gauss hypergeometric function was constructed, and an elliptic hypergeometric equation was discovered that defines the most general Schrödinger equation, whose solutions are known in closed form. These results are the final achievements of the program for constructing the most general exactly solvable physical models, developed by Spiridonov over 15 years from the end of the 1980s.

Two versions of the elliptic generalization of the Faddeev modular double — the most general quadratic quantum algebras — have been constructed in the field of quantum integrable systems. An integral Bailey chain has been built, defining an elliptic analogue of the Fourier transform and determining the most general star-triangle relation in operator form. It was shown that the operator of the elliptic Fourier transform intertwines equivalent representations of the elliptic modular double and defines the most general solution of the Yang–Baxter equation. A generalization of a number of the above results to the case of rarefied functions of hypergeometric type associated with parafermion conformal field theory is constructed[303].

In 2008, Dolan and Osborne discovered that the superconformal indices of four-dimensional supersymmetric field theories are described by elliptic hypergeometric integrals, and their symmetry transformations prove the Seiberg hypothesis of the electromagnetic duality of different theories in the BPS sector. Thus, the elliptic beta integral[302] justifies confinement in the simplest supersymmetric quantum chromodynamics. In the works of Spiridonov and Vartanov, many new Seiberg-type dualities were proposed, and the connection between the 't Hooft conditions for the agreement of anomalies and the modular properties of superconformal indices, as well as the connection between the confinement with chiral symmetry breaking with the singularities of these indices, was discovered. Moreover, Spiridonov found a connection between the partition functions of two-dimensional integrable Ising-type systems and the superconformal indices of quiver models, showing that Seiberg duality underlies all quantum integrable models. New mul-

[302] *Spiridonov V. P.* // Usp. Mat. Nauk. 20028. V. 63, No. 3. P. 3; Additional chapter to the Russian translation of the book by R. Askey, R. Roy, G. E. Andrews "Special Functions". MCCME, Moscow, 2013 (in Russian).

[303] *Spiridonov V. P.* // Adv. Math. 2018. V. 331. P. 830; J. Phys. A. 2019. 52. 355201; *Sarkissian G. A., Spiridonov V. P.* // Proc. Steklov Inst. Math. 2020. V. 309. P. 269 (in Russian).

tiparticle integrable systems related to representations of the Lorentz group were discovered[304].

The significant progress achieved at BLTP in such topics as the theory of integrable systems and the theory of special functions explains the fact that they constituted a significant part of the program of the annual thematic conferences "Quantum and Classical Integrable Systems", which are well known among specialists and which, in particular, were organized by BLTP in 2012 and 2017.

TOPOLOGICAL DEFECTS, NANOSTRUCTURES AND TRANSPORT PHENOMENA

Topological and geometric methods are widely used to describe modern materials. This is due to the presence of objects with nontrivial topology in real materials, requiring an analysis of their influence on the entire spectrum of physical properties, as well as the discovery of an entire class of topological materials, the most well-known of which are topological dielectrics and topological semimetals. Linear defects known as dislocations and disclinations are carriers of nontrivial topology in elastic media. Until almost the end of the last century, the role of dislocations and translational defects was actively studied, while the study of disclinations, rotational defects, or vortices in elastic media was of more academic interest. The situation changed dramatically after the synthesis of carbon nanostructures, when it was discovered that such defects inevitably arise in closed nanotubes, cones, and fullerenes. The topic gained even greater relevance after the discovery of polycrystalline graphene, where crystallite boundaries are formed from disclination dipoles.

V. A. Osipov was the initiator and leader of this topic in BLTP. The work was carried out in two directions: the construction of a continuous field-theoretical model for describing topological defects and their influence on the electronic structure in materials with different geometries and the analysis of transport characteristics (thermal and electrical conductivity) of materials with a polycrystalline structure.

The first fundamental work that initiated the study of the electronic properties of carbon nanostructures at BLTP JINR was published[305] in 1999. It formulated a gauge theory of disclinations on arbitrary Riemann surfaces that can change both the Gaussian and mean curvatures during deformation. The model for describing the carbon film took into account the specifics of the electronic states (a Dirac-type model) and was expanded by self-consistent inclusion of fermion fields. An important advantage of this model was the possibility of an analytical description of the electronic characteristics and the ability to take into account the effects of long-range fields. Within the formulated model, it was possible to analyze the influence of disclinations on the electronic structure of graphite cones, fullerenes, spheroidal fullerenes, and closed nanotubes, as well as to investigate the role of

[304] *Sarkissian G. A., Spiridonov V. P.* // SIGMA. 2020. V. 16. P. 074; J. Phys. A. 2022. V. 55. P. 385203.

[305] *Kochetov E. A., Osipov V. A.* // J. Phys. A. 1999. V. 32. P. 1961.

an external magnetic field[306, 307, 308, 309]. One of the most significant results, which received a wide response among specialists, is the exact solution to the problem of the electronic properties of spherical (Ih) fullerenes[310], where the electronic wave functions and spectrum of fullerenes were found in explicit form for the first time, and restrictions on the number of zero modes and the energies of the first levels were also obtained.

Polycrystalline materials are characterized by the presence of grain boundaries, which are a source of additional elastic stresses, which, in turn, determines the specific transport characteristics of such materials. It turned out that the stress fields from grain boundaries can be modeled by a disclination dipole. The pioneering work, which ensured priority in the study of transport problems in polycrystalline materials and marked the beginning of a long-term cycle of articles on this topic, was the article[311], in which the problem of phonon scattering at a finite-length grain boundary was solved for the first time. S. E.Krasavin made a fundamental contribution to the development of this area of research. In particular, within the developed approach, it was possible to explain the behavior of thermal conductivity in amorphous dielectrics and other disordered materials[312]. The fact that the proposed model makes it possible to explain the low-temperature behavior of the thermal conductivity of glasses in the so-called plateau region is of particular interest. Of greatest interest are the results describing thermal conductivity[313] and, in particular, the behavior of resistivity in single-layer polycrystalline graphene[314]. An original model has been developed that allows for the description of the interaction of carriers (phonons, electrons) with deformations of the graphene lattice caused by grain boundaries. The actual structure of the grain boundary, as a sequence of disclination dipoles, was strictly taken into account. This made it possible to obtain for the first time good agreement with experimental data on specific resistivity measurements in a wide range of polycrystalline graphene samples with varying crystallite sizes.

A separate line of research, led by V. L. Katkov, involved the analysis of quantum and tunnel transport in various carbon nanostructures[315]. The most striking result in this area was the development of a fundamentally new version of a graphene-based tunnel field-effect transistor, operating on new, original principles[316]. A key factor in its operation is the use of localized electronic states present in graphene at the zigzag edge. The proposed switching mechanism has fundamentally expanded the range of known switching electronic devices (transistors). It effectively utilizes the unique properties of graphene, such as edge states and two-dimensionality,

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306 *Osipov V. A., Kochetov E. A.* // JETP Lett. 2001. V. 73. P. 631.
307 *Osipov V. A., Kochetov E. A., Pudlak M.* // JETP. 2003. V. 123. P. 161.
308 *Kolesnikov D. V., Osipov V. A.* // JETP Lett. 2004. V. 79. P. 660.
309 *Pudlak M., Pincak R., Osipov V. A.* // Phys. Rev. A. 2007. V. 75. P. 025201.
310 *Kolesnikov D. V., Osipov V. A.* // Eur. Phys. J. B. 2006. V. 49. P. 465.
311 *Osipov V. A., Krasavin S. E.* // J. Phys. Cond. Mat. 1998. V. 10. P. L639.
312 *Krasavin S. E., Osipov V. A.* // J. Phys. Cond. Mat. 2002. V. 14. P. 12923.
313 *Krasavin S. E., Osipov V. A.* // J. Appl. Phys. 2019. V. 125. P. 084301.
314 *Krasavin S. E., Osipov V. A.* // Sci. Rep. (Nature). 2022. V. 12. P. 14553.
315 *Katkov V. L., Osipov V. A.* // J. Vac. Sci. Technol. B. 2017. V. 35. P. 050801.
316 *Katkov V. L., Osipov V. A.* // Appl. Phys. Lett. 2014. V. 104. P. 053102.

while simultaneously avoiding the negative effect of the Klein paradox by using the gap between the electrodes (the "nanogap"). The uniqueness of the study also lies in the fact that a patent was issued for the invention of this tunnel field-effect transistor[317].

Another important result relates to the study of the mechanism of DNA molecule decoding using graphene electrodes separated by a nanogap[318]. The main idea here is to use the tunneling current in the graphene–nucleotide–graphene system as a factor for identifying the nucleotide type. Phenomena such as the possibility of random nucleotide orientation and localization during its passage through the nanogap and the influence of the Coulomb blockade effect on the tunneling current in this system were taken into account. The study yielded a conclusion important for practical implementation: when conducting statistical analysis, it is necessary to use not only the average tunneling current value but also its standard deviation as a factor for nucleotide identification.

The organization and holding of a series of international conferences "Dubna-Nano"[319], attended by leading specialists from more than 40 countries, evidenced the success achieved by the BLTP staff in the field of nanophysics. The program committee included prominent scientists, including Nobel laureate K. S. Novoselov. Several schools for young scientists were also held, featuring lectures on the physics of nanostructures and nanoscale phenomena.

METHODS OF QUANTUM FIELD THEORY IN CONDENSED MATTER PHYSICS

Methods of quantum field theory are an important and integral part of the mathematical arsenal of modern theoretical physics. Originally developed to describe the relativistic physics of elementary particles, they subsequently, in combination with methods of nonequilibrium statistical physics, became widely used in solving problems of classical physics in which fluctuations play a key role. N. N. Bogoliubov, a distinguished scientist and a classic figure in world science, made a significant contribution to the development of these methods. He was the first director of the Laboratory of Theoretical Physics, which now bears his name. His work at BLTP had a significant impact on the formation and development of many research areas at the Laboratory.

In 2022, at the initiative of M. Hnatic and V. A. Osipov, and with the support of D. I. Kazakov, BLTP Director, a new sector "Methods of quantum field theory in complex systems" was created within the Department of Condensed Matter Theory, bringing together scientists working in this field. The sector was headed by M. Hnatic, a representative of Slovakia, a JINR Member State. His huge experience at BLTP and extensive international contacts with leading scientists in this

[317] *Katkov V. L., Osipov V. A.* Graphene-Based Tunnel Field-Effect Transistor. Patent for Invention No. 2554694, Official Bull. "Inventions. Utility Models". 2015. V. 18. P. 2 554 694.

[318] *Isaeva O. G., Katkov V. L., Osipov V. A.* // Eur. Phys. J. B. 2014. V. 87. P. 272.

[319] *Osipov V. A. et. al.* // J. Phys.: Conf. Ser. 2008. V. 129. P. 011001; J. Phys.: Conf. Ser. 2010. V. 248. P. 011001; J. Phys.: Conf. Ser. 2012. V. 393. P. 011001.



Z. Alisultanov (MIPT) and N. M. Plakida



A. Yu. Cherny, E.-M. Anitas, and R. G. Nazmitdinov



V. A. Osipov



A. A. Donkov and K. K. Kesharpu



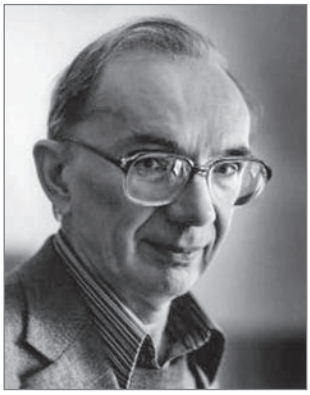
P. N. Pyatov, G. Yu. Chitov, V. P. Spiridonov, N. Zh. Bunzarova, and A. M. Povolotsky



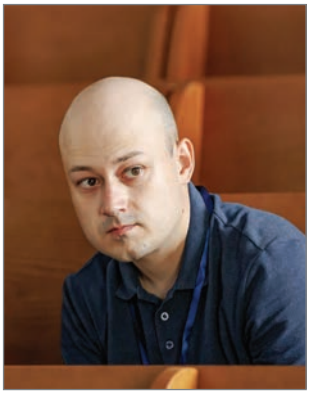
S. E. Krasavin



V. L. Katkov



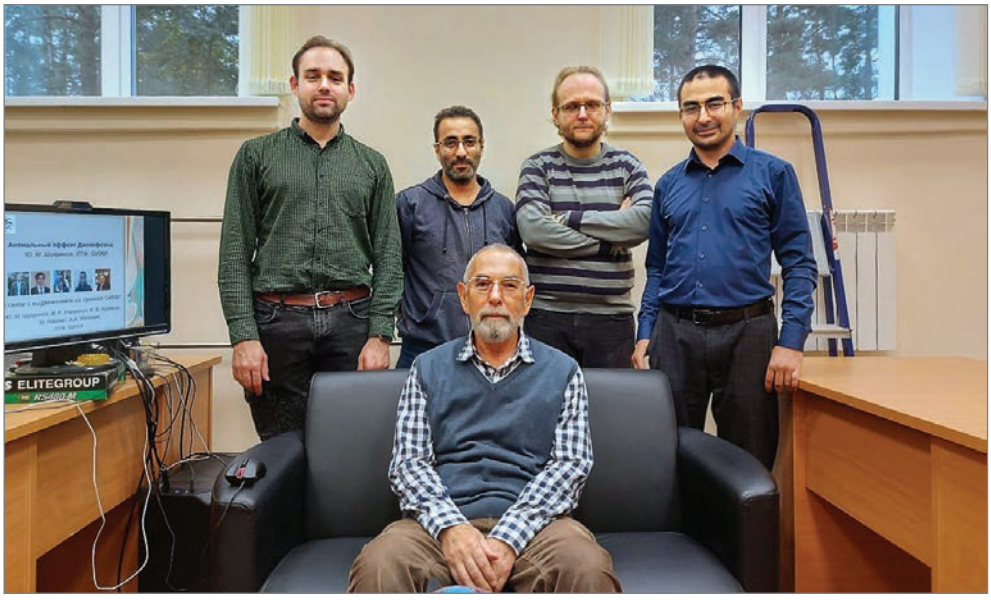
V. B. Priezzhev



P. A. Maksimov



Hoang Ngoc Cam



K. V. Kulikov, M. Abdelghani, Yu. M. Shukrinov, A. A. Mazanik, and I. R. Rahmonov



M. Hnatič



N. M. Lebedev (center)



M. Kecer and L. Mižišin



G. A. Kalagov (right)



The International Conference "Modern Problems of Condensed Matter Theory". Dubna, 2022

field allowed the sector to be quickly staffed with both highly qualified specialists and young researchers.

The research here is based on the fact that the development of statistical field theory methods, which combine approaches of quantum field theory and nonequilibrium statistical physics, allows formulating a wide class of stochastic dynamics problems as effective field models and investigate their universal scaling behavior over large-scale spatiotemporal coordinates. These approaches are being actively developed and applied to new areas, including problems in classical physics, for describing closed systems and their phase transitions, as well as open dissipative systems. The latter include stochastic dynamics problems such as developed turbulence, stochastic magnetohydrodynamics, percolation processes, chemical reaction kinetics, self-organizing systems, etc. The use of modern computational methods and high-performance computing systems ensures high accuracy in calculating critical exponents and control parameters. M. Hnatic's group is currently conducting research on a wide range of the aforementioned problems and has already obtained a number of internationally recognized results.

The theoretical description of turbulence is a critical unsolved problem in classical physics. Turbulent flows arising in various liquids or gases at very high Reynolds numbers exhibit a range of common properties and phenomena (a cascade of energy or other conserved quantities, scaling behavior with apparently universal power-law anomalous exponents, etc.), indicating that they can be described within an internally consistent theory. The most notable feature of developed turbulence, which does not fit within the framework of the classical phenomenological Kolmogorov–Obukhov theory, is intermittency arising from strong fluctuations in the energy dissipation rate and manifesting itself in a singular dependence, presumably a power-law one, of simultaneous correlation and structure functions on distance, characterized by an infinite number of independent anomalous exponents (multiscaling). Both experiments and numerical simulations show that anomalous scaling is more pronounced for the passive transport of scalar/vector fields of temperature, impurity density, and magnetic field than for the velocity field itself, so the problem of passive transport is an integral part of the study of scaling in turbulent media.

Methods of statistical field theory made it possible to analytically prove the existence of multiscaling for passive scalar and vector impurities in developed turbulent flows. Critical indices for composite operators that provide the main singular contribution to the operator Wilson expansion of structure functions were calculated with two- and three-loop accuracy. A decisive contribution to the development of this area, as well as to specific calculations, was made by L. Ts. Adzhemyan, N. V. Antonov, and other colleagues from A. N. Vasiliev's school[320, 321, 322]. Control parameters such as the Kolmogorov constant, Prandtl number, universal amplitudes, etc. are important experimentally measurable quantities in developed turbu-

[320] *Adzhemyan L. Ts., Antonov N. V., Barinov V. A., Kabrits Yu. S., Vasiliev A. N.* // Phys. Rev. E. 2001. V. 63. P. 025303(R).

[321] *Adzhemyan L. Ts., Antonov N. V., Hnatich M., Novikov S. V.* // Phys. Rev. E. 2001. V. 63. P. 016309.

[322] *Antonov N. V., Hnatich M., Honkonen J., Jurčišin M.* // Phys. Rev. E. 2003. V. 68. P. 046306.

lence. They were calculated with two-loop accuracy and published in the works of L. Ts. Adzhemyan, N. Antonov, M. Hnatic, and others[323, 324, 325, 326]. The obtained values are in good agreement with experimentally measured ones.

The generation and maintenance of the observed magnetic fields of planets, the Sun, stars, and entire galaxies is an intriguing theoretical problem that has fascinated scientists for decades. However, we are still far from a complete understanding of this interesting phenomenon. Formulating stochastic magnetic dynamics, which is the basis for describing magnetic fields in conducting turbulent media, as a field model allows viewing the generation of magnetic fields as a phenomenon closely related to the preservation or violation of certain symmetries in the turbulent medium. It turns out that in a parity-violated medium, the formation of a large-scale magnetic field, known as a turbulent dynamo, occurs spontaneously, violating spherical symmetry. This dynamo is the mechanism that allows eliminating the exponential growth of small-scale magnetic fluctuations. The study of this mechanism, begun 40 years ago, has now resulted in the calculation of the magnetic field with two-loop accuracy. An important result of the research by Hnatic et al. is the prediction, along with the generation of a uniform magnetic field, of the appearance of stable perturbations of Alfvén waves, reminiscent of Goldstone modes during phase transitions[327, 328].

Percolation is a striking example of the diverse phenomena of nonequilibrium statistical physics. It describes a wide range of phenomena such as the spread of epidemics, forest fires, the generation of turbulence, and others. Currently, the most studied models are those of directed and isotropic percolation, which describe two different classes of universality. The power-law behavior of statistical characteristics, such as the effective size of the agent cloud, their mass, and the size of active zones, on large time scales can be studied within field models. Using perturbative renormalization techniques, the corresponding critical indices with record-breaking three-loop accuracy for directed and isotropic percolation were calculated [329, 330].

Along with perturbative renormalization group methods, the functional renormalization group (FRG) has gained increasing importance in recent years. This modern method is particularly relevant for studying strongly interacting systems, as well as in situations where non-universal behavioral features are significant. Specifically, it was used to study the superfluid phase transition in multicomponent

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[323] *Adzhemyan L. Ts., Hnatich M., Horvath D., Stehlik M.* // Phys. Rev. E. 1998. V. 58. P. 4511.

[324] *Adzhemyan L. Ts., Antonov N. V., Kompaniets M. V., Vasil'ev A. N.* // Int. J. Mod. Phys. B. 2003. V. 17. P. 2137.

[325] *Adzhemyan L Ts., Hnatich M., Honkonen J.* // Eur. Phys. J. B. 2010. V. 73. P. 275.

[326] *Hnatič M., Honkonen J., Lučivjanský T.* // Acta Physica Slovaca. 2016. V. 66. P. 69.

[327] *Hnatič M., Lučivjanský T., Mižišin L., Molotkov Yu., Ovsiannikov A.* // Universe. 2024. V. 10. P. 240.

[328] *Hnatič M., Lučivjanský T., Mižišin L., Molotkov Yu., Ovsiannikov A.* // Phys. Rev. E. 2025. V. 112. P. 015211.

[329] *Adzhemyan L. Ts., Hnatic M., Ivanova E. V., Kompaniets M. V., Lucivjansky T., Mizisin L.* // Phys. Rev. E. 2023. V. 107. P. 064138.

[330] *Hnatič M., Kecer M., Kompaniets M. V., Lučivjanský T., Mižišin L., Molotkov Yu.* // Phys. Rev. 2025. V. 112. P. 014113.

Fermi systems with $SU(N)$ symmetry for arbitrary scattering lengths, allowing both perturbative and non-perturbative regimes to be covered. The functional renormalization group approach allowed for the correct inclusion of fluctuation corrections that are in principle not described in mean-field theory. It was established that for $N > 2$, the system undergoes a first-order phase transition, representing qualitatively new behavior. It was possible for the first time to quantitatively determine the most important characteristics of this transition — the critical temperature, the superfluid gap jump at the transition point, and the entropy jump associated with the release of latent heat. In addition, it was shown that the severity of the first-order transition enhances with an increase in the number of components N, which emphasizes the key role of the multicomponent nature in the formation of fluctuation-induced effects in strongly interacting Fermi systems[331, 332].

It is worth noting the longstanding and fruitful scientific ties on this topic between BLTP and the Saint Petersburg State University, the Pavol Jozef Šafárik University in Košice (Slovakia), and the University of Helsinki (Finland). Some of the results of scientific achievements in this area, obtained over the past decades, are summarized and published in a book chapter[333] and a review article[334].

MODERN MATHEMATICAL PHYSICS

In the early 2000s, due to the emerging demand for new mathematical methods in theoretical physics, modern mathematical physics was made a separate area at BLTP. Professor A. T. Filippov, who pioneered this field and was BLTP director at that time, sought to attract as many young people with a strong mathematical background as possible. Theorists were needed with a good command of methods in group theory and Lie algebras, Riemann geometry, topology, discrete mathematics, complex analysis of many variables, and other areas of pure mathematics. In formulating the new topic, A. T. Filippov conducted a broad discussion that extended far beyond the Institute and the country: Academician D. V. Anosov from the Steklov Mathematical Institute of the Russian Academy of Sciences, Yu. I. Manin, Director of the Max Planck Institute in Bonn, L. Alvarez-Gaume, Director of the Theory Department at CERN, J. Wess, Heinemann Prize winner and Professor of the University of Munich, and many others expressed their support.

Within the Institute, the idea of developing a new research topic also received support, as both V. G. Kadyshevsky and A. N. Sissakian, members of the central directorate, understood the need to strengthen the mathematical component of the Laboratory's life. The core of the new research area was formed by scientists who had worked at the Laboratory for many years and were well known for their

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[331] *Hnatič M., Kalagov G.* // Nucl. Phys. B. 2023. V. 991. P. 116192.

[332] *Kalagov G.* // Phys. Rev. B. 2025. V. 111. P. 214523.

[333] 50 Years of the Renormalization Group Dedicated to the Memory of Michael E. Fisher. World Scientific, 2024.

[334] *Antonov N. V., Hnatič M., Honkonen J., Kakin P. I., Lučivjanský T., Mižišin L.* // La Riv. Nuovo Cim. 2024. V. 47. P. 653.

results in gravitational theory, cosmology, and the theory of classical and quantum integrable systems. A. T. Filippov, B. M. Barbashov, V. V. Nesterenko, E. A. Ivanov, A. P. Isaev, S. O. Krivonos, A. S. Sorin, and P. Fiziev laid the foundation on which the new research area was built. Younger researchers who were brought into the work always found advice and support from the older generation, which helped create a wonderful atmosphere of collaborative creativity.

Below is a brief overview of the main topics of research conducted within modern mathematical physics in recent years.

GEOMETRY OF LAGRANGIAN SUBMANIFOLDS

One of the priority areas is the geometry of Lagrangian submanifolds of compact phase spaces. Lagrangian submanifolds, which initially arise in classical mechanics as Liouville tori, are closely related to the phenomenon of integrability: when a system is completely integrable, motion occurs along submanifolds of half the dimension, each being a Lagrangian. The term "Lagrangian submanifold" was introduced by V. P. Maslov in connection with his studies of short-wavelength asymptotics of partial differential equations. Finding a suitable compact Lagrangian submanifold in the phase space superposed on the configuration space — the carrier of the system of differential equations — is a key step in constructing the canonical operator. Another important subject in modern mathematical physics, in which Lagrangian submanifolds play a significant role, is geometric quantization. There are two main approaches to geometric quantization, and while the first is based on the study of vector bundles over phase space, the second is based on considerations of Lagrangian foliations.

Toric manifolds were proposed as a generalization of the phase spaces of completely integrable systems. Therefore, each toric manifold is associated with a class of Lagrangian submanifolds, which are obtained similarly to Liouville tori in the case of a completely integrable system. It is from these standard Lagrangian tori that one can construct a reasonable category within homological mirror symmetry. However, two problems arise from the standpoint of possible applications in string theory: first, there are no smooth toric Calabi–Yau manifolds; second, there is no guarantee that for a given toric manifold every Lagrangian torus is equivalent to the standard one. Even in the simplest basic case, when the phase space is considered to be the complex projective plane, there exists an exotic torus that is not equivalent to the standard Clifford torus.

In the context of geometric quantization problems, N. A. Tyurin presented the program "Geometric quantization in the framework of algebraic Lagrangian geometry", which implemented a nonlinear generalization of the construction of geometric quantization of a system with a compact phase space in terms of the Lagrangian geometry of this phase space. Specifically, for an arbitrary compact phase space satisfying the Arnold prequantization condition, a nonlinear version of the quantum-mechanical model can be constructed in which special Berezin symbols serve as quantized observables. The construction aroused intense interest in V. P. Maslov's school, since it implicitly utilized the geometric foundations of the

theory of semiclassical approximations. The results were presented in the dissertation[335] and in the review[336].

Furthermore, significant progress has been made in the construction of non-standard tori in toric manifolds, made possible by the introduction of the concept of a pseudotoric structure. This structure arose as a mathematical generalization of the concept of spin in the theory of elementary particles: an incomplete set of ordinary classical integrals is used instead of a complete set of first integrals, plus a set of complex-valued functions, with the commutation condition of the classical integrals and the last complex-valued integrals naturally introduced by analogy with the classical case. The construction of an exotic twisted torus was explained in terms of such structures, and numerous examples were given of how such exotic tori can be constructed on arbitrary toric manifolds in combinatorial terms. Furthermore, it was established that many phase spaces of incompletely integrable systems possess similar structures, which allows constructing analogs of the classical action-angle coordinates in more general cases (and hence finding solutions). The main results of this work are presented in the review[337].

A program called Bohr–Sommerfeld Special Geometry was proposed for the problem of constructing finite-dimensional moduli spaces of Lagrangian submanifolds. By developing the SYZ construction approaches, a suitable condition was found which links the prequantization data on an arbitrary compact Lagrangian submanifold and an auxiliary field — a holomorphic section of the prequantization bundle — in the case where the phase space is a Kähler manifold. This condition arises naturally not only in the case of Calabi–Yau manifolds, but also for a much wider class of target spaces. A large number of technical difficulties encountered along the way allowed connecting our constructions with purely mathematical hypotheses known in research on the geometry of symplectic manifolds. The main results obtained in this field are summarized in the review[338].

It was impossible not to take interest in the purely mathematical side of the matter during the course of work: as it turned out, the problem of classifying Lagrangian submanifolds of even the most basic algebraic varieties largely consists of blank spots. From a physical perspective, the Grassmannian $\mathrm{Gr}(r, n)$ is a remarkable example of an algebraic manifold. This manifold simultaneously admits solutions to the Einstein equation (in this case, Kähler–Einstein metrics are involved) and admits a decomposition of the tangent bundle into a tensor product of a pair of Hermitian bundles, which act as analogs of spinor bundles, so that the Grassmannian has analogs of Dirac operators. Furthermore, modern approaches to supersymmetry are impossible without Grassmann variables. And yet, until recently, there were only two examples of Lagrangian submanifolds in this algebraic manifold. In a series of works, specifically in the latest and most general one[339],

[335] *Tyurin N. A.* Geometric Quantization in the Framework of Algebraic Lagrangian Geometry. Doctoral (Phys.–Math.) Dissertation. Moscow: Steklov Math. Inst. RAS, 2002.

[336] *Tyurin N. A.* // LMS Lect. Notes. 2007. V. 338. P. 279.

[337] *Tyurin N. A.* // Usp. Mat. Nauk. 2017. V. 72, No. 3. P. 131 (in Russian).

[338] *Tyurin N. A.* // Usp. Mat. Nauk. 2025. V. 80, No.2. P. 123 (in Russian).

[339] *Tyurin N. A.* // Izv. RAN. Ser. Mat. 2025. V. 89, No.2. P. 146 (in Russian).

a large series of examples of Lagrangian submanifolds in Gr(r, n) were constructed, and their topological properties were also investigated.

SPLIT CASIMIR OPERATOR, DEGREES OF THE ADJOINT REPRESENTATION, AND VOGEL PARAMETERS

It is known that a special invariant operator, the split (or polarized) Casimir operator C, plays an important role both in the description of Lie algebras g and in the study of their representation theory[340]. On the other hand, the split Casimir operator C is a building block for constructing g-invariant solutions r and R of the semiclassical and quantum Yang–Baxter equations. It is worth recalling that g-invariant rational solutions of the Yang–Baxter equations allow defining Yangians $Y(g)$ — the latest objects in symmetry theory — within the so-called RTT realization. Split Casimir operators have also proven useful[341] in calculating color coefficients for Feynman diagrams in non-Abelian gauge theories.

In a series of papers by A. P. Isaev, S. O. Krivonos, and colleagues[342, 343, 344, 345], the usefulness of the g-invariant split Casimir operator (and its generalizations, the k-split Casimir operators $C_{(k)}$) in the representation theory of Lie algebras was demonstrated. Specifically, for all simple Lie algebras g, explicit formulas were found for invariant projections onto subrepresentations that appear in the decomposition of the tensor product $ad \otimes ad \otimes ad = ad^{\otimes 3}$ of three adjoint representations ad. The idea of using g-invariant operators to construct such invariant projections is not new. For example, invariant projections acting in tensor representations of $sl(n)$ algebras are called Young symmetrizers and are constructed as images of special elements (idempotents) of the algebra of the symmetric group S_r. However, using split Casimir operators $C_{(k)}$ allows decomposing tensor products of representations into invariant subrepresentations, most of which are irreducible (and are called Casimir subrepresentations), in a uniform way for all simple Lie algebras.

Interest in the study of the split Casimir operator was motivated by the possibility of constructing explicit g-invariant solutions of the Yang–Baxter equation, as well as by the concept of a universal Lie algebra, which was introduced by P. Vogel[346]. It was assumed that the universal Lie algebra would be a model of all complex simple Lie algebras g. For example, the set of quantities that characterize the algebra g in various representations T (possibly reducible) included in the decomposition $ad^{\otimes k}$ can be expressed analytically as functions of three Vogel parameters.

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[340] *Isaev A. P., Rubakov V. A.* Theory of Groups and Symmetries: I. Finite Groups, Lie Groups and Lie Algebras. World Sci., 2018.

[341] *Isaev A. P., Provorov A.* // Phys. Part. Nucl. Lett. 2025. V. 22. P. 556.

[342] *Isaev A. P., Krivonos S. O.* // J. Math. Phys. 2021. V. 62. P. 083503.

[343] *Isaev A. P., Krivonos S. O., Provorov A. A.* // Int. J. Mod. Phys. A. 2023. V. 38. P. 2350037.

[344] *Isaev A. P., Krivonos S. O.* // Symmetry. 2001. V. 13. P. 1046.

[345] *Avetisyan M., Isaev A. P., Krivonos S. O., Mkrtchyan R.* // Russ. J. Math. Phys. 2024. V. 31. P. 379.

[346] *Vogel P.* The Universal Lie Algebra. Preprint, 1999; https://webusers.imjprg.fr/~pierre.vogel/grenoble-99b.pdf.

These parameters take specific values for each of the complex simple Lie (super) algebras g.

In Vogel's original paper[346], the notion of a universal Lie algebra was obtained using rather nontrivial considerations arising from knot theory. An assumption was made and then proved that the $ad^{\otimes 3}$ and $ad^{\otimes 4}$ representations of exceptional Lie algebras allow for a universal decomposition[347]. In the papers of A. P. Isaev and S. O. Krivonos, many of Vogel's results were derived using a fairly simple approach of using the split Casimir operators $C_{(3)}$ and $C_{(4)}$ to decompose $ad^{\otimes 3}$ and $ad^{\otimes 4}$ into subrepresentations for all simple Lie algebras. Moreover, a universal decomposition of $ad^{\otimes 5}$ for exceptional Lie algebras was obtained. This shows that the use of split Casimir operators provides a general simple and universal algorithm for decomposing various representations of Lie algebra into a direct sum of invariant subrepresentations. After using it to obtain the main results, it is planned to apply this method to find a universal decomposition of the $ad^{\otimes 5}$ representation for all simple Lie algebras.

Characteristic identities were constructed[342, 343] for 3-split (polarized) Casimir operators $C(3)$ of simple Lie algebras in the defining and adjoint ad representations, and a special class of universal subrepresentations in $ad^{\otimes 3}$ was constructed. Projectors onto invariant subspaces for these subrepresentations were directly obtained from characteristic identities for 3-split Casimir operators. For all simple Lie algebras, universal expressions were found for the traces of higher powers of Casimir operators $C(3)$ and the dimensions of subrepresentations in $ad^{\otimes 3}$. All the formulas agree with the universal description of (irreducible) subrepresentations in $ad^{\otimes 3}$ for simple Lie algebras in terms of three Vogel parameters.

Characteristic identities for split (polarized) Casimir operators of simple Lie algebras in the adjoint representation were constructed[344]. Using these characteristic identities for all simple Lie algebras, explicit formulas for invariant projections onto irreducible subrepresentations of $T^{\otimes 2}$ were derived in the case where T is the adjoint representation. These projections and characteristic identities are considered from the point of view of a universal description of simple Lie algebras in terms of Vogel parameters.

A universal decomposition into Casimir eigenspaces (most of which are irreducible) of degree four of the adjoint $ad^{\otimes 4}$ representation was obtained for all simple Lie algebras[345]. Universal, in the sense of Vogel, formulas were presented for the dimensions and eigenvalues of the Casimir operator $C(4)$ for all terms of this decomposition. It was assumed that a similar universal decomposition into Casimir eigenspaces with universal dimension formulas exists for an arbitrary tensor power of the adjoint representations.

By using the split Casimir operator $C(5)$, a decomposition of the antisymmetric part of $ad^{\otimes 5}$ was found[348]. This decomposition contains the representations that appeared in the decomposition of $ad^{\otimes 4}$, and only one new representation, $X5$.

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[347] *Deligne P.* // C. R. Acad. Sci. 1996. V. 322. P. 321326; *Landsberg J. M., Manivel L.* // Adv. Math. 2006. V. 201. P. 379.

[348] *Isaev A. P., Krivonos S. O.* // Izv. Math. 2025. V. 89. P. 15.

HOLOGRAPHIC APPROACH

The holographic approach allows studying the dynamics of strongly coupled quantum field theories using dual supergravity solutions. To eliminate gravitational divergences, a holographic renormalization procedure similar to the renormalization procedure in QFT was proposed, which incorporates the concept of a holographic renormalization group flow suggested in the works of E. Akhmedov, K. Skenderis, J. de Boer, E. Verlinde, and H. Verlinde. In this case, the UV divergences of the dual field theory correspond to the IR gravitational divergences. The holographic RG flow is associated with the RG flow of the dual field theory between conformal fixed points. Thermal RG flows represent a special case, allowing the study of the consistency of dual QFTs and the dynamics of the overhorizon region of black holes. In the holographic duality framework, finite-temperature RG flows are described by asymptotic *AdS* black holes, with their behavior near the horizon encoding the thermalization process in the dual QFT.

A. A. Golubtsova studied a 5-dimensional supergravity model, including a dilaton with a potential, in the context of the holographic approach. A reduction to an effective integrable mechanical model of the Toda chain type was constructed. Analytical solutions for the metric and scalar field, including those with *AdS* asymptotics, were found, which describe holographic RG flows at zero and non-zero temperatures. A. A. Golubtsova also proposed a method for studying thermal holographic RG flows using a reduction of supergravity equations to an autonomous dynamical system with a cylindrical configuration space. This method allows understanding the behavior of flows based on the stability analysis of fixed points, and finding an analytical representation of the near-horizon region of flows. In addition, a class of flows corresponding to the deformation of the dual theory by "light" operators that do not change the background geometry was discovered[349, 350].

STRINGS, DUALITY, AND INTEGRABILITY

H. Dimov conducted research in the field of string realizations of quantum field theory. This work is based on the Maldacena conjecture on the duality between string theory in supergravity background geometries and gauge theories defined on the holographic boundary of these geometries. This is the concept of holographic correspondence (AdS/CFT). In the most general sense, the general problems are related to the verification of this correspondence in the supergravity and beyond the supergravity approximation. The solved specific problems and the achievements are related to the study of integrable models on background string geometries imposed by their symmetries and string dynamics. Various classes of string solutions, such as giant magnons, spikes, rotating strings, etc., were obtained by reducing to the integrable Neumann-Rosochathius model[351]. Semiclassical quantization was performed and dispersion relations between conserved charges were obtained. Using the method of quantization of pulsating string configurations,

[349] *Aref'eva I. Y., Golubtsova A. A., Policastro G.* // JHEP. 2019. V. 05. P. 117.
[350] *Golubtsova A., Nikolaev A., Podoinitsyn M.* // Phys. Rev. D. 2024. V. 110. P. 066011.
[351] *Dimov H., Rashkov R. C.* // Nucl. Phys. B. 2008. V. 799. P. 255.

anomalous dimensions of operator classes from holographic dual gauge theories of various classes of background geometries, including those with broken supersymmetry and finite temperature, were obtained[352]. The information content of holographic background geometries (e.g., holographic black holes) was also studied, and criteria for their stability were obtained[353].

SUPERSYMMETRIC SCHWARZIANS

The Schwarz derivative, or Schwarzian, is a third-order nonlinear differential operator invariant under linear-fractional transformations of its argument. From the standpoint of mathematical physics, interest in this object results from its appearance in operator expansions in two-dimensional conformal field theory, as well as in low-dimensional models of the AdS/CFT correspondence. Supersymmetric generalizations of the Schwarzian are known, appearing in superconformal theories, as are Schwarzians with higher-order derivatives. The properties of Schwarzians allow suggesting that they are completely determined by symmetry and can be constructed using the method of nonlinear realizations. Indeed, the works of N. Yu. Kozyrev and S. O. Krivonos[354] showed that the known super-Schwarzians can be constructed by applying the method of nonlinear realizations to the supergroups $osp(1|2)$, $su(1,1|1)$, $osp(3|2)$, $su(1,1|2)$, $D(1,2,\alpha)$. The parametrization of the groups turns out to be similar to that in the construction of superconformal mechanics, but all the parameters are considered as functions on an additional inert ("boundary") superspace. The necessary irreducibility conditions in all cases arise as conditions on the Cartan forms of the generators of shifts, supershifts, and dilations, after which all other Cartan forms can be expressed only in terms of the super-Schwarzian and its derivatives. Using these forms, supersymmetric Schwarzian mechanics were also constructed. Interestingly, the group-theoretical approach made it possible to construct super-Schwarzians invariant under the supergroups $OSp(N|2)$ for all N, which are unknown in conformal field theory.

SUPERSYMMETRY

Research into gauge fields, supersymmetry, and related questions was pioneered by renowned theoretical physicists M. A. Markov, V. I. Ogievetsky, and I. V. Polubarinov. BLTP researchers working on this topic maintain the succession in their research in regard to their renowned teachers. Among the most important areas of research are the creation and study of new promising supersymmetric theories. Research conducted in recent years has focused on developing previously proposed approaches and methods in supertheories. Among these, the harmonic approach to superfield theories with extended supersymmetry, pioneered by BLTP scien-

[352] *Geytota O. V., Golubtsova A. A., Dimov H., Nguyen Vu H., Rashkov R. C.* // Gen. Rel. Grav. 2023. V. 55. P. 29.

[353] *Avramov V., Dimov H., Radomirov M., Rashkov R. C., Vetsov T.* // Eur. Phys. J. C. 2024. V. 84. P. 281; Eur. Phys. J. Plus. 2024. V. 139. P. 939.

[354] *Kozyrev N., Krivonos S.* // Phys. Rev. D. 2022. V. 105. P. 085010; JHEP. 2022. V. 03. P. 120; Phys. Rev. D. 2023. V. 107. P. 026018; *Krivonos S.* // Phys. Rev. D. 2024. V. 109. P. 065029.

tists, occupies a special place. Another "hot" area is research into supersymmetric quantum mechanics. Other areas of theoretical physics, such as the development of methods and approaches to constructing models of fundamental interactions beyond the Standard Model and the study of their mathematical structure, including the phenomenology of elementary particles, the conceptual and mathematical foundations of quantum mechanics, and studies of gauge theories and gravity at the classical and quantum levels, have also been the objects of intensive research. All the results obtained in these areas are in full agreement with global scientific trends and represent significant scientific achievements, in many cases exceeding the world level. They are of great interest to colleagues from various scientific centers in Russia and worldwide. Below is only a selection of the important and priority results obtained in this area in recent years. The bulk of the work here is authored by I. L. Buchbinder, E. A. Ivanov, and S. A. Fedoruk, as well as A. P. Isaev, S. O. Krivonos, A. P. Nersessian, G. A. Sarkissian, A. O. Sutulin, S. S. Sidorov, N. M. Zaigraev, M. A. Podoinitsyn, N. Yu. Kozyrev, and other co-authors.

MODELS OF PARTICLES AND FIELDS WITH HIGHER AND CONTINUOUS (INFINITE) SPINS

The $N = 2$, $D = 4$ harmonic superspace, discovered at BLTP[355] in 1984, has found numerous applications in theoretical physics and continues to be used in a wide range of problems. One of the striking and rather unexpected discoveries made in recent years has been the application of the $N = 2$, $D = 4$ harmonic superspace to higher-spin theory.

A complete superfield formulation of free $N = 2$ off-shell integer higher-spin theories was constructed for the first time[356]. It was demonstrated that such theories are obtained as a result of generalization of the linearized superfield theory of $N = 2$ supergravity. As in all previously known $N = 2$ gauge theories, harmonic superspace and the property of Grassmann analyticity play the key role in the formulation. The degrees of freedom in such theories are described by a set of analytic superfields, and the constructed Lagrangians have a simple and clear structure, which distinguishes them favorably from the cumbersome Lagrangians of $N = 0$ and $N = 1$ higher-spin theories. As shown[357], the structure of half-integer $N = 2$ higher spins differs significantly from the theories of integer spins.

These results were further developed[358], and superfield cubic interactions of higher spins with a fundamental $N = 2$ matter multiplet — a hypermultiplet — were constructed. As was shown, such interactions have an elegant geometric interpretation: the interaction is caused by the "extension" of the harmonic derivative by a higher-order differential superoperator constructed from higher-spin superfields,

[355] *Galperin A., Ivanov E., Kalitzin S., Ogievetsky V., Sokatchev E.* // Class. Quant. Grav. 1984. V. 1. P. 469.

[356] *Buchbinder I., Ivanov E., Zaigraev N.* // JHEP. 2021. V. 12. P. 016.

[357] *Ivanov E., Zaigraev N.* // Phys. Lett. B. 2025. V. 862. P. 139333.

[358] *Buchbinder I., Ivanov E., Zaigraev N.* // JHEP. 2022. V. 05. P. 104; JHEP. 2023. V. 03. P. 036.

and the interaction itself is completely fixed by the requirement of $N = 2$ supersymmetry and the property of harmonic analyticity.

Work on cubic interactions has naturally developed in the case of $N = 2$ superconformal theories. Superconformal symmetry is a much more "rigid" supersymmetry and allows for advances in constructing interactions at orders higher than cubic. The $N = 2$ superconformal off-mass-shell higher-spin multiplets were constructed, and a consistent theory of the interaction of an infinite tower of conformal higher-spins with a hypermultiplet was proposed for the first time[359]. The Lagrangian structure of the constructed theory is very illustrative — it is also obtained by extending the harmonic derivative by a differential superoperator of infinite order. Using such a model makes it possible to construct an effective quantum action of a consistent higher-spin theory. Moreover, the constructed superconformal multiplets play an important role in constructing higher-spin theories against the background of $N = 2$ AdS superspace, which are currently being studied at the laboratory.

The structure of more general superfield $N = 2$ interactions was investigated, and a family of gauge-invariant $N = 2$ supercurrents was constructed[360]. These results were a natural continuation of another study[361], where the invariants of linearized supergravity were examined. Their generalizations to higher spins are the building blocks for $N = 2$ higher-spin supercurrents.

Another important direction in the description of higher-spin states is the construction and study of models of relativistic particles with continuous (infinite) spin. A distinctive feature of the models under consideration was the use of additional commuting spinor variables to describe irreducible representations of the Poincaré group of continuous spin. Research on continuous (super)spin forms a series of works. In the first works of this series, within the twistor formulation, a Lagrangian model of a four-dimensional massless relativistic particle was proposed, a Hamiltonian formalism was constructed, a primary quantization of the model under consideration was carried out, and a twistor field of continuous spin was constructed and its expansion in helicities was described[362]. The BRST approach was also developed, on the basis of which a Lagrangian formulation of fields with half-integer continuous spins was constructed[363]. An important and interesting result is the proof that the continuous integer and half-integer spin fields in four dimensions form an $N = 1$ supermultiplet[364], for constructing a superfield Lagrangian description of which outside the mass shell it is necessary to use six chiral and antichiral superfields[365].

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[359] *Buchbinder I., Ivanov E., Zaigraev N.* // JHEP. 2024. V. 08. P. 120.

[360] *Ivanov E., Zaigraev N.* // Phys. Lett. B. 2024. V. 858. P. 139056.

[361] *Ivanov E., Zaigraev N.* // Phys. Rev. D. 2024. V. 110. P. 066020.

[362] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Rusnak A.* // JHEP. 2018. V. 07. P. 031; *Buchbinder I. L., Fedoruk S., Isaev A. P.* // Nucl. Phys. B. 2019. V. 945. P. 114660.

[363] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Krykhtin V. A.* // Nucl. Phys. B. 2020. V. 958. P. 115114.

[364] *Buchbinder I. L., Fedoruk S. A., Isaev A. P.* // Nucl. Phys. B. 2019. V. 945. P. 114660.

[365] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Krykhtin V. A.* // Phys. Lett. B. 2022. V. 829. P. 137139.

In the context of this problem, new aspects of irreducible representations of the Poincaré group with continuous spin in six-dimensional space were also investigated[366]. A twistor formulation and a light-cone formulation of 6D fields of infinite spin were presented[367], where harmonic variables play an important role. Also, within the BRST approach, a Lagrangian formulation of 6D fields of continuous spin was obtained[368].

A generalization of the proposed models of 4D continuous-spin particles with additional spinor variables was carried out to the case of a background gravitational field[369]. A generalization was found to the case of a curved space of first-class constraints at the classical and quantum levels, and a Lagrangian formulation of the continuous-spin field was constructed using the BRST approach in the four-dimensional anti-de Sitter space, on which, in this case, an irreducible representation of the four-dimensional anti-de Sitter group $SO(3,2)$ is realized[370].

The twistor formulation of massive higher-spin fields in three-dimensional and four-dimensional space-time was studied in detail[371].

The results obtained open up a multitude of new problems in which additional commuting coordinates — harmonics in $N = 2$, $D = 4$ supersymmetric higher-spin theories or commuting spinors in continuous spin field theories — play a significant role. The main advantages of these approaches are their explicit accounting for the fundamental properties of the theories under consideration, which will inevitably lead to a significant technical simplification of both supersymmetric higher-spin theories and infinite spin theories.

EFFECTIVE ACTION IN SUPERSYMMETRIC QUANTUM GAUGE THEORIES

In the context of research on this issue, the structure of the quantum effective action in six-dimensional supergauge theories was investigated[372]. Such theories can be obtained by dimensional reduction in superstring theory and allow studying low-energy aspects of string theory using quantum field theory methods. A class of six-dimensional $N = (1,0)$ and $N = (1,1)$ supersymmetric gauge theories was formulated, describing the interaction of a gauge multiplet and a hypermultiplet in an arbitrary representation of the gauge group. The theories are described in terms of $N = (1,0)$ harmonic superfields, which ensures explicit $N = (1,0)$ supersymmetry

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[366] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Podoinitsyn M. A.* // Phys. Lett. B. 2021. V. 813. P. 136064.

[367] *Buchbinder I. L., Fedoruk S. A., Isaev A. P.* // Nucl. Phys. B. 2021. V. 973. 115576; Eur. Phys. J. C. 2022. V. 82. P. 733.

[368] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Krykhtin V. A.* // Nucl. Phys. B. 2023. V. 996. P. 116365.

[369] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Krykhtin V. A.* // Phys. Lett. B. 2024. V. 853. P. 138689; Eur. Phys. J. Plus. 2024. V. 139. P. 621.

[370] *Buchbinder I. L., Fedoruk S. A., Isaev A. P., Podoinitsyn M. A.* // Phys. Lett. B. 2025. V. 861. P. 139226.

[371] *de Azcarraga J. A., Fedoruk S., Izquierdo J. M., Lukierski J.* // JHEP. 2015. V. 04. P. 010.

[372] *Buchbinder I. L., Ivanov E. A., Merzlikin B. S., Stepanyantz K. V.* // Phys. Lett. B. 2016. V. 763. P. 375; JHEP. 2017. V. 01. P. 128; Nucl. Phys. B. 2017. V. 921. P. 127; Nucl. Phys. B. 2018. V. 936. P. 638; Phys. Lett. B. 2019. V. 798. P. 134957.

at all stages of the effective action calculation. In the case where the hypermultiplet is chosen in the adjoint representation, the theory has hidden $N = (0,1)$ supersymmetry on the mass shell, which corresponds to the maximally extended global supersymmetric theory in six dimensions. A harmonic superfield background field method was developed that preserves explicit gauge invariance of the effective action in addition to explicit $N = (1,0)$ supersymmetry. One-loop divergences of the effective action in the gauge multiplet and hypermultiplet sector were calculated using the harmonic supergraphs technique. An explicitly gauge-invariant and $N = (1,0)$ supersymmetric proper-time technique was developed, within which one-loop divergences were also calculated. Divergences in $N = (1,1)$ supergauge theory were considered, and it was shown that, although such a theory is index-nonrenormalizable, the corresponding quantum effective action is finite off-shell.

A six-dimensional $N = (1,1)$ supergauge theory with the gauge group $SU(n)$ formulated in harmonic superspace in terms of the ω-hypermultiplet was considered[373]. Using the superfield background field method, the structure of finite one-loop contributions to the effective action was investigated taking into account the spontaneous breaking of the $SU(n)$ symmetry to $SU(n-1) \times U(1)$, and the leading low-energy effective action was found. The obtained result was also extended to an arbitrary Abelian background, and a generalized six-dimensional $N = (1,1)$ supersymmetric effective Lagrangian in the $N = (1,0)$ superfield form was derived.

The structure of two-loop divergences in a six-dimensional $N = (1,1)$ supergauge theory, formulated in $N = (1,0)$ harmonic superspace in a hypermultiplet sector, was investigated[374]. The two-loop divergences were calculated in the gauge multiplet sector. Within the background field method, the two-loop effective action is described by four background-dependent vacuum diagrams. The hypermultiplet dependence of the two-loop divergences was reconstructed based on the discovered structure of the two-loop divergences in the gauge multiplet sector.

A six-dimensional $N = (1,0)$ supergauge theory with higher (fourth-order) derivatives, formulated in $N = (1,0)$ harmonic superspace, was considered[375]. A background field method and supergraph technique were developed, the structure of divergences was analyzed, and renormalizability in all loops was established for this theory.

Three-loop contributions to the superfield effective action, which depends only on chiral superfields, were investigated in the Wess–Zumino model. It was shown that there are only three corresponding three-loop supergraphs, two of which are finite and one contains a divergence eliminated by one-loop renormalization. This indicates the existence of a three-loop quantum correction to the classical chiral potential, which was found explicitly[376].

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[373] *Buchbinder I. L., Ivanov E. A., Merzlikin B. S.* // JHEP. 2018. V. 09. P. 039; Nucl. Phys. B. 2020. V. 954. P. 114995.

[374] *Buchbinder I. L., Ivanov E. A., Merzlikin B. S., Stepanyantz K. V.* // Phys. Lett. B. 2018. P. 778252; Phys. Lett. B. 2021. V. 820. P. 136516; JHEP. 2023. V. 05. P. 089.

[375] *Buchbinder I. L., Ivanov E. A., Merzlikin B. S., Stepanyantz K. V.* // JHEP. 2020. V. 08. P. 169; Nucl. Phys. B. 2020. V. 961. P. 115249.

[376] *Buchbinder I. L., Iakhibbaev R. M., Kazakov D. I., Tolkachev D. M.* // Phys. Lett. B. 2025. V. 866. P. 139954.

The renormalization of the Abelian theory of a massive vector field interacting with a charged metric in curved spacetime was investigated[377]. It was shown that, despite the fact that the propagator does not decrease at large momenta, such an Abelian theory is renormalizable.

NEW MODELS OF SUPERSYMMETRIC MECHANICS

The traditional research focus is on supersymmetric mechanics. Among the vast variety of papers on this topic, only a limited number of articles published in recent years will be highlighted.

The superfield gauge method[378] using the $N = 4$, $D = 1$ harmonic approach and semidynamical supermultiplets was applied to construct new models of supersymmetric mechanics with weakened (deformed) supersymmetry[379], as well as new $N = 2$ and $N = 4$ superextensions of the Calogero–Sutherland model[380]. When describing multiparticle systems, the superfield gauge method operates with matrix systems containing an increased number of physical fermions. This important and effective property for applications was used to construct a new N-extended supersymmetric $su(n)$-spin Calogero model[381], which posesses the dynamical superconformal symmetry $osp(N|2)$. A new realization of the $N = 4$ superconformal symmetry $D(2,1;\alpha)$ was also proposed[382], using the interaction of dynamical and semidynamical $N = 4$ supermultiplets.

Models of $N = 4$ supersymmetric mechanics on n-dimensional Riemannian manifolds[383] have also been constructed, described by the generalized Witten–Dijkgraaf–Verlinde–Verlinde equations. It was shown that solutions of the proposed equations, obeying modified covariant constancy equations, define a new class of $N = 4$ supersymmetric mechanics on Riemann manifolds. A complex analog of manifolds admitting such solutions are the well-known "special Kähler manifolds of rigid type". $N = 8$ supersymmetric mechanics were constructed on such manifolds[384], the bosonic parts of which are superintegrable deformations of oscillator- and Coulomb-like systems.

Various models of deformed $N = 8$ mechanics were also considered, and two variants of deformation with $su(2|2)$ and $su(4|1)$ superalgebras were studied[385]. By

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[377] *Buchbinder I. L., P. Rwany, Do Vale B. R., Oyadomari G. Y., Shapiro I. L.* // Phys. Rev. D. 2024. V. 110. P. 12505.

[378] *Fedoruk S., Ivanov E., Lechtenfeld O.* // Phys. Rev. D. 2009. V. 79. P. 105015.

[379] *Fedoruk S., Ivanov E.* // JHEP. 2016. V. 11. P. 103; *Fedoruk S., Ivanov E., Sidorov S.* // JHEP. 2018. V. 01. P. 132; *Fedoruk S., Ivanov E., Lechtenfeld O., Sidorov S.* // JHEP. 2018. V. 04. P. 043.

[380] *Fedoruk S., Ivanov E., Lechtenfeld O.* // Nucl. Phys. B. 2019. V. 944. P. 114633; *Fedoruk S.* // Nucl. Phys. B. 2020. V. 953. P. 114977; Nucl. Phys. B. 2020. V. 961. P. 115234.

[381] *Krivonos S., Lechtenfeld O., Sutulin A.* // Phys. Lett. B. 2018. V. 784. P. 137; Lett. B. 2022. V. 831. P. 137184; *Krivonos S., Lechtenfeld O., Provorov A., Sutulin A.* // Phys. Lett. B. 2019. V. 791. P. 385.

[382] *Fedoruk S., Ivanov E.* // JHEP. 2015. V. 10. P. 087

[383] *Kozyrev N., Krivonos S., Lechtenfeld O., Nersessian A., Sutulin A.* // Phys. Rev. D. 2017. V. 96. P. 101702; Phys. Rev. D. 2018. V. 97. P. 085015.

[384] *Krivonos S., Nersessian A., Shmavonyan H.* // Phys. Rev. D. 2020. V. 101. P. 045002.

[385] *Ivanov E., Lechtenfeld O., Sidorov S.* // JHEP. 2018. V. 08. 193; Symmetry. 2019. V. 11. P. 135.

considering the interaction of dynamical and semi-dynamical $N = 4$ supermultiplets, the $N = 8$ supersymmetric mechanics with semi-dynamical variables were constructed for the first time[386]. As was subsequently shown[387], this model has dynamical $N = 8$ superconformal symmetry $osp(8|2)$. Moreover, the boson part of the Hamiltonian of the system describes a free particle on an eight-dimensional cone, and the fermion part can be interpreted as spin-orbit interaction. A complex analog of this system, defined by a simple model of two-dimensional $N = 2$ superconformal mechanics, and its quaternion analog, describing $N = 4$ superconformal $D(2,1;\alpha)$ mechanics, were proposed. The bosonic parts of the Hamiltonians of these systems also describe free particles on cones, and the fermionic parts necessarily include a spin–orbit interaction term. Further generalization of the proposed systems made it possible to describe all variants of superconformal mechanics associated with the $osp(8|2)$, $F(4)$, $osp(4^*|4)$, and $su(1,1|4)$ superalgebras[388]. Multiparticle systems of $N = 8$ supersymmetric mechanics possessing the superconformal symmetry $F(4)$ were also constructed[389] from a consideration of the interaction of dynamical and semi-dynamical $N = 4$ supermultiplets.

An important application of extended supersymmetric mechanics is its use for the mathematical description of various geometries and its application to physical problems with a definite geometry. In particular, hyper-Kähler and bi-hyper-Kähler geometries with torsion were studied in detail[390]. In addition, a new superintegrable mechanical system on a complex projective space, including both a potential term and an interaction with a constant magnetic field, was proposed and studied[391]. This system can be considered as a CP^N analog of a flat singular oscillator, as well as its spherical version, known as the "Rosochatius system". It was shown that this system belongs to the class of "Kähler oscillators" admitting a deformed supersymmetric extension in the presence of a magnetic field. Deformed $N = 4$ and $N = 8$ supersymmetric mechanics on generic Kähler manifolds were constructed and studied. In special cases, these include harmonic oscillator models on complex Euclidean and complex projective spaces, as well as their superintegrable deformations, namely the CN–Smorodinsky–Winternitz and CP^N–Rosochatius systems. The quantization of the deformed $N = 4$ supersymmetric extension of the CN–Smorodinsky–Winternitz system[392] shows that deformed $N = 4$ supersymmetry implies an "even-odd" splitting in which bosonic and fermionic states belong to separate energy levels.

Another application of one-dimensional supersymmetric systems was the consideration of superintegrable models with dynamical symmetry $so(1,2)$ and general

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[386] *Fedoruk S., Ivanov E.* // Phys. Rev. D. 2024. V. 109. P. 085007.

[387] *Khastyan E., Krivonos S., Nersessian A.* // Int. J. Mod. Phys. A. 2025. V. 40. P. 2450165.

[388] *Krivonos S., Nersessian A.* // Phys. Lett. B. 2025. V. 863. P. 139373.

[389] *Fedoruk S., Ivanov E.* // Nucl. Phys. B. 2019. V. 938. P. 714.

[390] *Fedoruk S. A., Smilga A. V.* // J. Math. Phys. 2016. V. 57. P. 042103; *Fedoruk S., Ivanov E., Smilga A.* // J. Math. Phys. 2018. V. 59. P. 083501; *Delduc F., Ivanov E.* // Nucl. Phys. B. 2019. V. 949. P. 114806.

[391] *Ivanov E., Nersessian A., Shmavonyan H.* // Phys. Rev. D. 2019. V. 99. P. 085007; *Ivanov E., Nersessian A., Sidorov S., Shmavonyan H.* // Phys. Rev. D. 2020. V. 101. P. 025003.

[392] *Ivanov E., Nersessian A., Sidorov S.* // JHEP. 2021. V. 01. P. 015.

superintegrable deformations of oscillatory and Coulomb systems in terms of the multidimensional Klein model, playing the role of the phase space[393]. As a development of this approach, a class of superconformal mechanics was found, formulated in terms of a superextension of the specified phase space, including superintegrable oscillatory and Coulomb-like systems with the dynamical superalgebra $su(1,N|M)$[394]. Moreover, a supersymmetrization scheme for general one-dimensional systems with a positive Hamiltonian was proposed, which yields an a priori integrable family of $N = 2k$ supersymmetric Hamiltonians parameterized by $N/2$ arbitrary real functions[395]. As a special case, it includes the Euler top, formulated as a system on the complex projective plane, which is the phase space of the system.

It is also necessary to note the work of G. A. Sarkissian and V. P. Spiridonov[396], which describes the reduction of the elliptic hypergeometric equation to the level of complex hypergeometric functions, which is important in the study of the Hamiltonian problem in new multiparticle rational integrable systems arising as a result of special degenerations of the elliptic models of Ruijsenaars and van Diejen.

BOSON STARS, BLACK HOLES, AND PROBLEMS IN TWO- AND THREE-DIMENSIONAL FIELD THEORIES

One of the most challenging areas of research in modern theoretical physics is the study of solutions of general relativity that describe black holes. Interest in this area arises from the recent emergence and rapid development of experimental gravitational astrophysics, particularly the direct detection of gravitational radiation during black hole collisions, as well as observations of their shadows. Physical processes associated with the presence of an event horizon allow for accurate determination of the limits of applicability and possible extensions of classical gravitational theory. Furthermore, solutions describing black holes with matter fields play a fundamental role in holographic duality models of non-Abelian Yang–Mills theory and classical gravitation in anti-de Sitter space.

In the works carried out in 2013–2025, a number of important, priority results of great scientific interest were obtained for the first time. In particular, in the works of Y. M. Shnir and co-authors[397], a new class of stationary solutions of the Einstein theory with matter fields was discovered, describing fermion modes localized by a strong gravitational field, and their behavior in the presence of an event horizon was investigated. In the analysis of a gravitating scalar field, the existence of multicomponent configurations of boson stars was shown, the stability of which is ensured by the presence of conserved non-topological charges[398]. Another pri-

[393] *Khastyan E., Nersessian A., Shmavonyan H.* // Int. J. Mod. Phys. A. 2021. V. 36. P. 2150055.

[394] *Khastyan E., Krivonos S., Nersessian A.* // Phys. Rev. D. 2022. V. 105. P. 025007.

[395] *Khastyan E., Krivonos S., Nersessian A.* // Phys. Lett. A. 2022. V. 452. P. 128442.

[396] *Sarkissian G. A., Spiridonov V. P.* // J. Phys. A. 2022. V. 55. P. 385203.

[397] *Herdeiro C., Perapechka I., Radu E., Shnir Y.* // Phys. Lett. B. 2019. V. 797. P. 134845; Phys. Lett. B. 2022. V. 824. P. 136811; *Dzhunushaliev V., Folomeev V., Shnir Y.* // Phys. Rev. D. 2023. V. 108. P. 065005.

[398] *Herdeiro C., Kunz J., Perapechka I., Radu E., Shnir Y.* // Phys. Lett. B. 2021. V. 812. P. 136027; Phys. Rev. D. 2021. V. 103. P. 065009.

ority result is the discovery of a new family of stationary solutions of the Einstein–Skyrme theory in an asymptotically flat space with Kerr geometry[399], as well as in a space with anti-de Sitter geometry[400].

The existence of new axially symmetric stationary solutions of the massive Einstein–Klein–Gordon theory with Kerr geometry in synchronous rotation with the event horizon was proven[401]. From the point of view of holographic duality, the study of the thermodynamic characteristics of black holes with non-Abelian matter fields in the $SU(2)$ Einstein–Yang–Mills theory with anti-de Sitter geometry[402] is important. In the course of work in this area, a new technique for numerical solution of equations of general relativity, based on the Einstein–de Turck formalism, was developed and successfully applied.

The behavior of multicomponent electrically charged gravitating matter field systems was investigated, and it was shown that long-range fields with Coulomb asymptotics significantly affect the observed characteristics of the Reissner–Nordström solutions. In the analysis of gravity-localized scalar fields in the two-component Friedberg–Lee–Sirlin model, a bifurcation of these configurations with the Reissner–Nordström electrovacuum solution was discovered[403]. A one-loop correction to the effective potential of the quantum Friedberg–Lee–Sirlin theory was calculated, and it was shown that the scale induced by the Coleman–Weinberg mechanism changes the asymptotic behavior of the fields of a non-topological soliton of this model[404]. It should be noted that the results of studies of localized field configurations in scalar field theories are summarized in the monograph[405].

The properties of black holes also manifest themselves in the study of certain one-dimensional mechanical systems. The dynamics of test particles moving near the horizon of extremal Myers–Perry black holes of arbitrary dimension was investigated[406]. The integrability of this system was proven, and special cases of background geometry were analyzed, where the system has a large number of constants of motion and is therefore superintegrable.

A new approach to the description of dual-symmetric models of nonlinear electrodynamics, developed in papers[407], deserves special attention. Subsequently, it was extended to interactions with dilaton and axion fields[408].

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[399] *Perapechka I., Radu E., Shnir Y.* // JHEP. 2018. V. 10. P. 119.

[400] *Perapechka I., Shnir Y.* // Phys. Rev. D. 2017. V. 95. P. 025024.

[401] *Kunz J., Perapechka I., Shnir Y.* // Phys. Rev. D. 2019. V. 100. P. 064032.

[402] *Kichakova O., Kunz J., Radu E., Shnir Y.* // Phys. Rev. D. 2016. V. 93. P. 044037.

[403] *Kunz J., Loiko V., Shnir Y.* // Phys. Rev. D. 2022. V. 105. P. 085013; Phys. Rev. D. 2024. V. 110. P. 125020.

[404] *Kim E., Nugaev E., Shnir Y.* // Phys. Lett. B. 2024. V. 856. P. 138881.

[405] *Shnir Y.* Topological and Non-Topological Solitons in Scalar Field Theories. Cambridge University Press, 2018.

[406] *Demirchian H., Nersessian A., Sadeghian S., Sheikh-Jabbari M. M.* // Phys. Rev. D. 2018. V. 97. P. 104004.

[407] *Ivanov E. A., Zupnik B. M.* // Yad. Fiz. 2004. V. 67. P. 2212; Phys. Rev. D. 2013. V. 87. P. 065023; Phys. Rev. D. 2013. V. 88. P. 045002; *Ivanov E. A., Nurmagambetov A. J., Zupnik B. M.* // Phys. Lett. B. 2014. V. 731. P. 298.

[408] *Ivanov E. A., Lechtenfeld O., Zupnik B. M.* // JHEP. 2015. V. 03. P. 123.

A separate interesting problem in the research was the solution of important mathematical problems in two- and three-dimensional field theories. The integrals of products of sparse hyperbolic gamma functions[409] arising as partition functions of three-dimensional supersymmetric field theories on a general oblate lens space $L(r,p)$ were studied. In particular, an integral identity was obtained for parafermionic hyperbolic gamma functions, which describes the star–triangle relation for the parafermionic two-dimensional Liouville field theory, and the matrix of modular transformations of one-point conformal blocks in the $N = 1$ supersymmetric two-dimensional Liouville field theory was calculated.

The limit was considered[410] in which the ratio of quasi-periods of the Faddeev modular quantum dilogarithm (or hyperbolic gamma function) tends to a value equal to -1. This limit gives rise to a set of integral relations for the complex gamma function with numerous applications.

The hypergeometric function describing the 6j-symbols for the $SL(2, C)$ group was studied[411]. It was shown that it is a special degeneration of the elliptic generalization of the Euler–Gauss hypergeometric function. Moreover, a new expression was obtained for the 6j-symbols of the $SL(2, C)$ group, which allows finding an analog of discrete Regge symmetry for them.

INTERNATIONAL WORKSHOPS "SUPERSYMMETRIES AND QUANTUM SYMMETRIES"

In 1989, Professor V. I. Ogievetsky initiated the holding of workshops "Supersymmetries and Quantum Symmetries" (SQS) at the Bogoliubov Laboratory of Theoretical Physics of the Joint Institute for Nuclear Research, which subsequently received the status of International Workshops. Recently, they have been held every two years in memory of V. I. Ogievetsky's outstanding contributions to theoretical physics and were devoted to discussing the most pressing issues in modern theoretical high-energy physics.

Leading experts in elementary particle theory, quantum field theory, gravity, string theory, noncommutative geometry, and integrable systems participated in all of the workshops. Furthermore, the SQS workshops have always been characterized by a high level of activity among talented young researchers from both Russia and abroad, which contributed to the development of the excellent traditions of the Russian (and Soviet) school of theoretical physics and supported its continuity.

The scientific programs of the SQS workshops included reports on the following topics: superstring theory, quantum and geometric aspects of supersymmetric theories, higher-spin theory, supersymmetric integrable models, quantum groups and noncommutative geometry, the Standard Model and its supersymmetric ex-

[409] *Apresyan E., Sarkissian G. A.* // JHEP. 2024. V. 07. P. 127; *Apresyan E., Sarkissian G. A., Spiridonov V. P.* // Nucl. Phys. B. 2023. V. 990. P. 116170; *Sarkissian G. A., Spiridonov V. P.* // JHEP. 2018. V. 10. P. 097.

[410] *Sarkissian G. A., Spiridonov V. P.* // J. Phys. A. V. 55. 2022. P. 385203; Funct. Anal. Appl. 2021. V. 55. P. 260; SIGMA. 2020. V. 16. P. 074; J. Geom. Phys. 2024. V. 203. P. 105274.

[411] *Derkachev S. E., Sarkissian G. A., Spiridonov V. P.* // Teor. Mat. Fiz. 2022. V. 213. P. 108 (in Russian).

tension. Research on these topics is at the forefront of theoretical physics and is often significantly ahead of experiment. Studies of supersymmetric models provide new insights into existing theories and lead to the creation of new physical and mathematical theoretical tools subsequently used in fields beyond particle physics.

MODIFIED GRAVITY THEORIES AND COSMOLOGY

In creating his general relativity, Einstein's goal was, above all, to construct a field theory of gravity capable of embodying the equivalence principle and reproducing Newton's law of universal gravitation in the non-relativistic limit. Unsurprisingly, immediately after the creation of general relativity, numerous attempts were made to modify it to achieve more ambitious goals. However, all early models of modified gravity were more complex than the simplest Einstein–Hilbert model and did not explain any observations that could not be explained by general relativity.

Essentially new observational data had become available by the end of the 20th century. The measured extremely low anisotropy of the cosmic microwave background and the discovery in 1998 of the accelerated expansion of the Universe based on supernova observations confirmed the concepts of cosmological inflation and dark energy, and stimulated attempts to incorporate the acceleration at the early stage of evolution of the Universe and the modern acceleration into a unified cosmological model. Interest in constructing consistent (phenomenological) models of modified gravity increased. At the same time, the discovery of gravitational waves and the development of increasingly accurate gravitational wave detectors made it possible in principle to filter out models that do not correspond to observational data.

Under the leadership of A. A. Starobinsky and A. T. Filippov, BLTP staff obtained a number of important results in the field of modified gravity theories and cosmology.

Along with phenomenological models constructed by adding new scalar fields, such as the inflaton and phantom fields, BLTP investigated theories in which new degrees of freedom arise naturally. Such theories include the Einstein–Weyl–Eddington affine gravity, which was considered in the works of A. T. Filippov and E. A. Davydov[412]. At the level of the effective action, in addition to the Einstein–Hilbert term, this theory introduces a cosmological constant, as well as a new massive vector field of geometric origin. A significant new result was the discovery of the duality of this model under spherical and cosmological reductions and the dilaton gravity model with scalar fields, as well as integrability conditions, demonstrating the compatibility of this gravity modification with the currently dominant phenomenological cosmological model ΛCDM.

It is worth mentioning the notable work[413], which considered the Friedmann Universe with an oscillating interaction between dark energy and dark matter and

[412] *Filippov A. T.* // Theor. Math. Phys. 2010. V. 163. P. 753; Theor. Math. Phys. 2013. V. 177. P. 1555; *Davydov E. A., Filippov A. T.* // Grav. Cosmol. 2013. V. 19. P. 209.

[413] *Odintsov S. D., Oikonomou V. K., Tretyakov P. V.* // Phys. Rev. D. 2017. V. 96. P. 044022.

proposed a scenario for the consistent unification of accelerated expansion at the early and late stages of evolution within a single approach. A. B. Pestov also addressed the problem of dark matter in his works.

In a series of papers by P. V. Tretyakov and co-authors[414], inflationary cosmology was investigated in models of $f(R)$-gravity, which is the simplest generalization of general relativity. A theory with two scalar fields, which are non-minimally coupled with the Ricci scalar R and an additional term R^2, violating conformal invariance, was considered. Models of inflation in the slow-roll regime with one or two dynamical scalar fields were constructed, and a generalization to the case of three scalar fields was proposed. It turned out that the spectral index of the scalar mode of density perturbations and the scalar-tensor ratio in such models can be compatible with the latest results of the Planck experiment. The regimes of accelerated and decelerated expansion of the Universe were studied for various models of $f(R)$-gravity in the representations of Einstein and Jordan.

The problem of cosmological perturbations in the theory of $f(T)$-gravity with a torsion scalar T, also known as teleparallel gravity, is the subject of the papers[415]. In the linear approximation, this theory and general relativity coincide; however, in general, teleparallel gravity differs significantly from general relativity. Since $f(T)$-gravity is a second-order theory, it is free from instability associated with higher derivatives. The problems arising in the standard approach to teleparallel gravity can be overcome in a covariant formulation that takes into account the spin connection. Scalar cosmological perturbations were calculated using the covariant approach. Solutions with bounce were found in theories of teleparallel gravity with matter in the form of a classical ideal fluid, which can solve the problem of the initial singularity[416]. Under certain conditions, these theories can also model the modern accelerated expansion of the Universe.

Models with extra dimensions of modified gravity have been discussed virtually since the development of general relativity. A special place among them is occupied by models with so-called dynamical compactification, in which extra dimensions became small during the evolution of the Universe, but can nevertheless indirectly influence the overall structure of space. The dynamics of a scalar field in Einstein–Gauss–Bonnet gravity models with dynamical compactification was investigated[417]. It was shown that if the field is not minimally coupled to curvature, its asymptotic value may not coincide with the minimum of the potential for certain parameters. This means that, due to the influence of extra dimensions, a scalar field with a simple fourth-order potential can stabilize far from the zero field value, which means effective symmetry violation in such a system.

A current area of research is Horndeski theory which encompasses a broad class of non-minimal gravity models free of Ostrogradsky instability. Models of this type arise at the effective action level when quantum corrections and dimen-

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[414] *Bahamonde S. et al.* // Phys. Lett. B. 2017. V. 766. P. 225;
Tretyakov P. // Eur. Phys. J. C. 2018. V. 78. P. 896.

[415] *Toporensky A., Tretyakov P.* // Phys. Rev. D. 2020. V. 102. P. 044049; Int. J. Geom. Meth. Mod. Phys. 2022. V. 19. P. 2250147.

[416] *Tretyakov P. V.* // Mod. Phys. Lett. A. 2022. V. 37. P. 2250046.

[417] *Chirkov D., Giacomini A., Toporensky A., Tretyakov P.* // Gen. Rel. Grav. 2024. V. 56. P. 110.

sional reductions are taken into account. There are two classes of such theories: vector-tensor and scalar-tensor.

In a cosmological context, the Horndeski vector-tensor theory with an $SU(2)$ Yang–Mills field ensuring the isotropy of the solution was first studied in detail by D. V. Galtsov (Moscow State University) and E. A. Davydov[418]. The natural emergence of an inflationary-type solution was demonstrated, capable of solving the problem of initial data for the observed inflation. It turned out that at the current level of experimental capabilities in cosmological observations for the Horndeski vector-tensor theory, the metric approach and the Palatini approach are indistinguishable, but they show significantly different behavior near the initial singularity.

Horndeski scalar-tensor theories and their extensions (Beyond Horndeski) modify general relativity by introducing an additional scalar degree of freedom into the gravitational sector, leading to a complex phenomenology. These models not only successfully describe inflation but also modify the physics of black holes, where a nontrivial scalar field configuration, called scalar hair, forms outside their event horizons. The new phenomenology provides various ways to test the applicability of these models.

The most general model of the Horndeski scalar-tensor gravity, which admits second-order field equations, encompasses all widely known scalar-tensor models, including the Brans–Dicke model, Einstein–Gauss–Bonnet scalar-tensor gravity, and Starobinski inflation.

Quantum effects can change the structure of scalar-tensor theory, generating new non-minimal couplings between the scalar field and gravity, which belong to the extended Horndeski theory. The possibility of generating such interactions was considered in a series of papers by B. Latosh[419]. Available data on the speed of gravitational waves in the modern Universe impose a constraint on the value of the corresponding coupling constant and the change in the scalar field over time. It was shown that new interactions are strongly suppressed, so the theory remains consistent with observations.

GRAVITATIONAL SHOCK WAVES IN GENERAL RELATIVITY

A gravitational shock wave is a geometry in which the transverse curvature components change abruptly at a null hypersurface — the wave front. These classical solutions of Einstein's equations became the focus of intense theoretical attention after G. 't Hooft's famous observation of the so-called dominance of gravitons in ultrahigh-energy scattering. It turned out that the amplitude of classical scattering on gravitational shock waves reproduces the contribution of all graviton exchange ladder diagrams to quantum amplitudes. Furthermore, colliding shock waves are a model for the formation of microscopic black holes in particle collisions at Planck energies.

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[418] *Davydov E., Gal'tsov D.* // Phys. Lett. B. 2016. V. 753. P. 622; *Davydov E.* // Int. J. Mod. Phys. D. 2017. V. 27. P. 1850038.

[419] *Latosh B.* // Eur. Phys. J. C. 2020. V. 80. P. 845; Mod. Phys. Lett. A. 2021. V. 36. P. 2150258.



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M. A. Podoinitsyn and L. N. Astrakhantsev



E. A. Ivanov



D. V. Fursaev



P. V. Tretyakov



I. G. Pirozhenko



E. A. Davydov



H. Dimov



The 17th DIAS Winter School "Supersymmetry and Integrability". Dubna, 2022

In a series of papers by the group of D. V. Fursaev, E. A. Davydov, I. G. Pirozhenko, and V. A. Tainov[420], the physical effects caused by the action of a plane gravitational shock wave on fields of different spins were investigated. Gravitational shock waves are generated by objects moving at the speed of light, such as, for example, massless particles, null cosmic strings, and null-branes. At BLTP, a method was developed that allows describing field perturbations from gravitational shock waves, both at the wave front itself and behind it. For these perturbations, a characteristic Cauchy problem with initial data at the gravitational wave front was formulated. It was shown that the gravitational memory effect for scalar and electromagnetic fields is determined only by these initial data, i.e., the shock wave profile, and is independent of the shape of the signal.

New physical effects were predicted: the generation of electromagnetic and gravitational waves during the interaction of point charges or masses with a gravitational shock wave, the generation of secondary shock waves within the field systems, and a number of other effects. A new mechanism for the generation of fast gamma-ray bursts (FRBs) was proposed.

QUANTUM GRAVITY, ANOMALIES, THE RELATIONSHIP BETWEEN GRAVITY, THERMODYNAMICS, AND QUANTUM ENTANGLEMENT

Although the perturbative approach to quantum gravity has a limited scope, its use has revealed a number of conceptual problems that must be resolved in a full-fledged theory of quantum gravity. The most important problems include understanding the evaporation of quantum black holes and explaining the information paradox, as well as identifying the microscopic degrees of freedom responsible for the entropy of black holes[421]. Following the direct detection of gravitational waves from binary black hole mergers and observations of the shadows of supermassive black holes, theoretical research in this area has received new impetus.

In the field of quantum gravity, BLTP actively developed the apparatus of quantum field theory in an external classical gravitational field and new methods for the approximate estimation of the effective gravitational action in various regimes. For problems of QFT with boundaries, finite-temperature QFT on stationary manifolds of general form, black hole thermodynamics, as well as for calculating the effects of quark–gluon matter taking into account rotation and acceleration, BLTP applied and improved methods of spectral geometry (spectral zeta functions, the method of heat kernel expansion), which was reflected in the monograph of D. V. Fursaev and D. V. Vassilevich[422], and in the works of V. V. Nesterenko and I. G. Pirozhenko.

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[420] *Fursaev D. V., Davydov E. A., Pirozhenko I. G., Tainov V. A.* // Phys. Rev. D. 2024. V. 109. P. 125009; JHEP. 2024. V. 11. P. 039; Phys. Rev. D. 2024. V. 109. P. 025012; Phys. Rev. D. 2023. V. 107. P. 025018; Phys. Rev. D. 2022. V. 105. P. 083510.

[421] *Fursaev D. V.* Black Hole Thermodynamics and Perturbative Quantum Gravity // Handbook of Quantum Gravity / Eds. C. Bambi, L. Modesto, I. Shapiro. Singapore: Springer, 2024.

[422] *Fursaev D., Vassilevich D.* Operators, Geometry and Quanta: Methods of Spectral Geometry in Quantum Field Theory. Springer, 2011.

In recent years, the connection between gravity, thermodynamics, and quantum entanglement, the holographic properties of gravity, and the AdS/CFT correspondence have been actively studied at BLTP[423]. Integral conformal anomalies in conformal field theory with boundaries were investigated[424]. Classical gravity on manifolds with conical singularities with broken isometries was studied[425].

QUANTUM FIELD VACUUM EFFECTS

The effects caused by the boundaries of a quantum field system are a traditional area of research. Initially, the influence of boundaries on the vacuum energy of a system was investigated by the group of B. M. Barbashov and V. V. Nesterenko in relation to string models[426], where the vacuum energy determines the critical dimension of space-time (fundamental strings) or the interquark potential (hadronic string theory).

The study of vacuum energy in (3+1)-dimensional spacetime, where physical boundaries lead to observable quantum effects such as Casimir forces, can be a complex problem that must take into account the properties of real materials, their geometry, background fields, etc. In a number of problems of applied importance, the influence of physical characteristics of material bodies on the vacuum forces between them was considered[427], in particular, the question of correctly taking into account dissipation when calculating the Casimir force between material bodies (V. V. Nesterenko[428]). Also, in connection with the needs of precision experiments, the combined influence of the system geometry and the temperature on the Casimir force was studied by M. Bordag and I. G. Pirozhenko[429].

In scalar field theory, A. S. Sorin, in collaboration with V. F. Mukhanov (Ludwig Maximilian University of Munich, Germany) and E. Rabinovici (Racah Institute of Physics, Hebrew University of Jerusalem, Israel), revised and generalized the approach to false vacuum decay and constructed a wide class of unbounded potentials for which Coleman instantons do not exist[430]. New instantons were proposed that ensure false vacuum decay for such potentials. For spaces of any number of dimensions, integrable potentials were found for which the instanton equations are completely integrable. A new method was developed for estimating the probability of false vacuum decay using regularized instantons.

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[423] *Fursaev D. V.* Boundary and Defect CFT: Open Problems and Applications // J. Phys. A. 2020. V. 53. P. 453002.

[424] *Fursaev D. V., Solodukhin S. N.* // Phys. Rev. D. 2016. V. 93. P. 084021.

[425] *Fursaev D. V., Patrushev A., Solodukhin S. N.* // Phys. Rev. D. 2013. V. 88. P. 044054.

[426] *Barbashov B. M., Nesterenko V. V.* Introduction to the Relativistic String Theory. World Sci., 1990.

[427] *Bordag M., Pirozhenko I. G.* // Phys. Rev. D. 2017.V. 95. P. 056017; Phys. Rev. D. 2015. V. 91. P. 085038; Symmetry. 2018. V. 10. P. 74.

[428] *Nesterenko V. V.* // Eur. Phys. J. C. 2022. V. 82. P. 874.

[429] *Bordag M., Pirozhenko I. G.* // Phys. Rev. D. 2010. V. 81. P. 085023; Phys. Rev. D. 2010. V. 82. P. 125016.

[430] *Mukhanov V. F., Rabinovici E., Sorin A. S.* // Fortsch. Phys. 2021. V. 69. P. 2000100; Fortsch. Phys. 2021. V. 69. P. 2000101; *Mukhanov V., Sorin A.* // JCAP. 2021. V. 10. P. 066.

INFORMATION TECHNOLOGIES

The Laboratory of Computing Techniques and Automation (LCTA) was established by JINR Order No. 149 of August 19, 1966 on the initiative of JINR Director Academician N. N. Bogoliubov. The organization of LCTA was entrusted to Mikhail Grigorievich Meshcheryakov, Corresponding Member of the USSR Academy of Sciences, a well-known experimental physicist, who already had leadership experience in creating the Synchrocyclotron and the first scientific laboratory (now the Dzhelepov Laboratory of Nuclear Problems) of the Institute since the late 1940s. The first to join LCTA were groups of mathematicians E. P. Zhidkov and N. N. Govorun from the Laboratory of Theoretical Physics and the JINR Computing Center, respectively, as well as several groups from the experimental laboratories of JINR under the supervision of Yu. A. Karzhavin, G. I. Zabiyakin, and V. I. Moroz.

The main areas of scientific activity of LCTA still remain relevant: the support of theoretical and experimental studies at JINR with computational and information resources, as well as the development of methods, algorithms and software for numerous researches conducted at JINR.

Soon after the formation of the Laboratory, the accumulated experience in the use of computing technology revealed the need for a variety of computing facilities, which ultimately predetermined the subsequent creation of a high-performance multimachine complex with a developed hierarchical structure. The data network environment technology that emerged in the early 1980s gave impetus to the construction of the first JINET local terminal network in Russia at LCTA, the creation of a high-speed telecommunication channel Dubna–Moscow, and further integration of the Institute into international global computer networks for science and education.

In 2000, LCTA was renamed as the Laboratory of Information Technologies (LIT). The JINR Scientific Council elected I. V. Puzynin, a mathematician known for his scientific work, including the mu-catalysis, as the first Director of LIT; V. V. Korenkov, V. V. Ivanov, and A. Polanski (Republic of Poland) became his deputies.

From 2003 to 2013, the Laboratory was headed by V. V. Ivanov, a recognized expert in the development and application of new mathematical methods to solve physical problems. His deputies were P. V. Zrelov, V. V. Korenkov,

Gh. Adam (Romania) in 2003–2009, and S. A. Adam (Romania) in 2009–2013.

In 2013, V. V. Korenkov, who had headed the development of computing and information technology since 1993, was elected LIT Director. His deputies were T. A. Strizh in 2013–2023, Gh. Adam (Romania) in 2013–2018, J. Buša (Slovakia) in 2019–2023, and O. Chuluunbaatar (Mongolia) since 2019.

In March 2021, the Committee of Plenipotentiaries decided to name the Laboratory of Information Technologies after M. G. Meshcheryakov for his outstanding contribution to the creation and development of the network infrastructure and the Information and Computing Complex of the Laboratory, the Institute, and the Member States.

Since 2023, the Laboratory has been headed by S. V. Shmatov, whose interests include the search for physics beyond the Standard Model, heavy-ion physics, and high-energy physics computing. Academician of the Mongolian Academy of Sciences O. Chuluunbaatar, N. N. Voytishin, and D. V. Podgainy were elected as his deputies.

During 60 years since the date of its formation, the Laboratory has come a long way along which it is possible to trace the development of computational and information technologies: from the first Ural-1 computer, then through the BESM-4, BESM-6 and ES, CDC, Sun, Vax, Convex and others to the Multifunctional Information and Computing Complex (MICC), which today is the unique basic JINR facility.

The MICC plays a defining role in scientific research requiring modern computing power and storage systems. The MICC uniqueness is ensured by the consolidation of all state-of-the-art information technologies: from a network infrastructure with a bandwidth from 2×100 up to 4×100 Gbps and a distributed data processing and storage system based on grid technologies and cloud computing, to a hyper-converged computing infrastructure with liquid cooling for supercomputer applications. Multifunctionality, high reliability and availability $24 \times 7 \times 365$, scalability and high performance, a reliable data storage system, information security and a developed software environment are the main requirements that the MICC satisfies. The reliability and availability of the MICC are ensured by a developed high-speed telecommunication system and a modern local network infrastructure, as well as a reliable engineering infrastructure that guarantees power supply and cooling for server equipment. The JINR computer infrastructure encompasses the IT ecosystem for the NICA project (BM@N, MPD, SPD), which includes all MICC computing components and storage systems owing to grid technologies: the Tier-1 grid site for the CMS experiment at the LHC and for experiments at NICA; Tier-2/CICC that provides support for all the experiments at the LHC, NICA and other large-scale experiments, as well as support for users of JINR's Laboratories

and Member States; the integrated cloud environment of the Member States to support users and experiments (NICA, NOvA, Baikal-GVD, JUNO, etc.); the HybriLIT platform with the Govorun supercomputer as the major resource for high-performance computing and the provision of capabilities for both the development of mathematical models and algorithms and for performing resource-intensive calculations, including on graphics accelerators, allowing the development of an ecosystem for ML/DL tasks, Big Data analysis, and quantum computing on simulators.

Another area of the Laboratory's activity is related to the organization and provision of computational, algorithmic, and software support for the preparation and implementation of experimental and theoretical research conducted with the participation of JINR, and the development, elaboration, and implementation of computational methods for modeling complex physical systems. The MLIT staff develop mathematical methods and software, including those based on machine and deep learning algorithms using recurrent and convolutional neural networks, for modeling physical processes and experimental facilities, processing and analyzing experimental data in the fields of elementary particle physics, nuclear physics, neutrino physics, radiobiology, etc. A special emphasis is made on the creation of systems for distributed processing and analysis of experimental data and information and computing platforms to support research carried out at JINR and other research centers.

TELECOMMUNICATION CHANNELS

The JINR computing network has a long history, rooted in the remote past, when the first connections of experimental facilities to computers, the connection of several computers to each other, the networks of BESM-6 and CDC terminals, etc. were successfully implemented. The first institute-wide terminal network, JINET (Joint Institute Network), was created in 1985; its unique software was entirely developed at LCTA. This work was carried out under the supervision of N. N. Govorun by a large team of programmers and engineers, including V. P. Shirikov, E. Yu. Mazepa, I. A. Emelin, N. S. Zaikin, V. Ya. Fariseev, V. E. Anikhovsky, V. V. Galaktionov, A. T. Dorokhin, S. G. Kadantsev, A. P. Kretov, D. N. Lopyrev, V. I. Pervushov, and S. A. Shchelev. It should be noted that LCTA always thoroughly monitored global trends in the field of information technology and implemented all the latest achievements.

The rapid development of network, computer, and information technologies has created the objective preconditions for the construction of a unified information and computing environment at JINR and the institutes of its Member States at a completely new level. This environment currently combines thousands of personal computers and hundreds of servers for various purposes, installed in all departments of the Institute and geographically distributed over several kilometers. The basis of this huge complex is the network infrastructure which includes fiber-optic cable structure, software and hardware providing for the reception, transmission and commutation of the information flows of the complex. This network infrastructure is being constantly upgraded, because it must comply with the current requirements for the level of equipment of information and computing structures of research organizations with reliable, fault-tolerant network services with the necessary bandwidth. Such a network must be highly scalable and possess all the necessary qualities to meet the ever-increasing demand for both improved network performance and the number of network and computer services; it must easily adapt to new network and server devices and software products emerging on the market.

The following main directions can be singled out in the fulfilment of the task for the development of JINR infrastructure:

1) development of external communication channels;
2) development of the JINR local area network;
3) development of the MICC and NICA megaproject network infrastructure.

EXTERNAL COMMUNICATION CHANNELS

In 2000, the capacity and bandwidth of the JINR telecommunication system was only 2 Mbps. The main Internet provider for JINR was the Russian Institute for Public Networks (RIPN), which by the end of 2000 provided JINR with paid access to international networks at a level of 1 Mbps in the general flow, as a user of the Russian Backbone Network (RBNet), and access to Russian networks within the framework of the interdepartmental program for the development of networks and telecommunications for science and higher education. However, such a bandwidth did not meet the needs of JINR.

In 2001, a tripartite agreement was signed among JINR, RIPN and RSCC (the Russian Satellite Communications Company) on the creation of ATM — a channel with a bandwidth of 155 Mbps between Moscow and Dubna. The main partner for solving this problem was RSCC, which owned the fiber-optic cables between Moscow (Shabolovka) and Dubna (Satellite Communications Centre (SCC) "Dubna"). The total length of one cable is about 200 km and has three intermediate points (Starbeyevo, Radishchevo, Konakovo). Thus, JINR received a port and leased a bandwidth of 30 Mbps in this channel.

The main service provider of JINR for Internet access, RBNet, had a well-developed infrastructure in Russia: backbone channels and access points in many large cities. The lead organization supporting the RBNet network was RIPN, which also operated the international channel for science and education and was responsible for the functioning of the Internet Exchange (IX) in Moscow. In 2002, a guaranteed bandwidth of 10 Mbps was allocated to JINR in the specified international channel.

Further development of JINR's external communications was associated with the implementation of the interdepartmental program "Creation of a New-Generation National Scientific Computer Network" for 2002–2006 and the Russian GRID segment. It should be noted that in 2003 the first project within the framework of the creation of the corporate computer network of JINR was implemented — the installation and adjustment of the network of resort hotel "Dubna" in Alushta was carried out in cooperation with SCC "Dubna". Computer communications were provided for participants, and conditions for teleconferences were created during three international meetings.

The task of providing JINR with high-speed communication channels had as its main goal the creation in 2005 of a JINR–Moscow data transmission channel with a bandwidth of 1 Gbps, which was successfully completed.

Since 2007, LIT specialists have been working on a full range of issues related to the creation of a 10-gigabit external channel.

In 2008, a new agreement was signed between JINR and RSCC on the lease of fiber-optic cable to organize communication channels between Moscow and Dubna. Within this project, a high-speed communication channel Dubna–Moscow was built using modern DWDM (Dense Wavelength Division Multiplexing) and 10 Gb Ethernet technologies. The implemented technology involves spectral division of the fiber bandwidth into several optical streams, which allows the use of multiple streams in a single optical fiber, dividing them by wavelength. The tech-

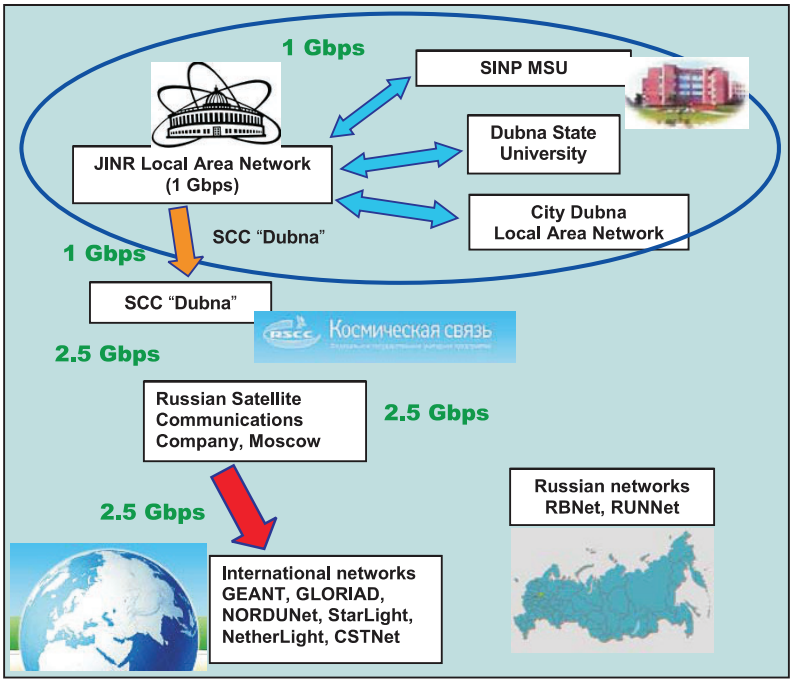


Fig. 1. Diagram of JINR telecommunication channels in 2005

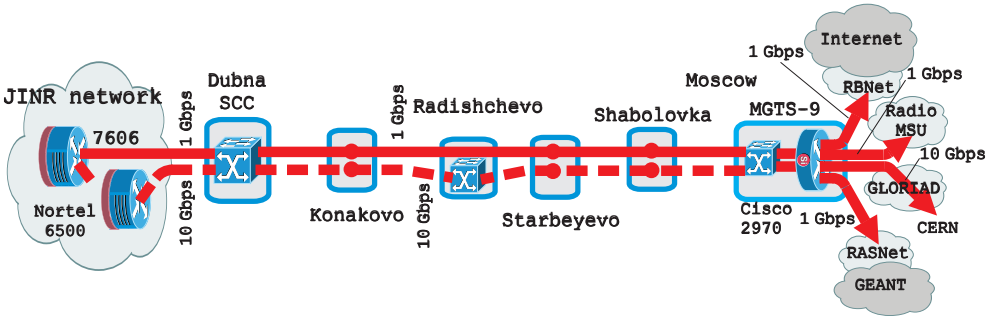
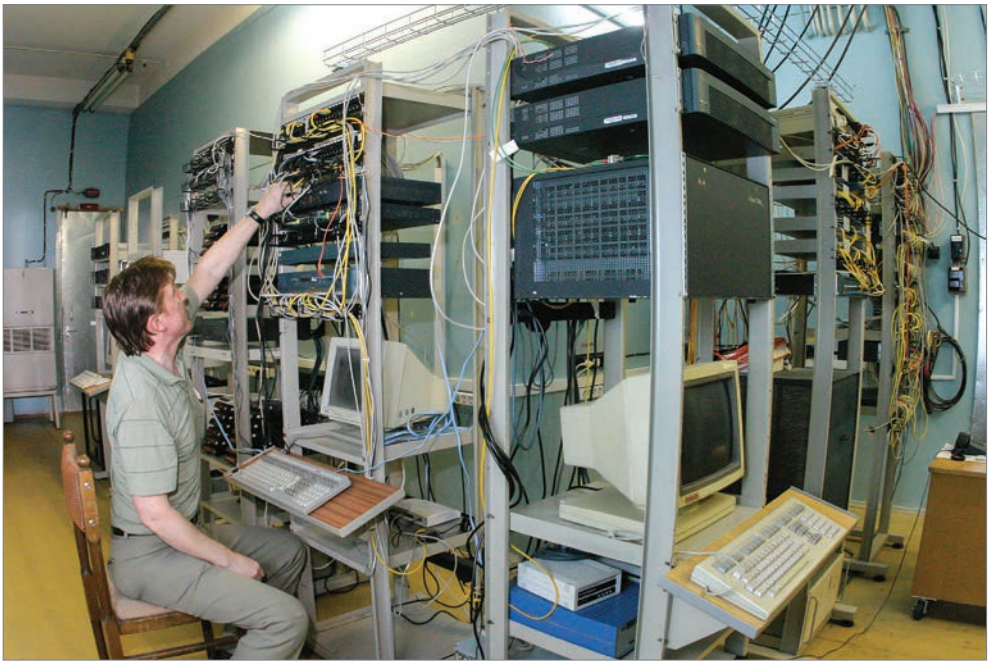


Fig. 2. JINR telecommunication channel diagram (2007): solid line — current 1 Gbps channel, dotted line — planned 10 Gbps channel

nologies used made it possible to gradually expand communication channels (from 10 Gbps to hundreds of Gbps) and move to a new level of service.

The development of the international segment of communication channels for science and education between Russia and Europe is carried out within the framework of the GEANT project. Regional and national research and educational networks were built in the JINR Member States, many of which were linked to the European GEANT network. As a result, the grid infrastructures of JINR and its Member States were connected through the high-speed European network



A. G. Dolbilov adjusting network equipment. 2005

GEANT. This approach is widely accepted in Europe for connecting regional networks for science and education.

In 2009, the channel capacity increased to 20 Gbps, a direct communication channel with CERN with a bandwidth of 1 Gbps, an RBNet channel with a bandwidth of 10 Gbps, a GEANT channel with a bandwidth of 10 Gbps, a channel through Moscow scientific networks with a bandwidth of 10 Gbps, and the Internet of 10 Gbps were used for communication with scientific networks and the Internet.

By the end of 2016, a gradual upgrade of the external channel to a speed of 100 Gbps was carried out. Thus, the JINR external distributed network was formed, which consisted of the external overlay network LHCOPN (JINR – CERN), passing through MGTS-9 in Moscow, Budapest, and Amsterdam, for connecting Tier-0 (CERN) and Tier-1 (JINR) centers and the external overlay network LHCONE, passing along the same route and intended for the JINR Tier-2 center; direct communication channels using RU-VRF technology with the RUHEP scientific centers collaboration (Gatchina, National Research Centre "Kurchatov Institute", Protvino), and with the RUNNet and RASNet networks. IPv6 routing was activated for Tier-1 and Tier-2 grid sites.

By 2019, a project to increase the bandwidth of the Moscow–JINR telecommunication channel from 100 Gbps to 3×100 Gbps was implemented.

Today, all JINR telecommunication channels are functioning reliably. First of all, this is Moscow backup channel with a bandwidth of 4×100 Gbps. To operate a Tier-1 grid site, one must be a full member of the LHCOPN network to connect

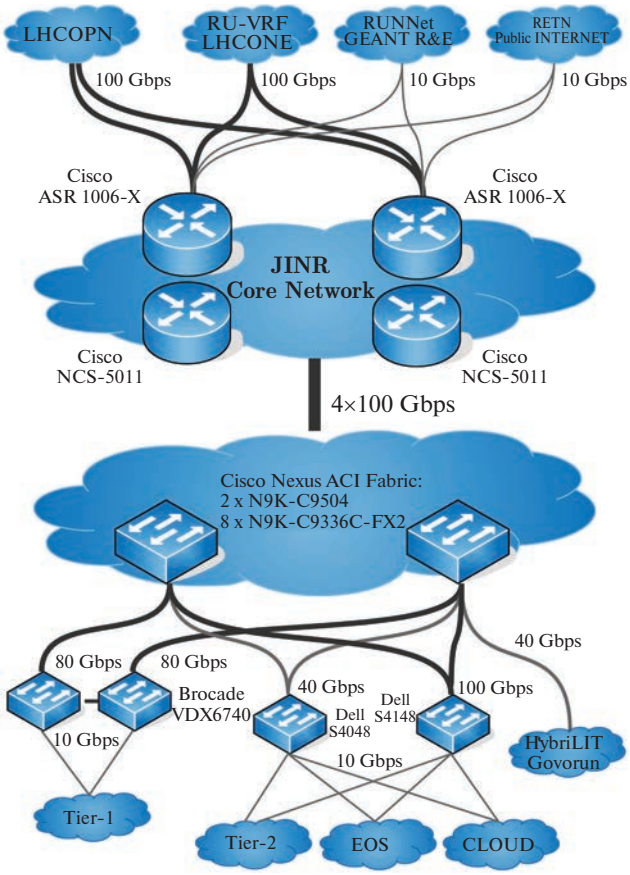


Fig. 3. JINR external distributed network diagram

to Tier-0 (CERN) and other Tier-1 sites. This connection is provided by a direct 100 Gbps JINR–CERN communication channel and its 100 Gbps channel passing through Moscow and Amsterdam. JINR's Tier-2 connectivity is provided by the LHCONE external overlay network, designed for Tier-2 grid sites. RU-VRF technology is used to communicate with Russian institutes involved in processing data from the LHC. The National Research Computer Network of Russia (NIKS), created as a result of the integration of the federal university computer network RUNNet and the network of organizations of the Russian Academy of Sciences RASNet, provides communication with scientific and educational organizations of the Russian Federation[1].

[1] *Velikhov V. E., Korenkov V. V., Ryabinkin E. A., Dolbilov A. G., Gugel Y. V., Strizh T. A.* The Russian Segment (RU-VRF) in WLCG Infrastructure: High Performance Computing Network // Intern. Conf. on Modern Network Technol. (MoNeTec), Moscow, Russian Federation, 2022. P. 1–4; doi: 10.1109/MoNeTec55448.2022.9960772.

JINR LOCAL AREA NETWORK

In 2001–2003, the JINR Local Area Network (LAN) operated using Fast Ethernet technology; data transmission speed was 100 Mbps. The task to construct a JINR backbone network using Gigabit Ethernet technology (data transmission speed of 1000 Mbps) was set by many leaders of scientific experiments at the PACs for Particle Physics and Nuclear Physics. A high-speed network was necessary for organizing distributed computing, for the efficient use of large computer complexes at JINR laboratories, and was especially important for processing data from the LHC experiments at CERN, where JINR has always been actively involved. This task was implemented in stages simultaneously with the uninterrupted operation of the network using the old technology. A high-speed backbone for the transmission of digital information was created, which complies with current requirements for the level of equipment of information and computing infrastructure of large research organizations with network services. A queuing system was implemented for several thousand JINR employees. The use of routing switches in the central core of the network and segments of JINR departments made it possible to scale the network in accordance with ever-increasing needs and created the preconditions for its further development. Users were provided with an impressive list of available network services, enabling the unification of all JINR computer resources into a single information space and the organization of network access to them for various user groups; they gave access to the information and computing resources of Russian and foreign scientific centers, provided remote access to JINR resources from the Institute employees' home PCs, enabled work with web servers, mail service, etc. The problem of network security, i.e., the protection of network and computer infrastructure from various types of attacks, unauthorized access, unqualified actions of personnel and users, etc., was resolved at a high level. In addition to software products and network devices (primarily Cisco, a world leader), the installation of a single-mode fiber-optic cable structure connecting all JINR departments was required for project implementation. Such a structure was built in 2003. Thirteen switching points were established during the cable installation in various rooms across the Institute's departments, requiring over 400 optical weldings. The gigabit backbone network can be considered a unique facility at JINR.

The JINR local area network based on Gigabit Ethernet became available to users in March 2004. 3 550 switches were installed across eight major JINR departments. All segments, interconnected by optical fiber, were connected to a central switch with Cisco Catalyst 6509 router capabilities at LIT, forming a star-shaped topology for the JINR backbone network based on Gigabit Ethernet technology. In 2005, the authors of the work on creating the gigabit backbone network were awarded the JINR First Prize (K. N. Angelov, B. A. Bezrukov, A. E. Gushchin, I. N. Emelin, V. V. Ivanov, L. A. Popov, A. G. Dolbilov, and S. V. Medved).

The network continued to be upgraded year after year, and by 2007 the upgrade of JINR's central telecommunication node was completed.

In 2010, along with the improvement and optimization of the external data transmission channel and the JINR LAN backbone network, work was carried out

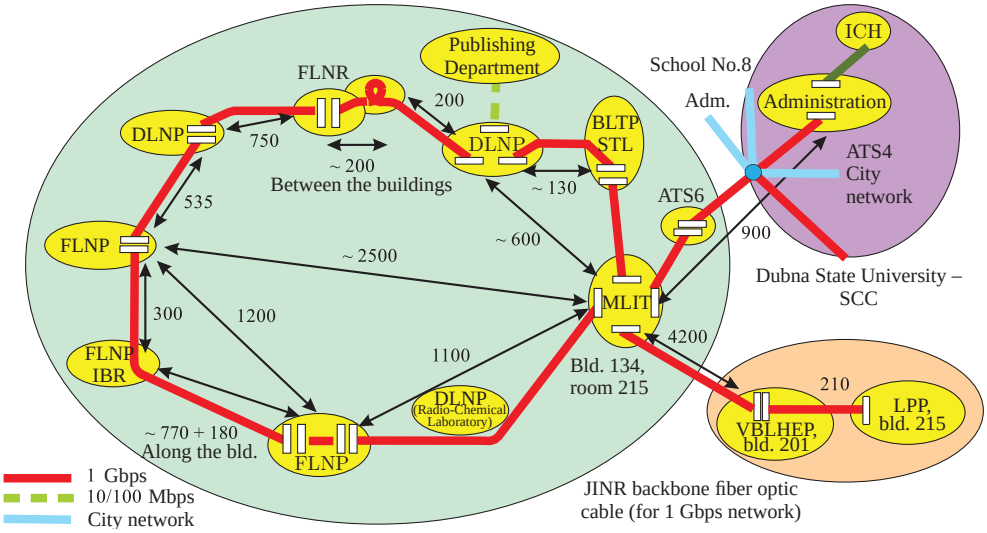


Fig. 4. JINR's gigabit backbone network. 2004

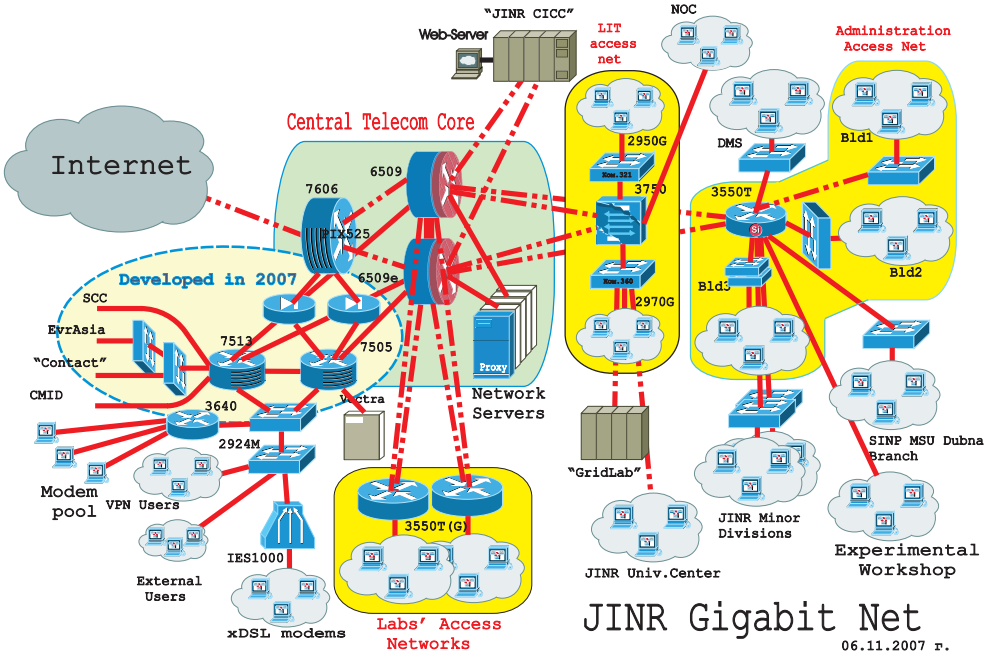


Fig. 5. JINR's computer network structure. 2007

to provide a test version of centralized wireless access to JINR, centralized VoIP and videoconferencing services.

In 2011, work on upgrading the JINR backbone network to 10 Gbps was completed (Fig. 6).

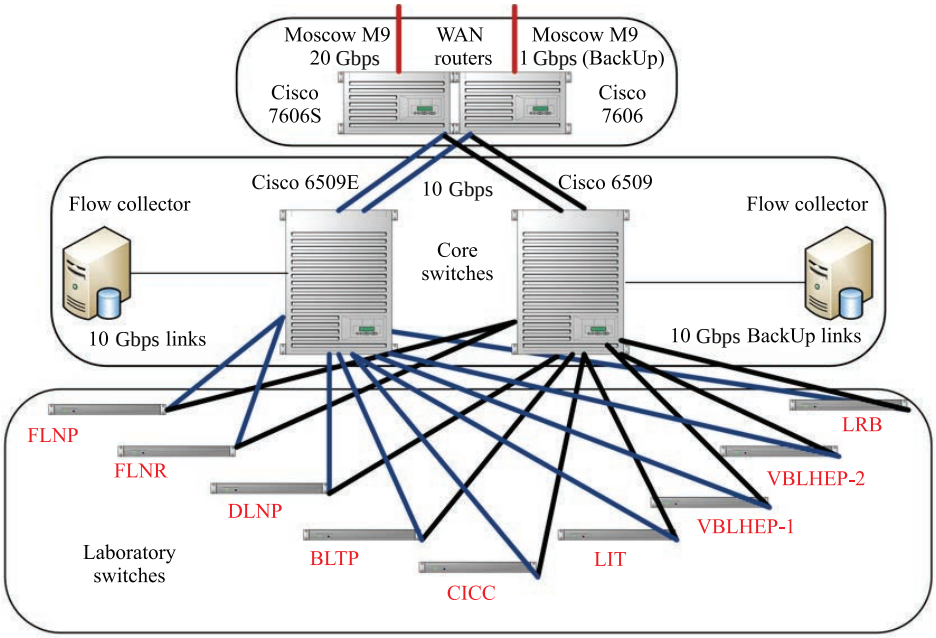


Fig. 6. Diagram of JINR departments' connection to the backbone network

In 2012, opportunities for videoconferencing were significantly improved. A Cisco/Tandberg MCU Codian 4505 conferencing server was installed, capable of providing a genuine high-definition multimedia environment and enabling multipoint videoconferencing. The NMIS (Network Management Information System) infrastructure monitoring system and the IPDB database of JINR network nodes have become some of the most important elements for ensuring a reliable and secure operation of the entire JINR information and computing environment. The IPDB database is still used today for registering and authorizing network elements and users, visualizing network usage statistics, maintaining a database of remote network users, a database of electronic library users, etc.

In 2013–2016, VoIP telephony was put into operation, enabling voice communication with JINR from anywhere in the world. JINR Content Server has been put into service, allowing completing the creation of a videoconferencing system with the ability to record and play streaming video in real time. The unified system of the international academic computing network with transparent eduroam roaming was connected, allowing JINR users to connect to this network. JINR departments have transitioned to a single institute-wide email service, user@jinr.ru, and authorized Wi-Fi was put into operation at JINR sites.

In 2017, the network components of JINR's IT structure continued to develop and improve with the aim to increase its efficiency. The local area network was transferred to DHCP (Dynamic Host Configuration Protocol).

In 2019, the bandwidth of the Institute's local area network backbone was increased to 2×100 Gbps, and a distributed computing cluster network with a bandwidth of 400 Gbps and dual redundancy was built between the DLNP and VBLHEP

sites to improve the reliability of the optical transport backbone. A Cisco ACI fabric based on Cisco Nexus 9504 and Cisco Nexus C9336C-FX2 equipment was put into operation, allowing the connection of MICC components at speeds of 100 Gbps and higher. The fabric was connected to the JINR backbone network via four 100 Gbps channels to ensure the required bandwidth and redundancy capability. The Tier-1 network was transferred to the ACI fabric and has a total connection of 160 Gbps (four channels, 40 Gbps each). The EOS distributed file system, the HybriLIT heterogeneous platform, the Govorun supercomputer, web services, Tier-2, and cloud computing networks are connected to the ACI fabric.

In 2021, the central network virtual cluster of the JINR network service was upgraded. It was designed on the open source software Proxmox VE (Virtual Environment) under the GNU license. This approach allowed the central network service cluster to operate continuously 24/7. It is especially important to note that the virtual machines running in the central cluster service all critical elements of the JINR network. New software (Proxmox mail gateway) was implemented on the @jinr.ru email cluster, which significantly reduced the amount of spam by training the system on spam filtering mechanisms.

Continuous availability monitoring and logging of network session logins were added to the SSO (single sign-on) system.

It should be noted that over the past 20–25 years, the number of network elements has increased from 3105 in 2000 to 13 905 at the beginning of 2025.

GRID ENVIRONMENT

Since 2000, the grid concept (named similarly to electric power grid)[2] has been intensively developing. It emerged due to the need to create a new type of computer infrastructure, providing global integration of information and computing resources on the basis of the creation and development of controlling and optimization middleware of new generation. The essence of the grid concept is to create a set of standardized services to provide reliable, collective, accessible, pervasive and secure access to geographically distributed high-tech information and computing resources — data storages, computers, clusters, supercomputing centers, specialized software and tools, and so on. Just as the emergence of electrical grids has led to a radical change in the paradigm of electricity use, the Internet has globalized information exchange, and the worldwide web WWW has standardized search and delivery of documents; grid, in its turn, has become the next stage in this chain of revolutionary transformations in high technology — standardization and globalization of the use of all kinds of computing resources.

The grid concept emerged due to a number of factors such as:

- a surge in performance of mass production microprocessors — the performance of a modern personal computer is comparable to that of supercomputers of the last century;

[2] *Korenkov V. V., Tikhonenko E. A.* The GRID Concept and Computer Technologies in the LHC Era // Part. Nucl. 2001. V. 32, No. 6. P. 1458–1493.

- emergence of high-speed communication lines;
- WWW/Internet phenomenon — globalization of information exchange;
- development of metacomputing methods — organization of massive and complex-structured computing processes.

Such a concept appeared to be very attractive when creating a model of processing (computing) data of experiments at the Large Hadron Collider (LHC) at CERN. This was due not only to the enormous amount of data that was planned to be obtained in the experiments but also to the need to provide access to this data for several thousand scientists at hundreds of research institutions and universities scattered around the world participating in the LHC experiments. In addition, all data had to be available over the entire lifetime of the LHC. This required unprecedented computation power and storage systems. The traditional approach would be to centralize it all in one place in close proximity to the experiments. The grid concept, as a completely new globally distributed LHC data storage and analysis model, was chosen because it allowed:

- distributing the costs of maintaining and upgrading the necessary resources across individual institutes and participating national organizations, which could finance local computing resources and bear responsibility for them by contributing;
- having fewer individual points of failure in a distributed system and at the same time having multiple copies of data and automatic distribution of computing tasks among available resources, which ensures resource loading balancing and facilitates access to data for all the participants regardless of their geographical location, and coverage of all time zones also facilitates round-the-clock control and support.

A special international MONARC project (MOdels of Networked Analysis at Regional Centers for LHC Experiments) was created in 1998 to model the distributed computing infrastructure of the centers for the LHC. The task of computing organization was very challenging as it required:

- a fast access to massive data arrays;
- a transparent access to geographically distributed resources;
- the creation of an extended reliable network infrastructure in a heterogeneous environment.

A basic computing model for the LHC experiments was developed under the MONARC project as a hierarchical centralized structure of regional centers involving centers of different levels.

The simulation modeling method has demonstrated the effectiveness of the hierarchical principle of LHC information and computing system organization, assuming the creation of centers of different levels, or tiers: Tier-0 (CERN) → Tier-1 → Tier-2 → Tier-3 → user computers.

The levels vary by the scale of resources (network, computational, disk, archival) and by the functions performed:

- Tier-0 (CERN) — primary event reconstruction, calibration, storage of overall databases copies;
- Tier-1 — full event reconstruction, storage of up-to-date event databases, creation and storage of analyzed event sets, modeling, analysis;

- Tier-2 — replication and storage of analyzed event sets, modeling, analysis;
- Tier-3 — clusters of individual research groups.

Requirements to the resources and functions of Tier-0, Tier-1, and Tier-2 regional centers were developed within the framework of this project. The developed model has been implemented and functioned successfully since the launch of the LHC. However, the experience of using it has shown the need to make changes to the hierarchical processing model. Additional data transfer channels between centers of the same tier (Tier-1 → Tier-1, Tier-2 → Tier-2) were introduced to optimize the load of data storage systems in different centers, improve data usage efficiency and processing speed. Additional channels were also introduced, connecting one Tier-2 center with several Tier-1 centers (instead of just one, as in the rigid hierarchical model). Currently, almost all Tier-1 and Tier-2 centers are interconnected via data transmission channels.

JINR actively participated in the ALICE, ATLAS, and CMS experiments at the LHC, starting from the detector design and construction stages, and currently continues to participate in the active phase of the accelerator and its physical facilities. During the acquisition and processing of real LHC data, it was necessary to ensure the full participation of JINR and its Member States in these works, which, in accordance with CERN's grid-based computing model for the LHC, required the creation of a grid segment at JINR and Russia and its subsequent integration into the global grid infrastructure.

For these purposes, a joint project "Russian Information and Computing Complex for Processing and Analyzing Experimental Data at the Large Hadron Collider" (RICC-LHC) was formed at the end of 1999 with the participation of nine leading Russian physics institutes-members in the LHC and JINR. The aim of the project was to create a regional computing complex in Russia for processing data from the LHC experiments[3]. In less than a year, LHC-focused personal computer farms were created at ITEP, IHEP, Physics Faculty of SINP MSU, and JINR. The software environment for these farms was fully standardized and matched the current state of specialized software used at CERN. This marked the beginning of a prototype Russian regional center development. The main contributions of the LCTA team led by V. V. Korenkov included installing the GLOBUS middleware, organizing a shared GRIS (Grid Resource Information Service) and GIIS (Grid Index Information Service) information servers, creating a certification center, testing the meta-dispatcher, to which users submit their tasks for distribution among available execution nodes, developing resource and service monitoring tools at JINR, organizing data management, conducting mass simulations of physical events for particle physics experiments, and creating a distributed database on the center's servers.

In September–October 2000, LIT JINR staff members (V. V. Mitsyn, E. A. Tikhonenko, V. V. Galaktionov, V. V. Trofimov, and others) participated in a session of mass event generation for the high-level CMS trigger on a PC farm (16 processor units at 500 MHz). The resulting data were transferred to CERN for inclusion in

[3] *Korenkov V., Ilyin V., Soldatov A.* Russian Segment of the Global LCG Infrastructure // Open Syst. 2003. V. 1. P. 56–60.



Personal computer farm at LIT, JINR. Left to right: A. Sh. Petrosyan, T. A. Strizh, D. Chkhaberidze, N. A. Kutovskiy, V. V. Korenkov, R. N. Semenov, A. V. Prikhodko, E. A. Tikhonenko, V. Pose, N. Khubua. 2004

an object-oriented database (Objectivity/DB), which was used to select basic information units, optimize trigger algorithms, and reconstruct events. The capabilities of the JINR computing center's mass storage system allowed for testing various models for working with large volumes of data, as well as for improving technologies for sharing the mass storage system with Moscow institutes.

In 2001, initial testing of the grid environment and individual grid services was carried out with the participation of JINR, and the development of systems for global and local monitoring of virtual organizations resources started within the European EU DataGrid project.

In 2003, the Russian Data Intensive Grid (RDIG) consortium[4] was formed to fully participate in the EGEE (Enabling Grids for E-SciencE) project. The memorandum establishing the consortium was signed by the heads of eight major institutes: the Institute for High Energy Physics (Protvino), the Institute of Mathematical Problems of Biology (Pushchino), the Institute for Theoretical and Experimental Physics (Moscow), the Joint Institute for Nuclear Research (Dubna), the Keldysh Institute of Applied Mathematics (Moscow), the Institute of Nuclear Physics of Moscow State University (Moscow), the Petersburg Nuclear Physics Institute (St. Petersburg), and the National Research Centre "Kurchatov Institute" (Moscow). JINR participated in the EGEE project under the leadership of V. V. Korenkov throughout its existence (2003–2010). Two areas of this project in Russia, "Dissemination of Knowledge about Grid" and "Application Selection and Support", were supervised by T. A. Strizh and E. A. Tikhonenko.

[4] *Ilyin V., Korenkov V., Soldatov A.* RDIG (Russian Data Intensive Grid) e-Infrastructure // Proc. of XXI Intern. Symp. on Nuclear Electronics & Computing (NEC'2007, Varna, Bulgaria). Dubna, 2008. P. 233–238.

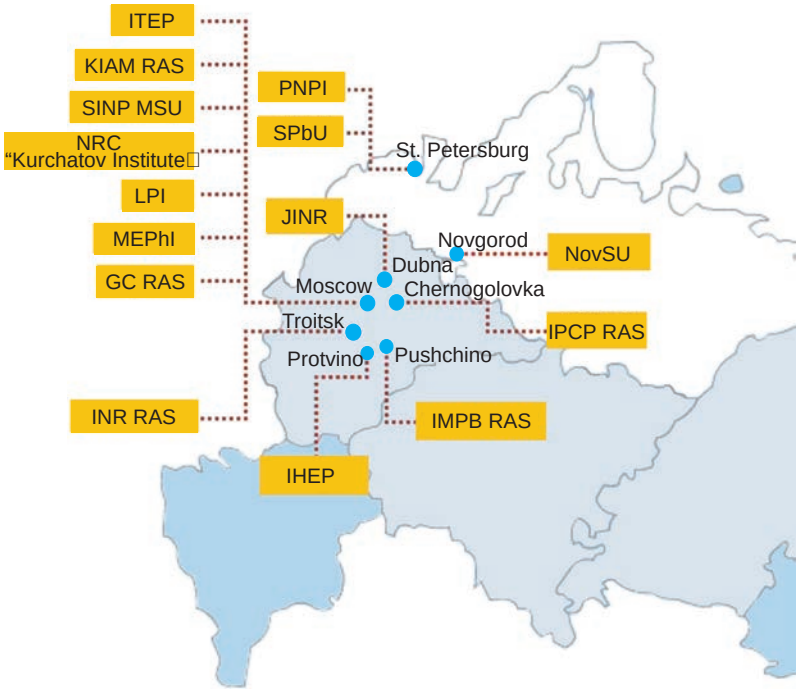


Fig. 7. Members of the RDIG consortium (2007)

During 2003, JINR participated in mass event simulation sessions for the CMS experiment. A new tool, the Storage Resource Broker (SRB), was used for event simulation. The SRB program, installed at JINR, provided direct access to the CMS experiment's shared databases on a server in the UK (Bristol), opening up new opportunities for data storage and exchange within the CMS collaboration.

Experimental data transfer sessions were conducted from Protvino to the ATL-2640 automated tape library in Dubna to evaluate the bandwidth and stability of the data transfer system, including communication channels and mass storage.

In 2004, Dubna hosted the international conference "Distributed Computing and Grid Technologies in Science and Education (GRID2004)". The conference was the first in Russia dedicated to discussing issues related to the use of grid and distributed computing in all fields. It became a regular event, and the eleventh one was held in 2025.

In 2004, the grid segment created at JINR became a systemically important component of the national grid network. The JINR grid site (JINR-LCG2) was successfully integrated into the global grid infrastructure of the EGEE project and the Worldwide LHC Computing Grid (WLCG) project and remains a second-tier resource center in the hierarchy of information and computing centers for experiments at the Large Hadron Collider. The JINR grid site's resources are successfully utilized within the global infrastructure, JINR-LCG2 is one of the best in the WLCG infrastructure in terms of reliability.

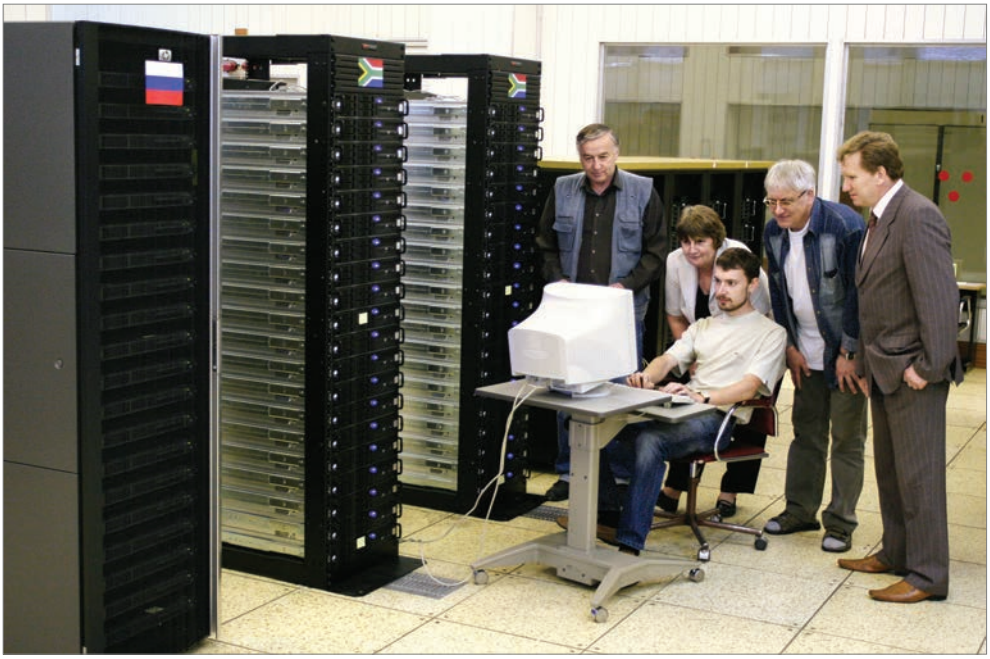
LIT has participated not only in international but also in Russian projects related to distributed computing. Since 2007, LIT has been participating in the

SKIF-Grid project, implemented under the Russia–Belarus Union State scientific and technical cooperation program "Development and Use of Grid Software and Hardware for Advanced High-Performance (Supercomputer) Computing Systems of the SKIF Family".

In collaboration with the Institute of Nuclear Physics of Moscow State University, the Kurchatov Institute, and Petersburg Nuclear Physics Institute, LIT participated in the GridNNN project to create a national nanotechnology network, which was implemented within the framework of the federal special-purpose program for the development of nanoindustry infrastructure in the Russian Federation in 2008–2010.

JINR staff make a significant contribution to the testing and development of grid middleware, the development of grid monitoring systems, as well as support for various virtual organizations.

The creation, operation, support, and management of an industrial-grade grid infrastructure requires collection and analysis of operating data on functioning of both the basic grid services and various services of each resource center (grid site). Therefore, resource monitoring is a key task for each grid infrastructure, particularly EGEE, WLCG, and RDIG. By the time of completion of the EGEE project (May 2010), the RDIG consortium included 15 resource centers (so-called grid sites) in Russia, as well as one center in Belarus and one in Ukraine. Along with its significant geographical distribution, RDIG had impressive resources: over 4000 computing slots and approximately 2 PB of data storage.



Setting up the first grid clusters. I. M. Tkachev is at the terminal. Standing: N. S. Astakhov, T. A. Strizh, V. V. Mitsyn, and V. V. Korenkov. 2007

Starting from 2005, S. D. Belov and I. M. Tkachev developed resource usage monitoring and accounting tools to track the state of the RDIG infrastructure at JINR. A specialized grid monitoring package was developed and subsequently installed in all resource centers. An accounting system (detailed accounting of consumed computing resources) was created along with monitoring. This system operated simultaneously with the general EGEE project accounting system and sometimes surpassed it in terms of stability and data completeness.

The following main tasks were implemented in the monitoring system:

- regular monitoring of the state of services in the grid environment, both those common to the entire infrastructure and the ones in each resource center;
- obtaining information about the number of resources (number and performance of processors, disk space) and their workload (available/used resources);
- progress monitoring — for example, data transfers, task launches;
- monitoring the status of communication channels between resource centers;
- monitoring the use of storage resources by different user groups within a virtual organization.

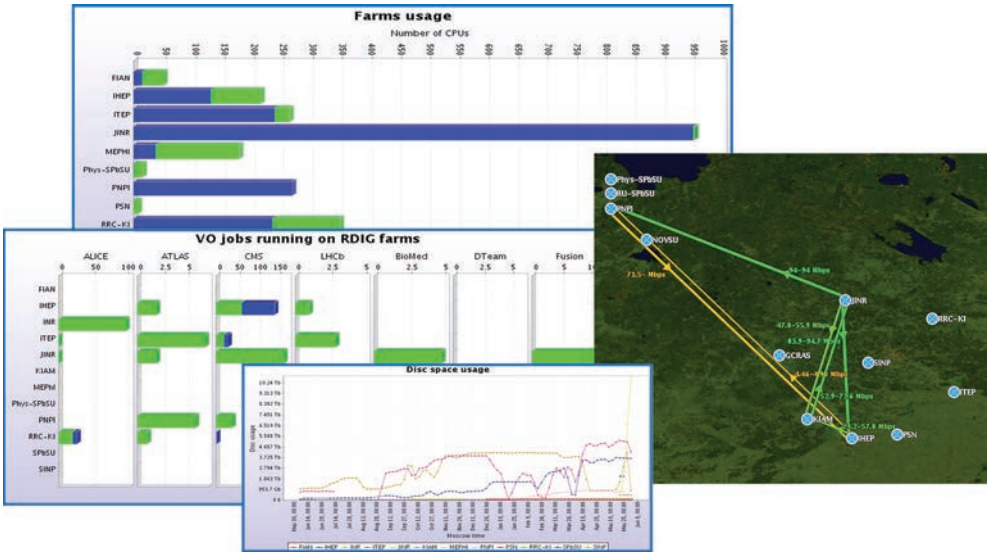


Fig. 8. RDIG monitoring: an example of displaying the current status of various infrastructure parameters

The developed monitoring tools and approaches enabled the creation of a modular, scalable architecture of a highly versatile nature. These developments were subsequently used in projects such as the SKIF-Grid supercomputer initiative of the Union State of Russia and Belarus, the Grid Infrastructure of the National Nanotechnology Network (GridNNN), and the Russian Grid Network for high-performance computing.

One of the key stages in the development of the monitoring systems is data transfer services monitoring. In 2006, two data transfer services were used in

WLCG: FTS (File Transfer Service), used in gLite software, and its equivalent in Globus software, RFT (Reliable File Transfer Service). Transfer volumes were steadily growing, but the monitoring tools available for FTS and RFT were quite limited, and neither system provided comprehensive information on the status of the services, their history, errors, potential sources of failure, and other important parameters. The reliability and correct operation of file transfer services was critical, and developing new and improving existing methods and tools for analyzing and processing information related to their operation was a crucial task. In 2007, A. V. Uzhinsky and A. V. Nechaevsky developed the first version of a monitoring system based on log files processing. Subsequently, a full-range monitoring system was developed, which received error information directly from the FTS database. The system provided a convenient tool for obtaining detailed information on the service operation, maintaining its performance, and promptly responding to parameter changes during large data transfers (up to 100 TB per day or more)[5]. The system had been used for several years until it was replaced by a system integrated into the WLCG Dashboard.

In 2010, at the invitation of the ATLAS experiment, LIT employees A. Sh. Petrosyan and D. A. Oleynik modernized the Deletion Service for the DQ2 distributed data management system. Problems with the previous implementation of this service had reached such a scale by the end of 2009 that data deletion was completely halted. Within a short timeframe, over the course of several weeks in the spring of 2010, the necessary changes were implemented to resume data deletion. Simultaneously with the refactoring of the service itself, a powerful monitoring system was developed to track the deletion process at all stages, making it understandable, transparent, and predictable. At the end of the year, the updated version of the Deletion Service was launched for all Tier-0 – Tier-2 centers storing and processing data for the ATLAS experiment. This implementation of the data deletion service freed up to 2 PB of disk space and up to 20 million files per week[6].

From 2011 to 2015, a group of LIT staff members participated in the development of the AGIS (ATLAS Grid Information System), its commissioning, as well as subsequent development and support[7]. Afterwards, the next generation of this system, called the Computing Resource Information Catalog (CRIC), was used by A. Sh. Petrosyan in a project to organize data processing in a distributed computing environment for the COMPASS experiment. CRIC later became the primary information system for the WLCG project, the CMS experiment, and other experiments utilizing distributed data processing. Currently, CRIC is used to manage

[5] *Korenkov V. V., Uzhinsky A. V.* Grid Data Transfer Service Architecture // Open Syst. 2008. No. 2. P. 52–56.

[6] *Oleynik D., Petrosyan A., Garonne V., Campana S. (on behalf of the ATLAS Collab.).* DDM DQ Deletion Service, Implementation of Central Deletion Service for ATLAS Experiment // Proc. 5th Intern. Conf. "Distributed Computing and Grid-Technologies in Science and Education, GRID-2012". Dubna, 2012. P. 189–194.

[7] *Anisenkov A., Belov S., Di Girolamo A., Gayazov S., Klimentov A., Oleynik D., Senchenko A.* AGIS: The ATLAS Grid Information System // J. Phys.: Conf. Ser. 2012. V. 396. P. 2.

the topology of the distributed computing environment components of the SPD experiment.

The most impressive results in organizing a global distributed computing infrastructure were achieved in the WLCG project while processing data from the LHC experiments. At a workshop on July 4, 2012, dedicated to the observation of a new particle similar to the Higgs boson at the CMS and ATLAS experimental facilities, CERN Director R. Heuer praised grid technologies and their significance for global science. He singled out three components that enabled this achievement: the CERN accelerator complex, the ATLAS and CMS experimental facilities, and the LHC grid infrastructure. The LHC grid infrastructure made it possible to process and store the colossal volume of data coming from the collider experiments, and, consequently, to make scientific discoveries. The JINR grid site, which had been the leading grid site in the RDIG consortium for all these years and was among the top ten Tier-2 grid sites in the world, contributed to this result.

In 2013, the JINR First Prize was awarded to N. S. Astakhov, S. D. Belov, N. I. Gromova, A. G. Dolbilov, V. V. Korenkov, N. A. Kutovskiy, V. V. Mitsyn, T. A. Strizh, E. A. Tikhonenko, and V. V. Trofimov for the work "The JINR Grid Environment — An Element of the Russian and Global Grid Infrastructure".

A number of projects within the ATLAS experiment computing framework are also noteworthy. In 2013–2014, work continued on improving the ATLAS collaboration PanDA (Production ANd Distributed Analysis) task processing system. Among other things, several utility programs were created with the active participation of S. D. Belov, D. A. Oleynik, and A. Sh. Petrosyan for saving, transferring, and filtering various types of data within the PanDA environment. A particular significance of this environment is noteworthy here. PanDA is a data processing task management system that implements a unified task queue for both user analysis and data modeling and mass processing. It was created as a resource management system for the ATLAS collaboration and allowed for the concealment of the entire complexity of the processes and infrastructure underlying task submission for processing, making the operation of the distributed processing environment simple and intuitive for the user.

Since 2012, some research groups in the ATLAS collaboration have begun to gain access to the largest supercomputers (HPC, High Performance Computing). However, the grid infrastructure, which is focused on high-throughput computing (HTC), did not support the efficient use of such resources. Thus, the challenge arose of full-range integration of the supercomputers into the experiment's distributed data processing system.

In 2013, a project called BigPanDA was launched with the primary goal of developing the PanDA workload management system, expanding the range of supported computing infrastructures beyond the grid. The Oak Ridge National Laboratory Computing Facility (OLCF) provided access to the Titan supercomputer and its associated infrastructure to conduct research within the BigPanDA project. In 2013, it was the second most powerful supercomputer in the world, according to the Top 500 ranking.

The experience gained during the development and operation of this project led to the recognition of the need to upgrade the PanDA architecture and revise the

software infrastructure[8]. It became clear that a specialized service was needed for an effective interaction with computing infrastructures. Such a service, called Harvester, was developed with the participation of LIT employees A. Sh. Petrosyan and D. A. Oleynik and was fully integrated into the PanDA system as a standard tool.

A. Sh. Petrosyan's experience gained during the work on the BigPanDA and PanDA projects enabled the development and maintenance of the distributed data processing management system for the COMPASS experiment at the SPS accelerator[9] at CERN from 2015 to 2022. Data processing for the experiment was transferred from a local CERN environment to a global one, and a distributed data processing environment was built for the experiment, enabling the use of not only CERN's grid resources but also those of JINR, INFN in Trieste, CNAF in Bologna, as well as the Blue Waters supercomputers at the University of Illinois at Urbana-Champaign and Frontera at the TACC supercomputing center in Texas. The system implemented all data processes: physical event reconstruction, event filtering, Monte Carlo generation, and reconstruction. After successful completion of all processing steps, results are migrated to tapes, processing logs are archived, and temporary files are deleted — the so-called post-processing.

In March 2011, joint work with the ATLAS collaboration on Tier-3 sites monitoring began. S. D. Belov, A. Sh. Petrosyan, D. A. Oleynik, and others completed the T3MON project, which was aimed at developing a software suite for monitoring Tier-3 sites[10]. This ensured a global accounting of the contributions of sites not included in the ATLAS grid infrastructure to the experiment's computational process.

JINR staff made a significant contribution to the development of the LHC virtual organizations monitoring system (Dashboard), developed and maintained at the Information Technology Department at CERN. This work included both the development of database tables and user interfaces and the upgrade of approaches and tools for collecting and presenting monitored data. LIT staff members I. A. Sidorova, I. S. Kadochnikov, and S. D. Belov worked on the Dashboard project under the supervision of J. Andreeva (CERN)[11]. During the creation of the EGEE grid infrastructure monitoring visualization system as a geographically distributed system, a new feature was developed and implemented in the Dashboard using Google Earth for visualizing dynamic data transfer monitoring in real time, thanks to the participation of LIT staff member S. V. Mitsyn.

The Dashboard project implemented both general monitoring mechanisms and tools, and those peculiar to specific virtual organizations, owing, for example,

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[8] *De K., Klimentov A., Oleynik D., Panitkin S., Petrosyan A., Schovancova J., Vaniachine A., Wenaus T. (on behalf of the ATLAS Collab.)*. Integration of PanDA Workload Management System with Titan Supercomputer at OLCF // J. Phys.: Conf. Ser. 2015. V. 664.

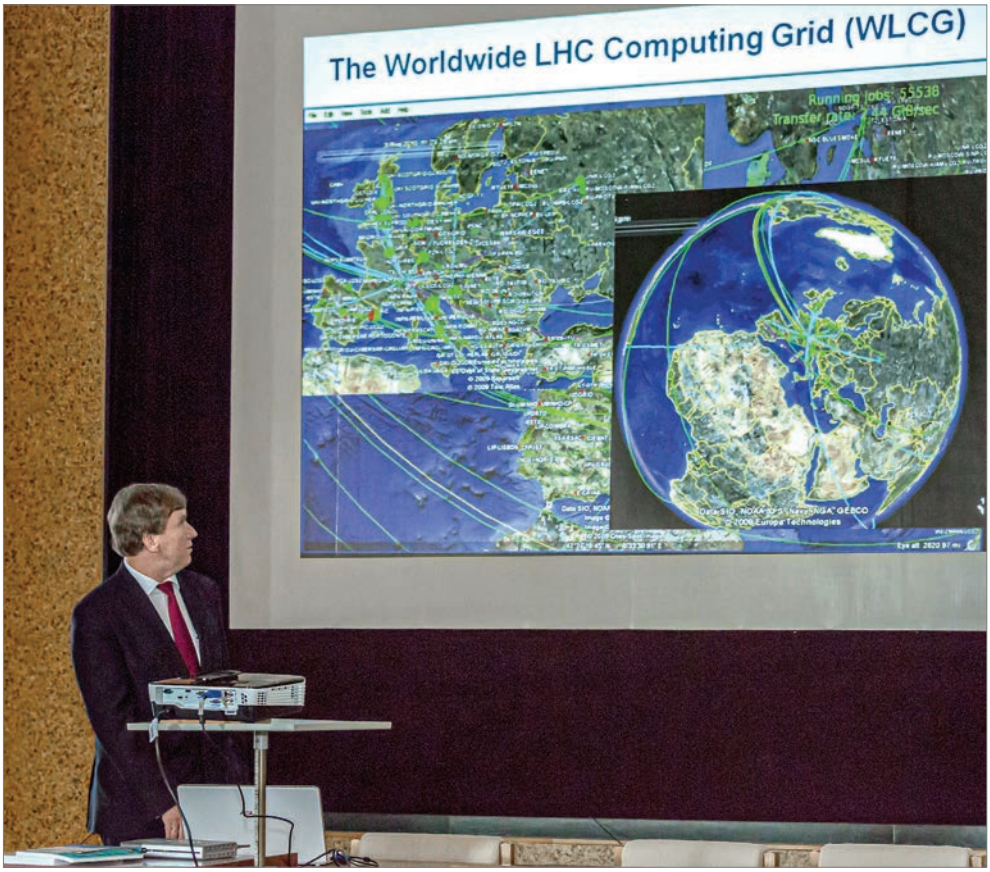
[9] *Petrosyan A*. COMPASS Production System: Frontera Experience // CEUR Workshop Proc. 2021. V. 3041. P. 80–85.

[10] *Andreeva J., Benjamin D., Campana S., Klimentov A., Korenkov V., Oleynik D., Panitkin S., Petrosyan A*. Tier-3 Monitoring Software Suite (T3MON) Proposal // CERN Note. ATL-SOFT-PUB-2011-001. 2011. P. 7.

[11] *Andreeva J., Beche A., Belov S., Kadochnikov I., Saiz P., Tuckett D.* WLCG Transfers Dashboard: A Unified Monitoring Tool for Heterogeneous Data Transfers // J. Phys.: Conf. Ser. 2014. V. 513. P. 3.

to differences in approaches and software packages for running computing tasks or transferring data. To cope with the increasing volume and diversity of resources as computing approaches at WLCG developed, monitoring began to evolve toward software solutions from the Big Data analytics stack. The implementation of the project since 2016 has resulted in the definition, development, and deployment of a unified monitoring architecture (UMA), designed to meet the requirements for collecting, transporting, storing, searching, processing, and visualizing both IT monitoring data and WLCG monitoring data. The MONIT monitoring project, which is currently successfully operating at CERN, was created based on the UMA architecture. The initial characteristics of MONIT's input data include over 100 data sources, approximately 100 000 messages per second, and approximately 3 TB of monitoring data per day.

Between 2014 and 2016, LIT employee S. D. Belov developed data transfer monitoring for the ATLAS global computing system as part of the MONIT project. Algorithms and software components were created for processing and aggregating file transfer information received from various sources. The data was processed and provided in near real-time. Various statistical sampling of data transfer parameters



V. V. Korenkov demonstrating visualization of dynamic monitoring of data transmission in real time

(speed, volume, technologies used, data sources, etc.) were also generated. The created service fully complies with the UMA architecture and is an integral part of the MONIT project.

The ATLAS experiment's distributed computing model involves storing multiple copies of data (replicas), depending on their class, across different data centers and storage types for subsequent processing. As data accumulates rapidly, data storages become full, which requires the selection of a replication and data management strategy based on the characteristics of access across different storage resources. Thus, the need arises for a tool for analyzing the demand for various types of data. "Data popularity" is a measure calculated using specialized algorithms based on the purpose of its use and taking into account such data interaction characteristics as the number and nature of accesses, data access frequency, time of last access, etc.

In 2016, S. D. Belov developed a software suite that regularly and automatically generated information about the demand for the ATLAS experiment datasets based on their type and storage location. This demand analysis is based on data access information obtained from the DQ2 and Rucio control systems, as well as on a description of the experiment's distributed computing infrastructure topology. The resulting data demand analysis tool allowed studying the impact of data management policy on access dynamics and, after selecting a strategy, more accurately assess and plan the required data storage capacity for the ATLAS experiment following the LHC detector and accelerator upgrade[12]. It freed up approximately 25% of the disk space occupied by rarely accessed modeling and analysis data, amounting to approximately 30 PB at the time of the study (Fig. 9).

In 2012, work began in Russia with the participation of JINR on the creation of a distributed Tier-1 center. The organization of the center included the support of the ALICE, ATLAS and LHCb experiments based on the computing complex of the National Research Centre "Kurchatov Institute", and support of the CMS experiment based on the JINR computing center at LIT. In 2013, a prototype of a JINR Tier-1 center for the CMS experiment was created[13]. It was presented at LIT on March 26, 2015. This center, built by a large team of software engineers and researchers from LIT under the supervision of V. V. Korenkov, created the conditions for physicists from the Institute, Member States and the RDMS–CMS collaboration to fully participate in the processing and analysis of the CMS experiment data. There are only eight CMS centers of this level in the world. During the creation of the center, an engineering infrastructure (uninterruptible power supply system, climate control, etc.); a high-speed, reliable network infrastructure with a dedicated, redundant channel to CERN (LHCOPN); a computing and storage system based on disk arrays and a high-capacity robotic tape library were developed. The commissioned systems ensure 100% reliability and availability of the center.

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[12] *Filipčič A. et al.* ATLAS Distributed Computing Experience and Performance during the LHC Run-2 // J. Phys.: Conf. Ser. IOP Publ., 2017. V. 898, No. 5. 052015.

[13] *Astakhov N. S., Belov S. D., Gorbunov I. N., Dmitrienko P. V., Dolbilov A. G., Zhiltsov V. E., Korenkov V. V., Mitsyn V. V., Strizh T. A., Tikhonenko E. A., Trophimov V. V., Shmatov S. V.* Automated Tier-1 Level System for Processing CMS Experimental Data // Inf. Technol. Comput. Syst. 2013. V. 4. P. 27–36.

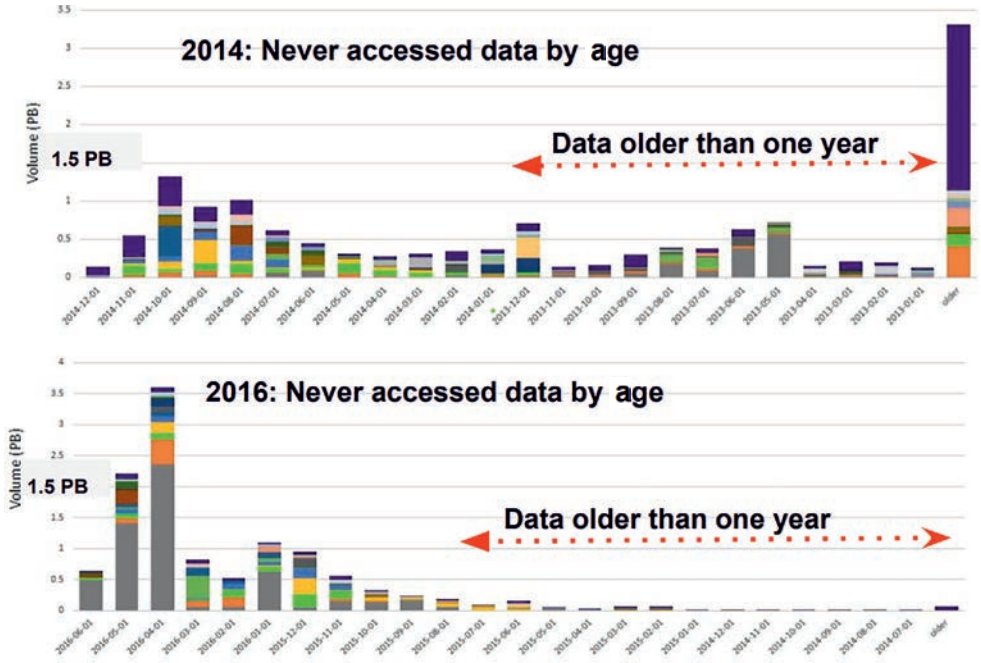


Fig. 9. Dataset sizes depending on access frequency: before and after optimization of management policies

JINR's Tier-1 site is second only to the Tier-1 center at Fermi National Accelerator Laboratory (USA) in terms of productivity among global Tier-1 centers processing data from the CMS experiment at the LHC.

At the same time, work began during these years on modeling the data storage and processing system of the NICA accelerator complex. The GridSim system was chosen as the platform for the simulation model. The modeling process allows for the selection of the minimum required equipment to meet data transmission, processing, and storage requirements, assessment of the required equipment performance margin to support potential increases in production capacity, selection of several equipment options based on current needs and future development prospects, system performance testing, and identification of bottlenecks, etc.

To ensure the reliable operation of the entire computing complex, it was necessary to monitor the status of all components in real time — from the power supply system to the robotic tape library. A new monitoring system for the JINR computing complex was developed and commissioned, and a control and management center for the complex was established under the supervision of V. V. Mitsyn, I. A. Kashunin and A. O. Golunov[14].

The data storage system is one of the most important elements of the JINR grid infrastructure, as well as the entire MICC. This system is built hierarchically, and

[14] *Kashunin I. A., Dolbilov A. G., Golunov A. O., Korenkov V. V., Mitsyn V. V., Strizh T. A.* Monitoring System of a Multifunctional Information and Computing Complex // CEUR Workshop Proc. 2016. V. 1787; http://ceur-ws.org/Vol-1787/256-263-paper-43.pdf.



V. V. Mitsyn in the module with the JINR Tier-1 computing servers. 2015

the storage level depends on the data retention period and its volume. Computing cluster machines have limited disk space intended for storing the operating system (OS) itself, some additional utilities, and limited-size temporary user files. The distributed global AFS system is used to store data and access user home directories and small-scale software. The globally accessible system for managing and accessing large software suites for collaborations and user groups is based on CVMFS software developed at CERN. dCache and EOS are used as the primary data storage systems. These are systems for medium-term data storage. EOS, as a system for storing very large volumes of data, is optimal in terms of cost/storage capacity; it supports multiple access protocols (POSIX when installed on the user's computer, xroot and http for fast remote access), it is designed to provide high-speed data access thanks to parallel copying from multiple servers, etc. A robotic tape system is used for long-term storage of large volumes of data.

With the start of NICA runs, intensive expansion of long-term data storage systems based on robotic tape libraries will be required. In addition to the tape robot for the CMS experiment, Tier-1 requires the creation of a long-term data storage for the NICA experiments, the neutrino program, and other user groups. This sys-



V. V. Mitsyn, A. O. Golunov at the MICC monitoring center. 2016

tem is being developed using the CERN Tape Archive (CTA) software developed at CERN. The main component of CTA is EOS, with the addition of infrastructure for operating tape robots and manipulating metadata in stored files. EOSCTA was launched into trial operation in 2023.

Currently, Tier-1 consists of 482 computing nodes (23 360 cores) with a performance of 427 920.04 HEP-SPEC06. The tasks for processing the CMS experiment data are launched by 16-core pilots, and all computing resources are available to them. Data storage is provided by the dCache system with a capacity of 15 PB and a robotic tape storage with a total capacity of 100 PB. The TS4500 robot operates with Enstore and dCache software. The TS3500 robot uses the EOSCTA system. A disk array with a capacity of 2.2 PB is used for working with tapes for data caching. Tier-2 consists of 485 computing nodes (10 356 cores) with a performance of 166 788.4 HEP-SPEC06. Data storage is provided by the dCache system[15] with a capacity of 4.88 PB.

CLOUD COMPUTING

The most versatile MICC service is the JINR cloud, which is built on the basic cloud resource delivery model of Infrastructure-as-a-Service (IaaS). This type of service provides end users with computing resources in the form of virtual machines (VMs), which can serve as both the final product of the cloud infrastructure and as the basis for building complex multicomponent systems consisting of multiple interconnected VMs. The ability to allocate only the required amount of resources (processor cores, memory, and disk space) to VMs, as well as the ability to create

[15] *Baginyan A., Balandin A., Dolbilov A., Golunov A., Gromova N., Kashunin I., Korenkov V., Mitsyn V., Pelevanyuk I., Shmatov S., Strizh T., Trofimov V., Vorontsov A., Voytishin N.* JINR Grid Infrastructure: Status and Plans // Phys. Part. Nucl. 2024. V. 55, No. 3. P. 355–359.

and delete VMs on demand, allows for the flexible redistribution of resources between different users and systems in the cloud according to their current needs.

To improve the efficiency of resource utilization for solving a wide range of problems in these areas, in the early 2000s, N. A. Kutovskiy, under the supervision of V. V. Korenkov, examined the synthesis of cloud and grid technologies and explored possible options for their combined use[16]. Based on the research conducted at LIT JINR, requirements for cloud grid systems for educational and research purposes were developed. Taking these requirements into account, methods for creating such cloud grid systems were elaborated. To meet the growing demand for solving educational and research problems in the field of cloud and grid technologies, a cloud grid system was created at LIT JINR in 2013 using the methods mentioned above. The core of this infrastructure was the educational and research grid infrastructure, created in 2004 using the resources of the JINR UC (six desktop servers), operating using virtual resource sharing at the operating system level based on OpenVZ containers. The JINR cloud infrastructure (http://cloud.jinr.ru) was put into operation since the beginning of 2014. JINR cloud resources have been used in three main areas[17]:

- for educational, research and testing tasks in various projects;
- for hosting services with high availability and reliability;
- as computing resources, including as an expansion of the computing capabilities of grid infrastructures.

The following services and testbeds were deployed in the cloud infrastructure:

- a polygon based on the EMI grid middleware for training, testing, development and solving research problems within the framework of JINR's participation in various projects related to the use of this middleware, including the WLCG project;
- PanDA polygon for the development of the PanDA product and its use to solve problems of the ATLAS and COMPASS experiments;
- a polygon based on the DIRAC middleware for developing monitoring tools for the distributed computing infrastructure of the BES-III experiment, as well as one of its computing resources;
- a set of containers for users participating in the NOvA experiment (modeling and analysis);
- a polygon for studying and evaluating middleware for building a computing infrastructure for experiments at the NICA accelerator;
- a polygon based on the EOS data storage system to fulfill obligations within the framework of participation in a project to study heterogeneous cyberinfrastructures, develop and create a prototype of a computer federation based on high-speed computing, cloud computing and supercomputers for storing, processing and analyzing Big Data;

[16] *Korenkov V. V., Kutovskiy N. A.* Distributed Training and Testing GRID Infrastructure // Proc. 4th Intern. Conf. "Distributed Computing and Grid-Technologies in Science and Education, GRID-2010". Dubna, 2010. P. 148–152.

[17] *Kutovskiy N., Korenkov V., Balashov N., Baranov A., Semenov R.* JINR Cloud Infrastructure // Procedia Comput. Sci. 2015. V. 66. P. 574–583.

- HybriLIT computing complex services (Indico — a service for organizing scientific events; FreeIPA — a centralized system for managing user identification, setting access and audit policies; Git — a local Git repository based on a popular version control system);
- Helpdesk — a support system for users of IT services provided by MLIT;
- a polygon based on BOINC software for assessing the possibility of using volunteer computing in solving problems of JINR scientists;
- HepWeb service, which provides the ability to use various tools for Monte Carlo simulation in high-energy physics;
- test copies of the JINR document server and project management service for debugging the transition to new versions and testing new functionality;
- a container for website development, including the new JINR web portal;
- GitLab — a local installation of the GitLab service for all JINR users;
- a Hadoop-based polygon;
- a set of virtual machines and containers of users for their own needs;
- containers for evaluating the existing monitoring systems and developing new service monitoring systems based on them.

In subsequent years, N. A. Kutovskiy, N. A. Balashov, E. Mazhitova, R. N. Semenov, A. N. Makhalkin, and others continued their active work on optimizing the cloud infrastructure and its services[18]. Today, the JINR cloud is used to solve a wide range of tasks, including hosting web services, testing new versions of various systems, debugging software under development for operating system versions, and deploying numerous information and computing services, such as a batch cluster based on the HTCondor system for distributed computing; the JupyterHub interactive programming service; the GitLab service for managing software development projects, etc.

Currently, the JINR cloud operates on the OpenNebula platform and includes 180 servers, providing approximately 5 700 processor cores and 69 TB of memory for more than 800 virtual machines deployed within it. The cloud also includes three Ceph-based cloud data storages:

- ~615 TB of SSD-based storage is used to provide network-attached virtual block devices as cloud VM disks.
- ~2.2 PB of HDD-based storage provides disk space to VMs with less disk I/O requirements. It is also used as object storage, providing access to data via the S3 protocol for integration with third-party systems. For example, the GitLab service at JINR uses it to organize a registry of Docker container images.
- Additional storage of ~3.2 PB based on HDD is used to store experimental data and is provided to users in the form of a network file system.

All three storage systems utilize triple redundancy for all data, which ensures a high level of data security and system fault tolerance.

An important distinguishing feature of cloud infrastructure is the ability to manage virtual resources using a software interface.

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[18] *Balashov N. A., Kuprikov I. S., Kutovskiy N. A., Makhalkin A. N., Mazhitova Ye., Pelevanyuk I. S., Semenov R. N.* JINR Distributed Information and Computing Environment: Participants, Features and Challenges // CEUR Workshop Proc. 2021. V. 3041. P. 280–284.

Although the MICC cloud resources are used by a large number of projects, the largest consumers of cloud resources at JINR are currently the Baikal-GVD, JUNO, NOvA, Borexino, and DayaBay neutrino experiments.

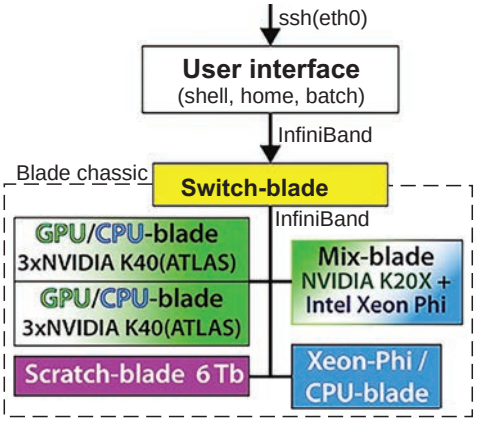
HETEROGENEOUS COMPUTING

HybriLIT CLUSTER

The history of the HybriLIT heterogeneous computing platform began in 2013 with the decision to expand the JINR MICC by adding a heterogeneous computing cluster to its structure. This decision followed contemporary trends in global computing technology at the time, a trend that has only intensified due to the active development and implementation of artificial intelligence methods. In 2014, the HybriLIT computing cluster was commissioned, comprising four nodes: two nodes with three NVIDIA Tesla K40 (Atlas) graphics accelerators each, a node with two Intel Xeon Phi 7120P coprocessors, and a node containing an NVIDIA Tesla K20x and an Intel Xeon Phi 5110P coprocessor. All computing nodes contained two Intel Xeon E5-2695v2 processors. The HybriLIT cluster also included a control node and a data storage node.

It should be noted that the cluster incorporated leading computing architectures of the time, namely, multicore MIC processors from Intel — first-generation Intel Xeon Phi architecture — and NVDIA K20X and K40 graphics accelerators. This allowed for the integration of two key accelerator development trends at the time, enabling cluster users to utilize the primary computing tools available on the HPC market.

Although the cluster was small and had a performance of approximately 18 TFlops for double-precision operations, it provided users of the Institute and Member States with the opportunity to implement heterogeneous computing in scientific research in three main areas:



❑ **Computing resources:**

CPU Intel Xeon **8** x E5-2695v2	96 cores
GPU 6 x K40 & K20	199 68 cores
Intel Xeon Phi 3 x 7120P&5110P	182 cores

RAM **512** GB
EOS storage **14** TB

InfiniBand **40** Gbps

❑ **Peak performance** for computations with floating point:

Single precision	46.914 TFlops
Double precision	17.979 TFlops

Peak demand: 10 kW

Fig. 10. Structure of the HybriLIT heterogeneous computing cluster in 2014 (left). Key parameters of the computing cluster and its performance (right)

- creation of an in-house software for conducting research that requires resource-intensive calculations;
- usage of application software packages and mathematical libraries that have already been adapted for hybrid architectures;
- development of parallel algorithms for solving various problems using the heterogeneous computing paradigm.

Simultaneously with the creation of the cluster, a group of specialists for its maintenance and user management, dubbed "HybriLIT"[19], was organized. It was comprised of employees from various departments and sectors of LIT. D. V. Belyakov, M. Valya (at that moment an employee of the Institute of Experimental Physics of SAS and the Technical University of Košice, Slovakia), M. A. Matveev, and Yu. A. Butenko became the cluster's system administrators. M. I. Zuev, E. I. Alexandrov, A. V. Kazymov, D. S. Golub, and T. F. Sapozhnikova were responsible for the software, including application and licensing. M. K. Kirakosyan, Sh. G. Torosyan, L. Valeva (at that moment an employee of the Institute of Experimental Physics of the SAS), and T. N. Zaikina were responsible for user registration and their support on various issues. O. I. Streltsova, A. I. Streltsov (at that moment an employee of the University of Heidelberg, Germany), E. V. Zemlyanaya, A. S. Ayriyan, and M. V. Bashashin were responsible for algorithm development and user support on the application of parallel programming technologies. P. V. Zrelov became the first head of the HybriLIT group, his deputy was D. V. Podgainy, and the scientific leader was Gh. Adam. From the moment of its creation, the group began actively developing the software and information environment of the HybriLIT cluster. The implementation of this environment was motivated by increased efficiency in application development and calculations using the cluster's resources.

The first version of the software and information environment, created in 2014, contained two levels. The first level, the system level, included the basic software: the operating system (at the time, Scientific Linux 6, due to its compatibility with all MICC components), and the NFS4 and EOS file systems. SLURM was chosen as the task scheduler, responsible for distributing the workflow among the heterogeneous cluster nodes, depending on the load. The choice of this scheduler was influenced by its widespread use in various systems from the Top 500 list of the world's most powerful supercomputers and on the MICC grid components, which became a weighty argument for its use. SLURM organized the distribution of tasks across various queue types to effectively utilize various types of accelerators. A dedicated nanoramfs system was developed to improve the efficiency of cluster system administration. It included network configuration commands suitable for each class of server within the cluster. Nanoramfs solved three cluster administration problems:

1) implement dynamic expansion of the cluster in the future by adding new computing nodes;

[19] *Adam G., Korenkov V., Podgainy D., Streltsova O., Strizh T., Zrelov P.* HybriLIT — The Main Component of the MICC for Heterogeneous Computations at JINR // CEUR Workshop Proc. 2017. V. 2023. P. 351–356.

2) provide the ability to synchronously update or change software on all current and future computing nodes;
3) quickly install nodes after failures and reboots.

The first level of the software and information environment also implemented the idea of connecting remote open-source software packages to the cluster. This was necessary to enable the use of the open-source software cluster, tailored for parallel applications in the CERN repository. This was achieved by implementing CVMFS (CERN Virtual Machine File System) into the software and information environment, allowing users to import the necessary remote modules via a special extension to the MODULES package. The cluster was equipped with the appropriate software packages: OpenMPI, CUDA, Intel Parallel Studio, and others for developing, debugging, and profiling parallel applications and performing resource-intensive calculations.

The second level of the software and information environment — the user level — was designed to efficiently organize user workflows and provide access to necessary information. A set of services was installed and maintained on the cluster for this purpose. Among those, several services were primarily designed to provide users with the necessary information for working on the cluster, facilitate active and close interaction with users, and provide information about various events held by the HybriLIT group:

- the HybriLIT website which contains detailed information about the resources provided to cluster users;
- Indico HybriLIT system for organizing conferences, seminars and meetings dedicated to parallel programming technologies;

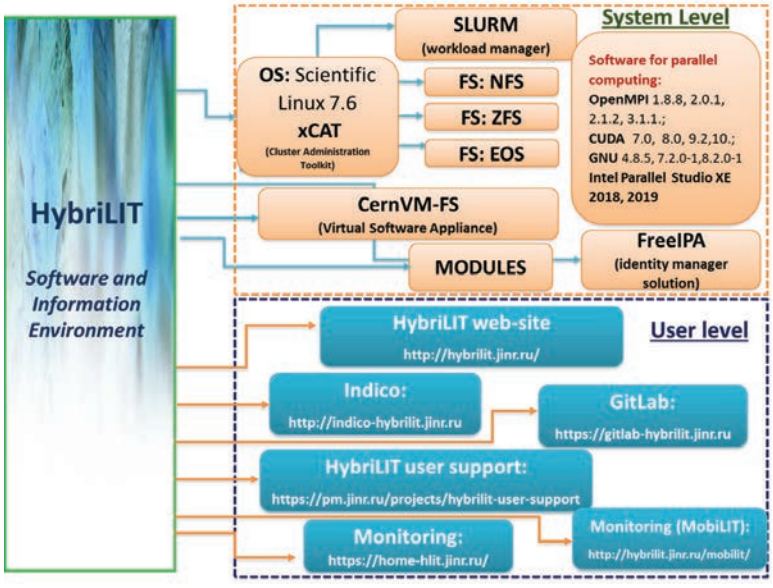


Fig. 11. Software and information environment of the HybriLIT cluster in 2014

- HybriLIT User Support implemented in the Project Management Service system (http://pm.jinr.ru) and allowing for prompt responses to cluster users' questions, posting useful materials, news, etc.;
- GitLab — a service for collaborative parallel application development.

Further development of the HybriLIT cluster was carried out in two main directions. The first one involved increasing the computing power of both the HybriLIT cluster's multicore component, which contained multicore Intel Xeon Phi processors and coprocessors, and the GPU component, which contained NVIDIA accelerators. This increase in computing power was driven by both the growing number of users and the increasing number of application software and specialized libraries requiring accelerators. In 2015, cluster performance increased by 1.5 times due to the addition of two computing nodes with the latest-generation NVIDIA K80 graphics accelerators, reaching 40 TFlops for double-precision operations.

In this case, the cluster was used to solve problems requiring massively parallel calculations in various fields of physics, biophysics and applied areas, in particular, quark propagators for the designs of various observable quark condensates of internal energy within the framework of the theory of quantum chromodynamics (QCD) on lattices, calculation of Josephson junctions, design and optimization of a cryogenic cell, study of the dynamics of many-particle boson systems in magneto-optical traps, modeling the structure and the transmission mechanism of the NMDA glutamate receptor, mathematical modeling of the interactions of antiprotons with protons and nuclei in the computing environment of the future PANDA experiment on the FAIR accelerator — PandaRoot, using the DPM, FTF and UrQMD+SMM generators developed at JINR and of interest to the MPD experiment at NICA, development of parallel algorithms for computed tomography for the MARS (Medipix All Resolution System) X-ray microtomograph, calculation of corrections for the matrix element in the first Born approximation in the case of the reaction of direct ionization of the helium atom by a fast proton, taking into account various models of the final state, etc.

The second direction involved systematical exploration of the capabilities of new computing architectures emerging in the field of high-performance computing, with a view to their subsequent integration into the cluster. This direction ultimately led to the design of the Govorun supercomputer and provided JINR users with modern computing tools for improving the efficiency of scientific problem solving as well as enabled the implementation of more complex mathematical models of the studied physical processes.

GOVORUN SUPERCOMPUTER

As noted above, the development of the HybriLIT cluster led to the creation of the Govorun supercomputer in 2018. It is named after Nikolai Nikolaevich Govorun, whose name has been associated with the development of information technology at JINR since 1966. The need for a supercomputer arose, on the one hand, from the increasing demand for and effectiveness of the latest computing architectures in solving the Institute's problems, and on the other hand, from the growing number of users, including through numerous training courses on paral-



Opening ceremony of the Govorun supercomputer in 2018

lel programming technologies conducted for JINR staff and those from the JINR Member States. The constant growth in the number of users and the expanding range of problems solved necessitated not only a significant increase in the cluster's computing capacity but also the development and implementation of new technologies, which led to the creation of a new computing system — the Govorun supercomputer. It was designed as a high-performance, scalable, liquid-cooled system with a hyperconverged and software-defined architecture.

The creation of the Govorun supercomputer at JINR was an important technological achievement and is of great significance for the implementation of the scientific program and international cooperation of JINR[20]. Important assistance in solving this decisive task to develop a multifunctional information computing complex at JINR based on cutting-edge technologies was provided by the Institute's Directorate with the personal support of V. A. Matveev.

The presentation of the first stage of the Govorun supercomputer took place on March 27, 2018, during a session of the Committee of Plenipotentiaries of the Governments of the JINR Member States. The Govorun supercomputer was launched as a joint project of the Bogoliubov Laboratory of Theoretical Physics, the JINR Laboratory of Information Technologies, RSC Technologies, Intel, NVIDIA, and IBS Platformix, and was supported by the JINR Directorate.

The Govorun supercomputer system was initially equipped with computing modules containing GPU and CPU components. The combined peak performance of the Govorun supercomputer was 0.5 PFlops for double-precision calculations (1 PFlops for single-precision calculations).

Direct liquid cooling technology from RSC Technologies, a leading Russian developer and integrator of full-cycle supercomputer solutions and an owner of

[20] *Belyakov D., Nechaevskiy A., Pelevanuk I., Podgainy D., Stadnik A., Streltsova O., Vorontsov A., Zuev M.* Govorun Supercomputer for JINR Tasks // CEUR Workshop Proc. 2020. V. 2772. P. 1–12.

innovative proprietary technologies, was selected for the supercomputer's CPU components. Thanks to the implementation of these technologies, the Govorun supercomputer system achieved a record density of computing nodes per cabinet (153 nodes versus 25 nodes for air cooling), while operation in hot water cooling mode enabled year-round free cooling ($24 \times 7 \times 365$). Alongside with high energy efficiency, this approach significantly simplified the infrastructure of the supercomputer center. The Govorun supercomputer cooling system is designed using only dry cooling towers, which cool the liquid using ambient air. Thanks to liquid cooling, the system's average annual PUE (Power Usage Effectiveness) indicator, which reflects its level of energy the efficiency, is less than 1.06. This means that cooling accounts for less than 6% of the total electricity consumed by the Govorun supercomputer, a remarkable achievement for the HPC industry. The constructed system is the world's first 100% liquid-cooled system, meaning all components — computing nodes, network switches, and the data storage system — are liquid-cooled.

Another technology underlying the Govorun supercomputer is a hyperconverged approach to building a computing complex. It enables the creation of computing environments with hardware and software configurations optimized for specific user tasks, without changing the hardware of the computing nodes themselves. Hyperconvergence enables the orchestration of computing resources and data storage elements, enabling the creation of computing systems using RSC BasIS soft-



NVIDIA DGX-1 servers with graphics processors were installed. T. A. Strizh, V. A. Zhurkin, D. V. Podgainy, E. A. Kuzin, M. A. Matveev, O. I. Streltsova, M. S. Plyashkevich, A. S. Kamensky, S. V. Marchenko, A. S. Vorontsov. 2018

ware whose configurations are created on-demand, tailored to the needs of user applications. This feature enables the efficient solution of various user tasks, increases the level of data privacy, and avoids system errors that occur when resources for different user tasks overlap. The storage-on-demand system, implemented on the first-stage hyperconverged nodes and managed by the Lustre file system, allowed the Govorun supercomputer to take the ninth place in the IO 500 global ranking (June 2018) for HPC-class data storage systems.

The first stage of the Govorun supercomputer operating experience revealed the need not only to expand computing resources, driven by its relevance for solving JINR problems and the growing number of users, but also the need to create tools for working with Big Data, primarily for the NICA megaproject. In this connection, a hierarchical data processing and storage system with a software-defined architecture was developed and implemented on the Govorun supercomputer. The system is divided into layers based on data access speed: very hot data — the most frequently accessed data, which currently require the fastest access, hot data, and warm data. The implementation of a hierarchical data processing and storage system significantly improves the efficiency of working with large data sets, including for the NICA project. As a result, the second stage of the Govorun supercomputer was commissioned in 2019.

As a result of this upgrade, the performance of the supercomputer increased to 860 TFlops for double-precision calculations (1.7 PFlops for single-precision calculations); the Govorun supercomputer received the prestigious Russian DC Awards 2020 in the category "Best IT Solution for Data Centers" for its high-speed data processing and storage system.

The tasks of mass data generation and reconstruction for the MPD NICA experiment make active use of the Govorun supercomputer hierarchical data processing and storage system. At different stages of the workflow, the need for different data access speeds arises. For example, access speed is not a significant factor for long-term storage tasks, but it plays a significant role for reconstruction tasks. A number of MPD tasks also require a large amount of RAM, necessitating the inclusion of hyperconverged nodes with large memory capacity in the supercomputer

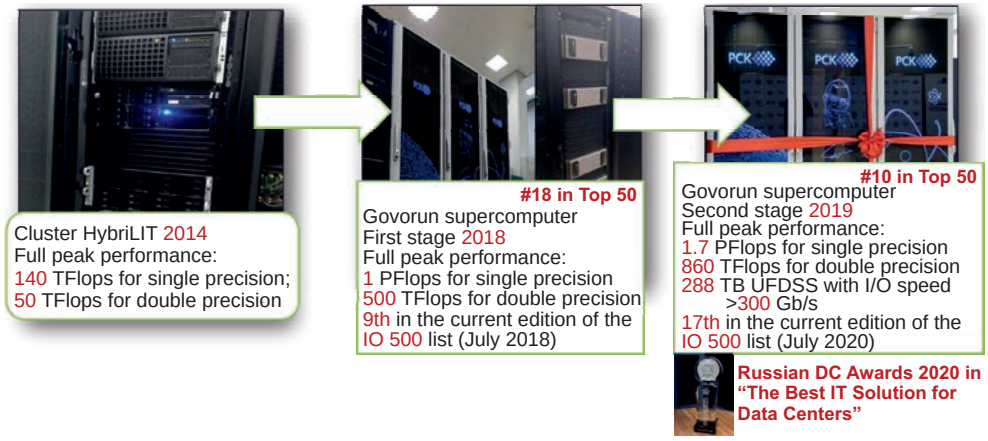


Fig. 12. Evolution of the HybriLIT cluster

architecture. Therefore, a system combining various types of computing architectures and a developed hierarchical data processing and storage system was created on the Govorun supercomputer to support all workflows for the NICA megaproject. The computing resources and the hierarchical data processing and storage system of the Govorun supercomputer were integrated using the DIRAC platform into a distributed heterogeneous environment, incorporating resources from JINR and its Member States.

The implementation of these technologies on the Govorun supercomputer enabled a number of complex, resource-intensive calculations in the field of lattice quantum chromodynamics to study the properties of hadronic matter at high energy densities and baryon charges and in the presence of supermaximal electromagnetic fields. This also significantly improved the efficiency of relativistic heavy-ion collision dynamics modeling, accelerated the generation and reconstruction of events for experiments within the NICA megaproject, and allowed for radiation safety calculations at JINR experimental facilities; it also improved efficiency in solving applied problems. It should be noted that the flexible architecture of the Govorun supercomputer allows not only for calculations but also for the use of the supercomputer as a research platform for developing hardware, software, and IT solutions for problems solved at JINR. This feature enabled the deployment of quantum computing polygons and processing of experimental data from LRB, as well as the integration of the Govorun supercomputer resources into a unified heterogeneous environment based on the DIRAC platform for the NICA project. It should be noted that some tasks, such as modeling MPD experiment data, can only be performed using the Govorun supercomputer resources.

Another area of research that utilized the resources of the Govorun supercomputer was the creation of a unified, scalable scientific research supercomputer infrastructure based on the National Research Computer Network of Russia (NIKS). In addition to the Govorun supercomputer, this infrastructure included supercomputers from the Joint Supercomputer Center of the Russian Academy of Sciences and Peter the Great St. Petersburg Polytechnic University. The created infrastructure allowed the participants to expand their local computing capacity, provide access to large-scale data storage and processing facilities, distributed data storage (data hubs), and leverage each other's capacity during peak loads.

The results obtained using the resources of the Govorun supercomputer since its commissioning in July 2018 to the present day are reflected in 488 user publications, two of which are in the Nature Physics journal.

Thus, operating experience with the Govorun supercomputer has demonstrated the demand and effectiveness of both the latest hyperconverged computing architectures and the hierarchical data processing and storage system included within it. Currently, the Govorun supercomputer resources are used by research groups from all of the Institute's Laboratories. The number of Govorun supercomputer users is 323, of which 262 are JINR employees and 61 are from the Member States. Access to the Govorun supercomputer resources is granted only to users directly involved in the implementation of the JINR Topical Plan.

In 2022, the series of works "Hyperconverged Govorun Supercomputer for the Implementation of the JINR Scientific Program" by a team of authors in-

cluding D. V. Belyakov, A. S. Vorontsov, M. I. Zuev, V. V. Korenkov, D. V. Podgainy, T. A. Strizh, O. I. Streltsova (MLIT JINR), A. A. Moshkin (VBLHEP JINR), E. A. Druzhinin, Yu. M. Migal (RSC Technologies), took first place in the JINR competition of works in the section of scientific-methodological and scientific-technical research.

The systematic development of the Govorun supercomputer continued, and it currently comprises 163 hyperconverged computing CPU nodes, containing 8 552 compute cores, corresponding to a performance of 800 TFlops for double-precision calculations and equipped with 96 GPU accelerators (40 NVIDIA V100, 40 NVIDIA A100, and 16 NVIDA H100) with a combined performance of 1.4 PFlops for double-precision calculations and 58 PFlops for half-precision ones. As a result, the total performance of the Govorun supercomputer has reached 2.2 PFlops for double-precision calculations, and the total capacity of the hierarchical data storage system currently amounts to 10.6 PB.

HybriLIT PLATFORM

With the commissioning of the Govorun supercomputer, the HybriLIT cluster continued to operate successfully but its role changed. Thanks to the previously developed and implemented software and information environment, the cluster and supercomputer resources were combined into a heterogeneous platform, which inherited the name "HybriLIT"[21]. The creation and further development of the platform required the expansion of the group, which included A. A. Kokorev as a system administrator, A. S. Vorontsov to support the engineering infrastructure, A. I. Anikina in the user support group, A. V. Stadnik, T. Zh. Bezhanyan, S. Shadmehri, K. A. Chizhov, I. S. Pelevanyuk, and A. A. Moshkin in the algorithm and service development group for solving applied problems, as well as J. Buša, Jr. and M. A. Lyubimova in the applied software group. Since 2018, the group has been headed by D. V. Podgainy, and O. I. Streltsova has become his deputy.

The main computing core of the platform is the Govorun supercomputer. Using the cluster's resources, dubbed the "education and testing polygon", platform users can utilize available application packages, develop their own applications, and perform calculations using various computing architectures (central processors and graphics accelerators), without the need to transfer data or recompile programs. For example, users can develop and debug parallel applications on the education and testing polygon, perform resource-intensive calculations on the Govorun supercomputer, and analyze and visualize the results within the ML/DL/HPC ecosystem. Furthermore, the cluster's resources have been and continue to be used for training courses.

The software and information environment of the platform has also been further developed. It has been enriched with new IT solutions, including the ML/DL/

[21] *Anikina A., Belyakov D., Bezhanyan T., Kirakosyan M., Kokorev A., Lyubimova M., Matveev M., Podgainy D., Rakhmonova A., Shadmehri S., Streltsova O., Torosyan Sh., Valya M., Zuev M.* Structure and Features of the Software and Information Environment of the HybriLIT Heterogeneous Platform // Distributed Computer and Communication Networks. DCCN 2024. Lect. Notes Comput. Sci. 2025. V. 15460. P. 444–457.

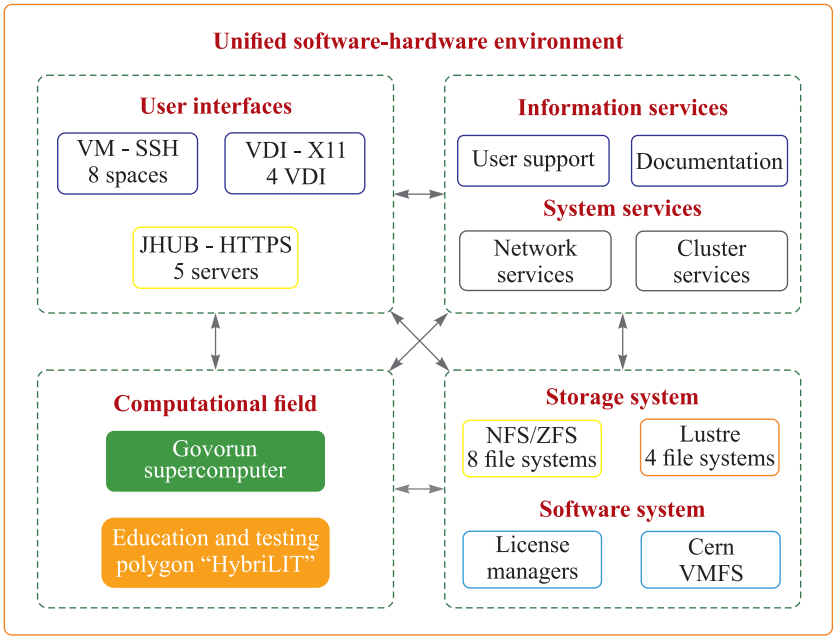


Fig. 13. Structure of the HybriLIT platform

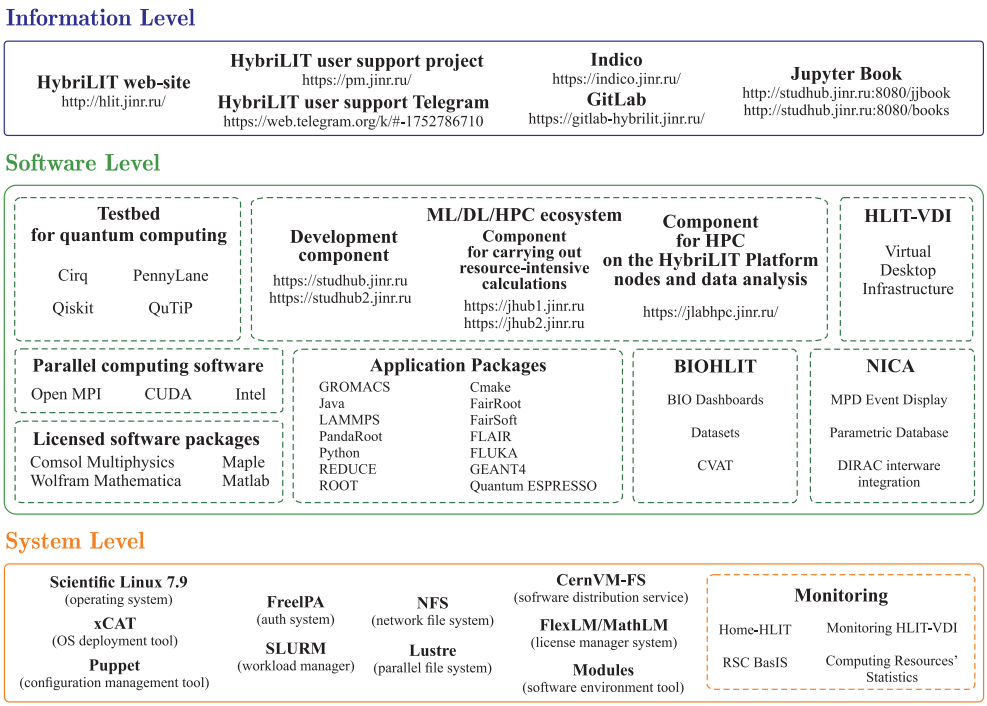


Fig. 14. Software and information environment of the HybriLIT platform



Participants of the youth seminar after the presentation of the modernized Govorun supercomputer. 2019

HPC ecosystem, the BIOHLIT information and computing system, a quantum computing polygon, a set of services for experiments at the NICA accelerator complex, and a number of specialized services for applied research.

The platform was equipped with the HLIT-VDI remote desktop system to work with application packages with a sophisticated graphical interface. In this mode, users can work with packages such as Matlab, Mathematica, Maple, COMSOL, and others.

To develop machine and deep learning algorithms, simplify work with Big Data, data analysis, and visualization, as well as conduct lectures, tutorials, and master classes for students, postgraduate students, and JINR researchers, the ML/DL/HPC ecosystem was developed and implemented. It contains key libraries and frameworks for machine and deep learning tasks, such as TensorFlow, PyTorch, Keras, and others, enabling training of neural network models on GPUs within the JupyterLab environment. The ML/DL/HPC ecosystem provides capabilities not only for solving machine and deep learning problems but also for conveniently organizing calculations and analyzing results. Examples of such solutions include the information and computing system developed for a joint project with BLTP to study theoretical models of Josephson junctions and the BIOHLIT information system for a joint project with LRB for processing, analyzing, and visualizing radiobiological research data.

As part of the development of the platform, the Quantum Computing Polygon is being developed using the ML/DL/HPC ecosystem to address problems related to the development of quantum algorithms and the use of quantum computing simulators. A set of quantum simulators, such as Cirq, Qiskit, PennyLane, and

QuTiP, capable of running on various computing architectures, has been implemented on the Polygon.

Among the services for experiments at the NICA accelerator complex, one can note specialized software for the collaboration of the MPD experiment developed on the dedicated resources of the Platform, such as the MPD EventDisplay web service for visualizing the structure of the MPD detector, visualizing experimental data and presenting information about registered events, Parametric Database — a series of databases for storing the settings and parameters of the MPD detector subsystems, current settings of the subsystems and beam parameters, as well as visualizing events in real time during a run.

Soon after its commissioning in 2014, the cluster's resources began to be used for educational purposes. Educational activities are aimed at training users on the Platform, new IT technologies, and the preparation of IT specialists, primarily for the JINR Laboratories. These activities include training courses and workshops attended by JINR staff and participants of scientific schools.

Since 2022, MLIT has been hosting the JINR School of Information Technologies (IT-School) for students from various universities of Russia and JINR Member States. The School aims to engage young professionals in solving the Institute's problems using high-performance and distributed computing, data analysis methods and algorithms, and modern information technologies. The IT-School consists of two stages. The first, Autumn School, aims to familiarize participants with the JINR program, research projects, and tasks. Students are encouraged to participate in research groups and have the opportunity to choose the topic of their final thesis at any level of education. During the second, Spring School, participants present reports on the results of their work on JINR projects. On average, approximately 60 students attend the School each year, many of whom go on to work at JINR. As part of the IT-School, the HybriLIT group conducts lectures and practical classes.



ROOT training course led by M. Valya



Participants of the JINR Spring School of Information Technologies in 2025

The resources of the Platform are used to regularly conduct training courses at Dubna State University in the following disciplines: "Architecture and Technologies of High-Performance Systems", "Parallel Distributed Computing", "Languages and Technologies for Data Analysis", and "Technologies for High-Performance Computing", while Tver State University offers a course on "Software for Mathematical Computing".

In addition to regular classes, students have the opportunity to complete internship at MLIT, solving specific research problems using the HybriLIT platform. This adaptive educational program allows teaching students and preparing specialists for the rapidly developing HPC sector in scientific computing for JINR and other organizations and IT companies whose activities involve the use of HPC platforms.

At the end of 2024, the master's program "Data Processing Methods and Technologies in Heterogeneous Computing Environments" was developed and licensed; the curriculum and course syllabi were prepared for the 01.04.02 Applied Mathematics and Computer Science program at the Moscow State University Branch in Dubna. It includes modules such as computing for megascience projects, mathematical modeling, numerical methods and software systems, deep machine learning, and Big Data analytics. Classes are taught using the HybriLIT platform. The first students began studying in this master's program in September 2025.

MICC RESOURCES INTEGRATION

Further development of the MICC required consideration of the possibility of integrating all JINR resources and enabling users to utilize them optimally. LIT faced the task of selecting software for this purpose. For a long time, the use

of large, geographically distributed grid infrastructures remained the preserve of large-scale experiments capable of dedicating entire teams of specialists to supporting software components, infrastructure, and developing workflows that utilize this infrastructure.

Although a set of middleware called gLite was developed in the mid-2000s as a universal tool for organizing data processing for the LHC experiments, it turned out to be insufficient to fully meet the specific requirements of individual experiments. As a result, each collaboration began developing its own tools and approaches for organizing distributed computing, using the gLite package as a base. For the ATLAS experiment, such middleware was the aforementioned PanDA and BigPanDA. Another tool was the DIRAC (Distributed Infrastructure with Remote Agent Control) platform, which had been developing since 2002 for the LHCb experiment. It gradually evolved into a comprehensive tool for organizing distributed computing, with management of user tasks, data, data transfers, and workflow automation. After LHCb, the next experiment to use DIRAC was Belle, followed by other experiments, including BES-III — an international experiment at the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences in Beijing, in which JINR is an active participant. In 2013, JINR began works on developing the computing infrastructure for the BES-III experiment, including creating a system for monitoring services and computing resources[22]. This work was carried out by I. S. Pelevanyuk, and the experience he gained demonstrated the feasibility of using the DIRAC platform to integrate computing resources for other experiments, including those at the NICA accelerator complex.

The DIRAC platform had the following key features that made it suitable for organizing the processing of experimental data at the NICA accelerator complex:

— sufficient performance;
— open community of users, administrators and developers with annual DIRAC Users' Workshops;
— full range of services for organizing distributed computing within a single system: task management, data management, workflow management, data transfer;
— opportunity to use one installation of the DIRAC platform for several independent virtual organizations (in our case, these could be virtual organizations associated with experiments at the NICA accelerator complex, BM@N, MPD and SPD).

In addition, I. S. Pelevanyuk had experience in developing DIRAC components, gained during the implementation of the project to create a service monitoring system for the distributed infrastructure of the BES-III experiment.

By 2018, I. S. Pelevanyuk, after installing and testing the DIRAC platform at JINR, had accomplished two key tasks. First, he proposed a method for generating Monte Carlo data for the BM@N experiment and conducted test runs using DIRAC. Second, that year, with the participation of N. A. Kutovskiy and his

[22] *Belov S., Suo B., Deng Z., Korenkov V., Li W. D., Lin T., Ma Z., Nicholson C., Pelavanyuk I., Trofimov V., Uzhinskiy A., Yan T., Yan X. F., Zhang X. M., Zhemchugov A.* Design and Operation of the BES-III Distributed Computing System // Procedia Comput. Sci. 2015. V. 66. P. 619–624.

group, the cloud resources of JINR and its Member States were integrated into the DIRAC system at JINR[23]. This integration required the development of a completely new module that would allow DIRAC to directly work with clouds built using the OpenNebula tool, which was the basis for the clouds of JINR and its Member States[24]. Subsequently, the developed OpenNebula module was used, among other things, at the IHEP in Beijing to integrate the cloud resources of the then-planned JUNO experiment.

2019 was a key year for the development of the geographically distributed heterogeneous computing environment built at JINR on the DIRAC platform. In addition to Tier-2 and clouds, DIRAC integrated the resources of the Tier-1 cluster, the Govorun supercomputer, and the EOS storage system[25]. This computing environment was used for the massive Monte Carlo data generation tasks for the MPD experiment.

In 2020, as the COVID-19 pandemic took over the world, a separate queue of tasks related to studying the molecular dynamics of the SARS-CoV-2 coronavirus was created in the Folding@Home volunteer computing system. JINR and its Member States made their contribution. After consultations with representatives of organizations whose clouds were integrated into the DIRAC system at JINR, approval was received to run Folding@Home tasks from the COVID-19 queue on cloud resources. These tasks were characterized by their low data transfer but high computational demands. They demonstrated stable operation under full load of the cloud resources integrated by DIRAC. In addition to JINR, the following universities participated in the execution of these tasks: Plekhanov Russian University of Economics in Moscow, North Ossetian State University in Vladikavkaz, Institute of Physics of Azerbaijan National Academy of Sciences, Research Institute for Nuclear Problems of Belarusian State University, Institute of Nuclear Physics of Kazakhstan, Academy of Scientific Research and Technology — Egyptian National Scientific and Technical Information Network, Bulgarian Institute for Nuclear Research and Nuclear Energy.

Following the successful launch of the Folding@Home tasks, the cloud infrastructure of JINR and its Member States began to be used for Monte Carlo tasks of the Baikal-GVD experiment.

In 2021, two more experiments began using the DIRAC infrastructure at JINR to generate Monte Carlo data: SPD and BM@N. Since 2021, the infrastructure built in this way has been used for all three experiments at the NICA accelerator complex. Also in 2021, DIRAC completed its millionth task.

In 2021, the JINR Prize for the work "Development and Implementation of a Unified Access to Heterogeneous Distributed Resources of JINR and its Member

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[23] *Balashov N.A., Kutovskiy N.A., Makhalkin A.N., Mazhitova Ye., Pelevanyuk I.S., Semenov R.N.* Distributed Information and Computing Infrastructure of JINR Member States' Organizations // AIP Conf. Proc. 2021. V. 2377. 040001.

[24] *Balashov N., Kuchumov R., Kutovskiy N., Pelevanyuk I., Petrunin V., Tsaregorodtsev A.* Cloud Integration within the DIRAC Interware // CEUR Workshop Proc. 2019. V. 2507. P. 256–260.

[25] *Korenkov V., Pelevanyuk I., Tsaregorodtsev A.* Integration of the JINR Hybrid Computing Resources with the DIRAC Interware for Data Intensive Applications // Commun. Comput. Inf. Sci. 2020. V. 1223. P. 31–46.

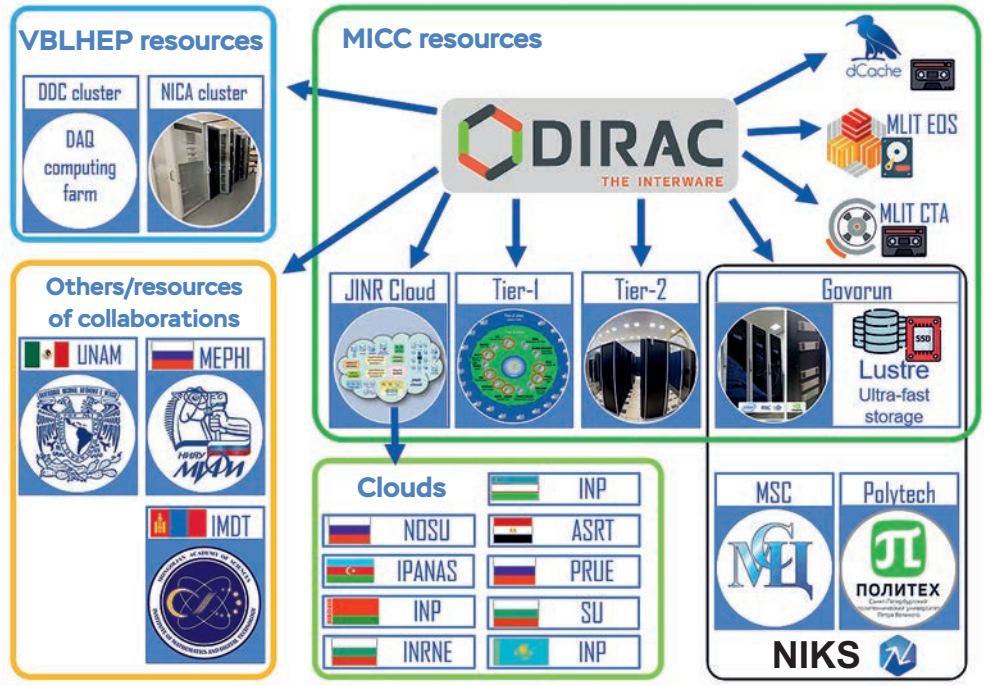


Fig. 15. General scheme of resources integrated into the DIRAC system at JINR in 2025

States on the DIRAC Platform" was awarded to V. V. Korenkov, N. A. Kutovskiy, V. V. Mitsyn, A. A. Moshkin, I. S. Pelevanyuk, D. V. Podgainy, O. V. Rogachevsky, V. V. Trofimov, and A. Yu. Tsaregorodtsev.

In 2023, a methodology for fully processing experimental data within a geographically distributed heterogeneous computing network built on DIRAC was developed for the BM@N experiment[26]. The BM@N experiment became the first to use this infrastructure for processing experimental data. By 2024, as the amount of data grew, the need arose to create backups for critical data. For this purpose, a tape library was integrated into the DIRAC system. It was used to create backups of the data collected during all eight BM@N experiment runs, as well as some of the MPD collaboration data.

As of April 2025, more than 3.5 million computing tasks have been completed using the built geographically distributed heterogeneous computing environment.

Currently, DIRAC Interware is the only system that integrates all the MICC components, acting as an intermediate layer between users and various computing resources, ensuring their efficient, transparent and reliable use, providing a common interface to heterogeneous resources.

[26] *Gertsenberger K. V., Pelevanyuk I. S.* BM@N Run 8 Data Processing on a Distributed Infrastructure with DIRAC // Phys. Part. Nucl. Lett. 2024. V. 21. P. 778–781.

MODELS AND SOFTWARE PACKAGES FOR DATA PROCESSING

Modern research in high energy physics and nuclear physics requires sophisticated modeling methods, data processing algorithms, and specialized software. The Laboratory of Information Technologies has developed and successfully implemented a range of tools and approaches for solving problems in physical systems modeling and experimental data processing and analysis. These methods and algorithms play a key role in such large-scale experiments as CBM (FAIR/GSI), BM@N, MPD and SPD (NICA), CMS and ATLAS (LHC), as well as in research on hadron interactions, the properties of quark-gluon plasma, and exotic states of matter.

This section addresses the main methods, algorithms, and software developed at MLIT JINR in the period from 2000 to 2025. Particular attention is paid to the following areas:

1. Event generators:
- development and modification of models (FRITIOF, UrQMD, AMPT) for describing nuclear and hadronic interactions;
- integration of generators into software packages such as Geant4 and HEPWEB for calculating interaction cross-sections and characteristics of secondary particles.

2. Simulation of physical processes:
- application of Monte Carlo methods to predict detector characteristics and optimize their geometry;
- development of models that take into account the peculiarities of particle interactions.

3. Event reconstruction:
- using Kalman filter, cellular automata and neural networks for tracking charged particles;
- development of fast algorithms adapted for real-time operation (e.g. in the CBM experiment).

4. Particle identification:
- application of machine learning (gradient boosting, deep neural networks) to separate electrons and pions in transition radiation detectors (TRD) and ring-imaging Cherenkov detectors (RICH);
- comparison of traditional statistical methods with modern approaches based on artificial intelligence.

The developed methods and algorithms not only ensure high data processing accuracy but also enable the efficient use of computing resources, including hybrid architectures and parallel computing systems. The results of their application are published and used in international collaborations, confirming the significant contribution of MLIT JINR to the development of modern physics data processing technologies.

EVENT GENERATORS

Event generators in high-energy physics are used to simulate particle collisions, predict their outcomes, and compare them with real experimental data. They help verify theoretical predictions (such as those of the Standard Model), optimize detectors, study rare processes, train data analysis algorithms, and separate useful signals from background noise, which is critical for the search for "new" physics, such as dark matter or extra dimensions.

MLIT successfully completed a number of projects on the development and application of event generators. For example, the FRITIOF model was improved and incorporated into various versions of Geant4 by A. S. Galoyan (VBLHEP) and V. V. Uzhinsky. It was used to simulate hadron interactions, including the production of strange particles (K mesons, Λ hyperons).

The UrQMD model and its modifications were used by MLIT staff to simulate nuclear collisions. This model was supplemented with the Statistical Multifragmentation Model (SMM) for analyzing azimuth correlations. Along with the previous AMPT (A Multi-Phase Transport) model, it was incorporated into HEPWEB for calculating secondary particle characteristics and tested at RHIC energies.

Thanks to the efforts of G. Musulmanbekov and colleagues from BLTP JINR, the Institute for Nuclear Research (INR RAS), and the Institute for Theoretical Physics (Frankfurt, Germany), the DCM-SMM generator for simulating heavy-ion collisions was developed and refined. It is currently used in the BM@N and MPD experiments. DCM-SMM demonstrates good fit to the experimental data, for example, for elastic scattering of protons and antiprotons.

Within the considered direction, V. V. Uzhinsky also developed new algorithms for taking into account diffraction dissociation in FTF to improve the description of the NA61/SHINE experiment data.

SIMULATION OF PHYSICAL PROCESSES

Simulation in modern high-energy physics experiments is essential for predicting and interpreting the results of particle collisions, as field experiments at accelerators (such as NICA and the LHC) generate vast amounts of complex data, including both signals of interest and background processes. Using computer models such as PYTHIA, MadGraph, and GEANT, physicists compare theoretical predictions with observations, optimize detector settings, distinguish rare events from noise, and search for deviations from the Standard Model that may indicate "new" physics. Analyzing experimental data would be extremely difficult without simulation, and many discoveries would be impossible.

A. S. Galoyan and V. V. Uzhinsky devoted a number of papers to the use of Geant4 for simulating detectors and physical processes, including the suppression of (uu)-diquarks in protons, which improved the description of NA49 data on $p+p \to p+X$ reactions. The authors also developed the HEPWEB system, which enabled calculations of hadron–hadron, hadron–nucleus, and nucleus–nucleus interaction cross sections using event generators such as CASCADE, FRITIOF, UrQMD, HIJING, and AMPT.

Monte Carlo simulations have been applied to various problems, such as predictions of secondary particle fluxes (e.g., neutrons and protons in subcritical assemblies), optimization of detector geometry (e.g., GEM in the BM@N experiment), and analysis of background processes in the LHC and NICA experiments, and assessing the influence of model parameters on agreement with experimental data.

RECONSTRUCTION OF CHARGED PARTICLE TRAJECTORIES

Track reconstruction algorithms (tracking) evolved alongside the development of experimental facilities and particle detection technologies in tracking detectors, reaching new levels with the advent of new particle acceleration methods and more complex detector types. As data flows grew, various scanning devices that transmitted the coordinates of all registered points to a computer emerged. Tracking, based on this information, required the use of coordinate transformations to "straighten" the tracks and a modification of the Hough transform for their detection, a task actively pursued by G. A. Ososkov[27]. With the advent of electronic experiments, tracking detectors that record particle tracks as signals transmitted to a computer in digitized form emerged. After multistage filtering and data adjustment procedures, tracking begins, which consists of several stages. First, hits — that is, spatial points where a particle was detected — are reconstructed from the signals received from the detector sensors. Then, tracks are constructed from these hits by searching the event for all hits left by the same particle. The shape of the particle's trajectory in a magnetic field can then be used to reconstruct the particle's physical parameters. Knowing the particle parameters in the event allows one to draw physical conclusions from the experiment.

With the further development of colliders and computer technologies, the most effective tracking method, which has become a classic one, is the Kalman filter (KF), since it allows for the non-uniformity of the magnetic field, multiple scattering, and energy loss as the particle passes through the detector medium.

An algorithm for reconstructing charged particle tracks based on the KF was proposed under the supervision of V. V. Ivanov. This algorithm is used to solve one of the key tasks of the CBM experiment at FAIR: identification of charged particle trajectories and determining their parameters. Since the CBM experiment plans to fully reconstruct signal events in real time, the developed algorithms were adapted for paralleling.

A modification of the KF, including the use of cellular automata, was developed and applied by D. A. Baranov and G. A. Ososkov together with colleagues from VBLHEP for the BM@N experiment and by I. V. Kisel for the vertex detector of the HERA-B experiment.

A number of algorithms were developed by V. V. Palichik and N. N. Voytishin for reconstructing charged particle trajectories in the cathode strip chambers (CSCs) of the CMS experiment. All algorithms and methods have been implemented in

[27] *Nikitin V. A., Ososkov G. A.* Automation of Measurements and Processing of Physical Experiment Data. M.: MSU Press, 1986. 185 p.



Discussing data processing. Sitting: P. V. Zrelov, G. A. Ososkov, V. V. Ivanov, A. A. Lebedev, P. G. Akishin. Standing: A. P. Sapozhnikov, S. A. Baginyan, B. F. Kostenko. 2006

the experiment's official software package and are currently used as the primary methods for CSC reconstructions. These algorithms are aimed at improving the efficiency of reconstructing the trajectories of high-energy muons with transverse momentums above 1 TeV. It is worth noting that some of these algorithms have also been adapted for other detectors: the drift chambers of the BM@N experiment at NICA and the gas electron multipliers of the CMS experiment.

In addition to classical approaches, a number of algorithms using machine and deep learning were developed under the supervision of G. A. Ososkov. The TrackML[28] competition, organized by CERN, provided a significant impetus for this direction. The development of neural network methods for event reconstruction in track detectors under the supervision of G. A. Ososkov's group proceeded in two directions. The first is a local approach, in which, as in the Kalman filter, tracks are recognized sequentially one after another. This includes works[29] obtained outside the scope of TrackML, where, thanks to the use of deep recurrent neural networks, it was possible to implement the TrackNet neural network as a neural network analogue of the Kalman filter, and obtain good results for model events from BM@N, BES-III, and SPD experiments. The second approach is more general and global, in which track recognition among all event hits — real, fake, and noise — is performed across the entire event picture, as is done in a graph neu-

[28] https://arxiv.org/pdf/1904.06778.pdf
[29] https://doi.org/10.1063/1.5130102; https://doi.org/10.1063/5.0063993

ral network[30]. The same general properties are shared by an end-to-end trainable convolutional YOLO-like neural network called LOOT (Look Once On Tracks), which can process an entire event by representing it as an image[31].

Attempts to directly use the algorithms developed in the TrackML concept were not successful due to significant differences in the experimental data because of the specifics of the detectors used, as was the case when the graph neural network program[32] was applied to the data from the GEM BM@N experiment.

The TrackNet neural network program was applied to the SPD experiment data and impressive results were obtained when running 25 000 simulated SPD events, representing 625 time slices with 40 events each, on the Govorun supercomputer (Xeon(R) Gold 6148 CPU @ 2.40GHz, Single Nvidia V100 32Gb GPU), achieving a processing speed of over 2500 events per second (reduced to 1400 events/s when taking into account the inefficiency of the detectors).

PARTICLE IDENTIFICATION

Particle identification stage plays one of the key roles in modern high-energy physics experiments, as it allows for the determination of the type, charge, mass, and other characteristics of particles produced in collisions. This is essential for testing the predictions of the Standard Model and searching for new physics (for example, dark matter or supersymmetry), as well as for reconstructing complex decay processes. It is impossible to correctly interpret detector data, separate signals from background, or detect rare events, such as the production of the Higgs boson, without accurate particle identification. In their work on particle identification, MLIT researchers have successfully used both neural network and statistical methods to improve particle separation in experiments.

G. A. Ososkov with S. A. Lebedev and A. A. Lebedev, in collaboration with colleagues from GSI, developed parallel particle identification algorithms using the Cherenkov detector (RICH), the transition radiation detector (TRD), and the muon system (MUCH) for the CBM (FAIR) experiment. The implemented software, which utilizes modern processor capabilities, such as vector data processing (SIMD) and multithreading, significantly increased the speed of the recognition process. The fast ring recognition algorithm in the RICH detector is based on the Hough transform. An algorithm using the Kalman filter method was implemented for track reconstruction in the TRD detector. An efficient algorithm based on an artificial neural network was developed for electron identification in both detectors. The developed algorithms made it possible to achieve high particle identification efficiency. A team led by V. V. Ivanov also developed a methodology for the reliable and rapid identification and reconstruction of $J/\psi \to e^+ e^-$ and $J/\psi \to \mu^+ \mu^-$ decays recorded by the CBM detectors. This methodology included a series of mathematical methods designed to reconstruct the trajectories and momenta of charged particles and their identification using the RICH, TRD, ToF and MUCH detectors.

[30] https://arxiv.org/pdf/2007.00149.pdf
[31] https://ceur-ws.org/Vol-2507/130-134-paper-22.pdf
[32] https://arxiv.org/pdf/2007.00149.pdf

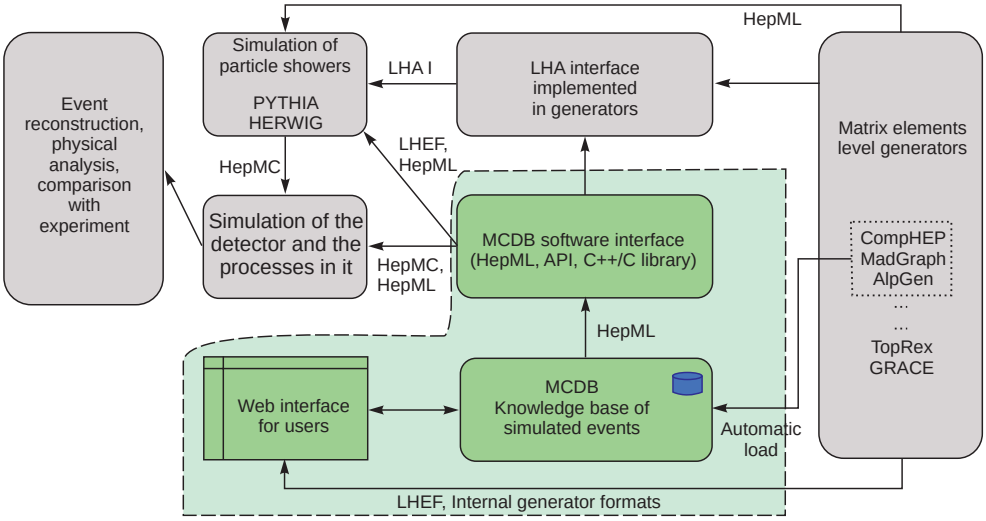
As part of the priority areas of developing and implementing machine learning (ML) methods for analyzing data from the MPD experiment of the NICA megaproject, methods for identifying charged particles based on their responses in detector systems are being developed. Methods based on gradient boosting on decision trees were developed under the supervision of A. S. Ayriyan. Models are trained on Monte Carlo generated datasets, where the true identity of the particles is known. Reconstructed track parameters, energy, time of flight, and geometric information are used as features. The developed models demonstrate high classification accuracy and significantly outperform standard threshold methods. This research was made possible thanks to the computing resources of the HybriLIT heterogeneous platform.

MONTE CARLO DATA BASE (MCDB)

Simulation of physical processes and events is of great importance in high-energy physics experiments. One of the primary methods for events simulation is the Monte Carlo method, or statistical simulations method. Accurate and reliable simulation requires significant computing resources — for example, approximately 20% of the computing time for the ATLAS experiment — and involves detailed comparison of results obtained using various modeling packages. Ensuring the accuracy of the final simulation results and the ability to obtain them quickly is an important task. This requires not only the creation and storage of correctly prepared and detailed samples of simulated physical events for future use but also the ability to access this data from a globally distributed computing infrastructure.

In the CMS experiment, the need for a system for storing and accessing events simulated by experts has historically been addressed by several projects. The first such a system was the PEVLIB system created at CERN — a database for storing parton-level events simulated using the CompHEP generator. All data was accessible in the AFS file system at CERN, and associated metadata was stored in the same directory as a text document. The next version of a similar database was created at Fermilab (USA). The database contained events simulated using Monte Carlo generators, stored on the ENSTORE tape system at Fermilab; documentation for those event files was accessible via the web. The next event database, CMS MCDB (Monte Carlo Data Base), was developed by the CMS collaboration. All of these projects had a number of significant shortcomings, so the MCDB of simulated events was developed as part of the LHC Computing Grid project. Its main differences from its predecessors were the ability to describe a wide class of events (not just those involving final-state partons), automatic loading and unloading of events and detailed information about them, and the ability to fully operate the system from a grid environment. The MCDB was developed from 2004 to 2013 at CERN by specialists from SINP MSU (L. V. Dudko, A. V. Sherstnev) and LIT JINR (S. D. Belov, D. V. Kekelidze)[33].

[33] *Belov S., Dudko L., Galkin E., Gusev A., Pokorski W., Sherstnev A.* LCG MCDB — A Knowledgebase of Monte-Carlo Simulated Events // Comput. Phys. Commun. 2008. V. 178, No. 3. P. 222–229.



HepMC — Object-oriented event recording format
LHA I — Standard for communicating event description via the FORTRAN COMMON block
LHEF — LHA-compliant, XML-based event file standard

Fig. 16. MCDB and HepML in the CMS experiment event simulation chain

The MCDB knowledge base, as intended, stores generated event files and corresponding metadata. Event descriptions (metadata) fully comply with the schemes of the HepML (High Energy Physics Markup Language) created by S. D. Belov[34]. Therefore, HepML documents are naturally used for automated, software-based interaction with the MCDB. Support for working with the MCDB and HepML was implemented and integrated into CMSSW (the CMS collaboration software). Access to MCDB files via various protocols (rfio, xroot, gsiftp, etc.) is provided by CMSSW's internal tools. Remote upload of new event files to the MCDB is also possible. This is implemented in a dedicated software script that utilizes standard grid user authentication tools (a proxy certificate with or without information from the virtual organization management service). The software script supports LHEF files, which can have HepML headers or be generated by the MadGraph generator. CASTOR, CERN Tape Archive, dCache, EOS, and other storage systems can be used. Support for standard authentication methods (digital certificate, Kerberos token) is required, and the RFIO, HTTP, XRootD, SRM, and GridFTP protocols are required for data loading. The MCDB service at CERN used CASTOR, and later EOS, as the primary storage system. Access to event files (uploading and downloading) is implemented using the aforementioned protocols, including those used in the grid environment. This allowed the MCDB knowledge base to be used to increase the automation of the official event simulation chain in the CMS experiment from 2010 to 2013.

[34] *Belov S., Dudko L., Kekelidze D., Sherstnev A.* HepML, an XML-Based Format for Describing Simulated Data in High Energy Physics // Comput. Phys. Commun. 2010. V. 181, No. 10. P. 1758–1768.

PARTICIPATION IN THE ATLAS TDAQ, EventIndex, AND CREST PROJECTS

It is worth noting the important work carried out by the sector of distributed real-time systems under the supervision of V. M. Kotov and then I. N. Alexandrov as part of the ATLAS experiment during the development and launch of the Trigger and Data Acquisition (TDAQ) system: the online system for making trigger decisions and collecting data in this experiment. This work began in the second half of the 1990s, jointly with the Department of Colliding Beams of DLNP, with the development of trigger algorithms for selecting useful events in the MDT tubes of the ATLAS muon detector within the second-level trigger. However, Livio Mapelli, who led the development of TDAQ at that time, recommended V. M. Kotov, due to the high cost of work directly related to the trigger and the need to invest in electronics, to engage in works on the back-end DAQ software — that is, works in the DAQ system not related to processing physical events; in short, all the software responsible for loading, starting, and managing the trigger system and the data acquisition and processing system. This work was carried out as part of the "ATLAS DAQ/Event Filter Prototype 1" project. Within this project, V. M. Kotov's group was tasked with creating a prototype of the Resource Manager component. All development in the CERN back-end group was carried out in strict compliance with the European Space Agency's PSS-05 standard. This meant that before programming began, it was necessary to create a User Requirements document, architectural design, detailed design, object models, and numerous other models. This was because the ATLAS TDAQ back-end system was a long-lifecycle system, and errors made at the initial stage were difficult to correct. The design of the components and their interactions were discussed within the CERN ATLAS back-end group for several years, and then, after the decision was made to begin the next stage, everything was programmed and operational within six months.

Along with V. M. Kotov, V. S. Yamburenko and I. N. Alexandrov participated in this work, and E. I. Alexandrov later joined in. Based on the prototype, component software was created and incorporated into the core of the TDAQ ATLAS back-end software. In 2005, the software suite for the TDAQ ATLAS Resource Manager was incorporated into the core of the final version of the entire TDAQ software. This was the only core component for which CERN employees were not responsible.

In 2002–2003, the Event Dump program was developed. It monitored the correct formation of raw physical data and was incorporated into the standard software for the ATLAS triggering and data acquisition system in 2008.

The experience gained and the advances in grid technologies have made it possible to consider the task of remote control and monitoring of the ATLAS facility from virtually anywhere in the world.

Work on developing a remote access system for taking and processing data from the ATLAS experiment at JINR began in 2007 by specialists from the Dubna TDAQ group (led by V. M. Kotov) and DLNP (led by A. S. Zhemchugov). In 2011, the development of a full-fledged real-time remote access system at JINR was completed and integrated into the global grid system for taking and processing experimental

data at the LHC. The development of this system for remote monitoring of the ATLAS data taking and processing is the result of long-term collaboration between JINR and CERN on the TDAQ ATLAS project.

In 2013, a new WMI (Web Monitoring Interface) plug-in service was launched, which, using the WebIS information service introduced at CERN, allowed users located outside of CERN and the TDAQ environment to obtain data from the Information Service (IS) component.

The TDAQ ATLAS group at LIT JINR developed and maintained software packages, such as Event Dump, Resource Manager, and Web Monitoring Interface, and also provided remote access to the ATLAS data from JINR. The work of this group, which included E. I. Alexandrov, I. N. Alexandrov, A. A. Kazakov, A. I. Kazymov, M. A. Mineev, A. V. Yakovlev, and others, was led by V. M. Kotov until the end of 2014.

Later, under the supervision of I. N. Alexandrov, the group expanded its ATLAS activities to include offline software projects, participating in the development of the EventIndex project[35]. The goal of the project is to create a complete catalog of all real and simulated ATLAS events, containing links to all permanent files. Each year, the ATLAS experiment creates several billion event records in raw and other formats. The data is distributed across hundreds of computer networks worldwide. The EventIndex system catalogs all ATLAS events and provides a set of tools for searching and extracting information about individual events or groups of events based on user selection. The primary goal of EventIndex is to enable ATLAS participants to search and extract one or more individual events from tens of millions of data files for detailed inspections or more thorough analysis. The first EventIndex prototype was deployed in 2015.

LIT staff joined the project in 2018. They developed a new monitoring system, which increased the speed of query processing by several times. The EventIndex core was redesigned in 2021, and the updated system was launched in 2022.

Sometimes, physics analysis requires massive event selection to pick a set of interesting events from the vast ATLAS dataset and process them using advanced algorithms or retain additional variables that can assist in subsequent analysis stages. EventIndex can help with this, but its manual use requires significant user time. LIT JINR staff played a key role in developing the Event Picking service which aimed to automatically perform all these steps.

Some EventIndex developers at CERN also participated in the CREST project with the goal to create a new database of conditions. The CREST system is intended to replace the currently used COOL/COREL systems in Run4. Following the successful involvement of the LIT team in the EventIndex project, a proposal was made to join the CREST project as well. The MLIT team is currently actively involved in this project. The Laboratory has developed programs for converting data from COOL to CREST, which was a priority at the time of joining the project, and has also implemented a C++ API for querying the CREST server.

[35] *Barberis D., Alexandrov I., Alexandrov E. et al.* The ATLAS EventIndex // Comput. Soft. Big. Sci. 2023. V. 7. P. 2.

DEVELOPMENT OF COMPUTATIONAL PHYSICS METHODS

The purpose of computing is insight, not numbers.
Richard Hamming

Physical research, both theoretical and experimental, requires quantitative estimates of the characteristic parameters of the observables being studied. Such fundamental problems are solved using computational physics methods.

The review of JINR's development in the first quarter of the 21st century provides an opportunity to reflect on the evolution of computational physics methods and discuss key achievements along this path at MLIT.

The emergence of computational physics by the mid-20th century was closely linked to the creation and rapid development of computers. The development of computational physics at MLIT has always been a complex process in which the human factor plays a driving role.

The key characteristic of activity in this field is the presence of strong individuals possessing exceptional mathematical competence, whose work leads to the identification of necessary long-term research directions. Unfortunately, the last two decades have seen the loss of a significant number of these individuals.

These lines are dedicated to our former colleagues, Professor E. P. Zhidkov (head of research in computational mathematics, modeling of magnetic fields in experimental facilities), Professor V. P. Gerdt (founder of research in computer algebra and a pioneer of quantum computing), Professor I. V. Puzynin (initiator of numerical schemes based on a continuous analogue of Newton's method, as well as the use of molecular dynamics methods in the numerical modeling of physical and biological systems).

It is our debt of honour to remember the scientists with exceptional personal results who have also left us: V. S. Barashenkov, I. M. Ivanchenko, I. L. Bogolyubsky, S. I. Serdyukova, I. V. Amirkhanov.

During 2001–2024, MLIT scientists working on the development of computational physics methods were awarded 18 JINR prizes as part of collaborations in which they participated.

Of particular note is the Distinguished Paper Award by Association of Computing Machinery (ACM) at the International Symposium on Symbolic and Algebraic Computation (ISSAC) 2017 awarded to V. P. Gerdt (http://www.issac-conference.org/2017/awards.php)[36].

Over the past 25 years, our Laboratory staff and colleagues from the Member States working at MLIT JINR have defended 13 doctoral and 34 candidate dissertations in physical and mathematical sciences. Of these, 11 doctors and 23 candidates of science are still working at MLIT.

Below is a brief summary of some selected achievements in the development of computational physics methods.

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[36] *Gerdt V. P., Lyakhov D. A., Michels D. L.* // Proc. of ISSAC 2017. ACM Press, 2017. P. 285–292.



Standing: E. V. Zemlyanaya, P. Atanasova, Yu. L. Kalinovsky, I. V. Amirkhanov, I. Sarkhadov. Sitting: T. P. Puzynina, I. N. Kukhtina, I. V. Puzynin. 2005

Computational schemes based on the continuous analogue of Newton's method (CANM) represent a powerful tool for the numerical solution of nonlinear problems of various types, flexibly adapting to the characteristics of specific problems, ensuring rapid convergence and high accuracy of the resulting numerical solutions.

The cornerstone of the four-decade development of CANM at LCTA–LIT under the supervision of Professor I. V. Puzynin was a review published in PEPAN[37].

There are several research areas based on CANM. These include studies of a number of new localized states in systems described by various versions of the nonlinear Schrödinger equation with dissipation and pumping, including stationary multisoliton complexes, periodic and quasiperiodic localized structures, parametrically pumped oscillons, and others. The corresponding numerical approaches have been adapted and used for the numerical study of 3D oscillons in the φ^4 theory based on their approximation by standing waves in a finite-radius sphere. These studies were conducted in collaboration with the University of Cape Town (E. V. Zemlyanaya, I. V. Barashenkov, N. V. Alekseeva, A. A. Bogolyubskaya, and others) and shed light on some little-studied properties of oscillons. It should be noted that the oscillon (or "pulson") model, discovered in pioneering computational experiments on nonlinear fields by Bogolyubsky–Makhankov (1976–1977) on the BESM-6 computer at LCTA in the early days of computational physics, remains a standard tool in quantum field theory and cosmology.

[37] *Puzynin I. V., Boyadzhiev T. L., Vinitsky S. I., Zemlyanaya E. V., Puzynina T. P., Chuluunbaatar O.* On Methods of Computational Physics for Studying Models of Complex Physical Processes // Part. Nucl. 2007. V. 38, No. 1. P. 144–232.



Participants of the QPC'2007 conference. O. Chuluunbaatar, A. A. Gusev, Professor Nguyen Van Hieu, V. P. Gerdt. 2007

The next area of application of CANM is the numerical study of multifluxon states in systems of long Josephson junctions of various configurations. Here, an original approach developed by T. L. Boyadzhiev and his colleagues was used, based on the joint solution of the corresponding systems of sine-Gordon equations and a linearized eigenvalue problem applying CANM to analyze the stability of the resulting fluxon solutions to small perturbations. This allowed establishing the relationship between different branches of coexisting stationary multifluxon states for models of Josephson structures described by the double sine-Gordon equation. These studies were conducted in collaboration with Bulgarian colleagues and with colleagues from BLTP, and involved T. L. Boyadzhiev, P. Atanasova, E. V. Zemlyanaya, S. N. Dimova, Yu. M. Shukrinov, and others.

New algorithms for calculating the Newtonian iterative parameter were proposed in the works of Vo Trong Thach, I. V. Puzynin, and T. P. Puzynina, and their effectiveness in solving a number of problems was demonstrated. Modified iterative schemes based on CANM were proposed in the studies of I. V. Puzynin, I. G. Khristov, and others, enabling the high-precision generation of new solutions families of a special type in the problem of three bodies on a plane.

The implementation of highly efficient numerical algorithms for solving boundary-value or initial-value problems in quantum physics was an unfulfilled dream in the second half of the 20th century. By the beginning of the 21st century, a group centered at LIT, including O. Chuluunbaatar, A. A. Gusev, S. I. Vinitsky (BLTP JINR), and A. G. Abrashkevich (Canada, formerly at LCTA), proposed formulating the original quantum mechanical problems in suitable boundary-value

or Cauchy forms and solving the resulting problems using *finite element method* (FEM) of high order of accuracy. This enabled obtaining numerical solutions to initial-boundary value and boundary value problems describing wave and hydrodynamic processes, photoionization of an atom in a magnetic field, tunneling of clusters of several identical particles through potential barriers and wells, subbarrier heavy-ion capture reactions, and spectra and probabilities of transitions between the states of atomic nuclei, atoms, and molecules, with results consistent with theoretical estimates, benchmark calculations, and experimental data. Professor V. P. Gerdt's idea of combining computer algebra and digital programming tools significantly increased the efficiency of solving problems related to systems with long-range potentials. The outstanding program packages, such as KANTBP, ODPEVP, POTHEA, and others, developed in Fortran and Maple, have been published in the *program library* of the Computer Physics Communications journal[38] and in the JINR program library (JINRLIB).

Using these software packages, more than 50 papers, two monographs[39,40], and a review[41] were published in peer-reviewed journals. Upper and lower bounds for the energies of 252 bound states and real parts of complex energies, 58 metastable states of beryllium dimer were obtained, the existence of new metastable states was confirmed, and the subbarrier fusion cross sections of heavy ions were calculated. The work[42] on calculating the back-angle quasi-elastic scattering cross section of the superheavy ions ^{48}Ti + ^{208}Pb and ^{51}V + ^{248}Cm can advance the study of the *synthesis of superheavy elements* by providing reliable information on the barrier distribution function and the capture cross section based on constraints from quasi-elastic reactions. The above results were also co-authored by M. S. Kaschiev (Bulgaria), V. A. Rostovtsev, J. Buša (Jr.), G. Chuluunbaatar, A. V. Mitin (MIPT), V. L. Derbov (Saratov State University), A. A. Sargsyan (Armenia), P. M. Krasovitsky (Kazakhstan), A. Góźdź (Poland), C. J. Lin (China), P. W. Wen (China), L. L. Hai (Vietnam). The research was awarded two JINR Prizes (in 2015 and 2024).

The developed symbolic-numeric software allowed for the precise description of experimental results performed by international research groups. Numerical studies of models of single and double ionization reactions of helium atoms, hydrogen ions and molecules, nitrogen, and carbon dioxide by electron impact were

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[38] *Chuluunbaatar O., Gusev A. A., Vinitsky S. I., Abrashkevich A. G., Wen P. W., Lin C. J.* KANTBP 3.1: A Program for Computing Energy Levels, Reflection and Transmission Matrices, and Corresponding Wave Functions in the Coupled-Channel and Adiabatic Approaches // Comput. Phys. Commun. 2022. V. 278. 108397–1–14.

[39] *Vandandoo U., Zhanlav T., Chuluunbaatar O., Gusev A., Vinitsky S., Chuluunbaatar G.* High-Order Finite Difference and Finite Element Methods for Solving Some Partial Differential Equations. Switzerland: Springer Nature, 2024. 114 p.

[40] *Zhanlav T., Chuluunbaatar O.* New Developments of Newton-Type Iterations for Solving Nonlinear Problems. Switzerland: Springer Nature, 2024. 281 p.

[41] *Mitin A. V., Gusev A. A., Chuluunbaatar G., Chuluunbaatar O., Vinitsky S. I. , Derbov V. L., LuongH. L.* Dual Nature of Chemical Bond and Vibration-Rotation Spectrum of the Be_2 Molecule in the Ground $X^1\Sigma_g^+$ State // Chemical and Materials Sciences: Research Findings. V. 2. Ch. 6. P. 100–133. BP Intern. Publ. 2025.

[42] *Wen P. W., Chuluunbaatar O., Descouvemont P., Gusev A. A., Lin C. J., Vinitsky S. I.* Role of Multi-Phonon and High-Spin States on the Quasi-Elastic Barrier Distributions of Massive Systems // Phys. Lett. B. 2025. V. 863. 139383–1–5.

performed, and good agreement was achieved between theoretical and modern experimental ionization cross sections.

A *correct quantitative description* of the interference effects of coherent scattering of an electron on two Coulomb centers of a molecule, manifested in the established functional relationship of the differential ionization cross sections of a helium atom and a hydrogen molecule, was obtained for the first time in an experiment at the Laboratory of Atomic and Molecular Collisions, Orsay, France.

For the first time, it was possible to calculate the Compton ionization cross section in the keV photon energy range, which is approximately six orders of magnitude smaller than typical photoabsorption cross sections. This made it possible to accurately describe an experiment on the kinematically complete measurement of Compton scattering characteristics on free atoms using the highly efficient COLTRIMS (COLd Target Recoil Ion Momentum Spectroscopy) method, conducted at Goethe University in Frankfurt am Main, Germany[43].

The co-authors of the above results were also Yu. V. Popov (BLTP JINR, MSU), K. A. Kuzakov (MSU), B. Joulakian (France), R. Dörner (Germany), M. S. Schöffler (Germany), M. Kircher (Germany), S. Houamer (Algeria), and M. Takahashi (Japan).

The basic element method[44] (BEM), proposed by N. D. Dikusar, is a fundamentally new approach to solving problems in applied mathematics. A new class of hierarchical BEM polynomials, fault-tolerant and reducing computational complexity, was created using BEM. The following methods have been developed and implemented: a piecewise cubic approximation method (jointly with C. Török, Slovakia), a high-order piecewise polynomial approximation method, a method for approximating contours of complex topology, an explicit method for the numerical solution of fifth-order stiff Cauchy problems, and others. High-degree BEM polynomials are used to normalize the pulse energy density spectra of the IBR-2M reactor. In collaboration with FLNP (Yu. N. Pepelyshev and Ts. Tsogtsaikhan), fifth-degree BEM polynomials have been applied to analyze the neutron noise of this reactor.

New scientific projects with JINR participation required intensive *three-dimensional computer modeling of magnetic fields in the given geometries of experimental setups and improvement of design tools for new medical cyclotrons*.

The earliest solved problems involved calculating the forces acting in the magnetic system of the EXCHARM facility (IHEP, Protvino). A team of authors (E. P. Zhidkov, O. I. Yuldashev, and M. V. Yuldashev) proposed a new method for calculating the potential from a winding when calculating three-dimensional nonlinear magnetic fields that does not accumulate errors.

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[43] *Kircher M., Trinter F., Grundmann S., Vela-Perez I., Brennecke S., Eicke N., Rist J., Eckart S., Houamer S., Chuluunbaatar O., Popov Yu. V., Volobuev I. P. , Bagschik K., Piancastelli M. N., Lein M., Jahnke T., Schöffler M. S., Dörner R.* Kinematically Complete Experimental Study of Compton Scattering at Helium Atoms near the Threshold // Nat. Phys. 2020. V. 16. P. 756–760.

[44] *Dikusar N. D.* Basic Element Method // Math. Simul. 2010. V. 22, No. 12. P. 115–136.

For many decades, P. G. Akishin carried out research into magnetic field calculation methods[45]; he adapted and applied existing approaches to modeling magnetic systems in experiments carried out at JINR. This work included modeling the dipole magnet and superconducting screen for the ALICE experiment (CERN). The experience gained was used to model and optimize the dipole magnet for the CBM experiment (GSI). The use of a Nuclotron-type superconducting cable for current sources significantly facilitated the creation of optimal current windings. This, in turn, required the development of methods and algorithms for their adequate description. Initially, the developed mathematical and software tools were used to calculate fields in superconducting magnets at the GSI SIS100 accelerator complex. Subsequently, in collaboration with colleagues from VBLHEP JINR, the developed methods were intensively used to model and optimize magnetic systems for the NICA project. Based on 2D and 3D modeling of magnetic systems by varying the arrangement of current windings and the geometry of magnet elements, the characteristics of the superconducting dipole and quadrupole magnets of the NICA Collider and Booster, as well as the multipole corrector, final focus lens, and other magnets of the NICA project were optimized[46].

A. M. Chervyakov applied the finite element method to study the distribution of currents and magnetic fields in an alternating-current superconductor, which allowed him to determine the energy losses in the superconductor and thus optimize its design. Using the COMSOL Multiphysics® package, he developed an algorithm for modeling and optimizing a multiturn inductor coil based on a given magnetic field distribution to generate a charged particle beam with a superconducting magnet.

A. I. Amirkhanov, together with I. N. Kiyan (DLNP) and J. Sulikowski (Poland), carried out research that yielded a numerical determination of the high-resolution operating mode for the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland) with accuracy parameters exceeding the best known global accuracy. The JINRLIB software library included a program for calculating closed equilibrium orbits in the magnetic fields of an isochronous cyclotron, EORP.

The conceptual design of the proposed MSC230 isochronous cyclotron, a compact superconducting isochronous cyclotron for proton therapy, requires solving combined dynamic analysis problems involving both magnetic and electric fields. With the participation of T. V. Karamysheva, DLNP staff developed a MATLAB-based platform utilizing the recently developed CORD (Closed ORbit Dynamics) and beam dynamics programs.

Since the late 20th century, I. L. Bogolyubsky participated in major international collaborations studying QCD Green's functions using nonperturbative lat-

[45] *Akishin P. G.* Application of the Method of Volume and Boundary Integral Equations for Modeling Magnetic Systems Containing Superconducting Screens // Comput. Math. Math. Phys. 2001. V. 41, No. 7.

[46] *Khodzhibagiyan H., Akishin P., Bychkov A., Kovalenko A., Kozlov O., Kuznetsov G., Meshkov I., Mikhailov V., Muravieva E., Shabunov A., Starikov A., Trubnikov G.* Superconducting Magnets for the NICA Accelerator Complex in Dubna // IEEE Trans. Appl. Supercond. 2011. V. 21, No. 3.

tice simulation. The joint project involved researchers from JINR (BLTP and LIT), ITEP (Moscow), IHEP (Protvino), and several German institutes.

The use of supercomputers yielded qualitatively new results, leading to a revision of previously established ideas regarding the behavior of both propagators and the running coupling constant in the infrared limit of QCD. An analysis of the propagator behavior in momentum space led to the conclusion that a nonzero effective gluon mass appeared; detailed studies showed that this essentially nonperturbative effect is not an artifact of lattice computations[47]. The research, which included these contributions, was awarded the JINR Prize in 2015.

In the mid-2000s, software packages implementing a hybrid model of the microscopic optical potential (OP), the structure of which takes into account the distribution of nucleons in colliding nuclei, were developed based on the theoretical framework developed at BLTP (V. K. Lukyanov) for studying the mechanisms of nuclear reactions in the intermediate energy range. The real part of this OP is constructed within the framework of the double-folding model, and the imaginary potential is calculated as the optical limit of the Glauber theory. Using this foundation, co-authors from LIT (I. N. Kukhtina, K. V. Lukyanov, E. V. Zemlyanaya), BLTP, and FLNR conducted a series of studies analyzing reactions with light exotic nuclei.

Work on exotic nuclei was performed in collaboration with BLTP and INRNE BAS. Together with colleagues from South Africa, an analysis of experimental data obtained at iThemba LABS for reactions of ^{93}Nb(p, ^{3}He), ^{59}Co(p, ^{4}He), and others was carried out.

K. V. Lukyanov, E. V. Zemlyanaya, and E. I. Zhabitskaya in collaboration with BLTP and Cairo University conducted studies using microscopic OP of the influence of the nuclear environment on the amplitude of pion–nucleon and proton–nucleon scattering depending on the collision energy.

Since 2019, with the participation of M. V. Bashashin, M. Kakenov (Kazakhstan), and A. Ermekova (Kazakhstan), parallel versions of the program for calculating the nucleus–nucleus OP of double convolutions have been developed using MPI and OpenMP technologies, reducing the calculation time by more than 20 times. All developed programs for studying nucleus–nucleus scattering using the high-energy approximation have been transferred to the JINRLIB program library.

Since 2020, Yu. L. Kalinovsky and D. Goderidze, with the participation of A. V. Friesen (BLTP), have developed methods for calculating multidimensional singular integrals for calculating electromagnetic decays of particles in dense and hot nuclear matter[48].

The calculation of observable quasiparticle-phonon models of deformed nuclei is a striking example of the long-standing successful collaboration between MLIT and BLTP. The quasiparticle-phonon model of deformed nuclei (QPMDN) is

[47] *Bogolubsky I. L., Ilgenfritz E.-M., Muller-Preussker M., Sternbeck A.* Lattice Gluodynamics Computation of Landau Gauge Green's Functions in the Deep Infrared // Phys. Lett. B. 2009. V. 676. P. 69.

[48] *Friesen A. V., Goderidze D., Kalinovsky Yu. L.* Calculation of a Multidimensional Integral with a Singularity by Dividing the Integration Domain into Subsegments // Phys. Part. Nucl. Lett. 2024. V. 21, No. 4. P. 782–784.

a clearly defined model of nuclear physics refined at BLTP over several decades under the leadership of V. G. Soloviev. It requires complex calculations of various observables of primary interest. For half a century, N. Yu. Shirikova was the primary developer of software modules for this task and co-author of dozens of papers, several of which were awarded JINR prizes.

Modeling real physical, chemical, and biological systems based on molecular dynamics (MD) is a promising area of computational physics that was developed at LIT under the supervision of I. V. Puzynin.

Research using MD began in collaboration with the RIKEN Computing Center to study cluster-surface collision processes for metallic phases. Research on the collisions of various metallic nanoclusters with metallic surfaces was initially continued by B. Batgerel, E. G. Nikonov, and I. V. Puzynin, then joined by A. Yu. Didyk, S. N. Dimova (Bulgaria), T. P. Puzynina, Z. K. Tukhliev, Z. A. Sharipov, and later by I. G. Hristov and R. D. Hristova from Bulgaria.

E. G. Nikonov, together with his Slovak colleagues M. Pavluš, M. Popovičová, and others, applied the MD method to study various aspects of the interaction of water vapor and a porous structure.

D. R. Badreeva applied the MD method as part of a FLNP project led by N. Kučerka aimed at identificating the role of the beta-amyloid peptide Aβ(25–35) as a key factor in Alzheimer's disease. Both ordered lipid membranes in a hydrated environment and systems with incorporated protein or ionic components are modeled. Particular attention is paid to studying the influence of temperature, pressure, ions, and embedded molecules on the stability and mechanical properties of membranes. Characteristics, such as bilayer thickness, density profile, potential distribution, and diffusion coefficients, are analyzed. Computational resources of the HybriLIT platform and the Govorun supercomputer are utilized to perform long-term calculations and statistically reliable sampling of ensembles of molecular configurations[49]. This enables the modeling of systems containing tens and hundreds of thousands of atoms on time scales from nanoseconds to microseconds.

N. M. Plakida (BLTP) pioneered the theoretical description of high-temperature superconductivity in cuprates based on Zubarev–Green function theory, which led to the two-band Hubbard model. Under his supervision, numerical experiments were performed by L. Anton (Romania), S. A. Adam, and Gh. Adam. The results showed that, among the two sources of superconducting coupling, the contribution of the kinematic interaction of electrons with spin fluctuations in the second order in the coupling constant significantly exceeded the contribution of the antiferromagnetic interaction in the mean-field approximation. Numerical calculations of a strict mean-field approximation model in superconductivity theory for the Hubbard model revealed a number of specific quantum effects. This research was awarded the JINR First Prize in 2013.

[49] *Kurakin S. A., Ivankov O. I., Murugova T. N., Badreeva D. R., Dushanov E. B., Ermakova E. V., Kuklin A. I., Kučerka N.* Lipid Membrane Destabilization Induced by Amyloid-Beta Peptide in the Systems Mimicking Preclinical Alzheimer's Disease // Natural Sci. Rev. 2025. 2. 100202.

Since numerical experiments dedicated to the aforementioned study of the Hubbard model were difficult to conduct, attention was directed toward the numerical solution of Riemann integrals. Three key results have been obtained to date. First, the algebraic degree of accuracy of the floating-point interpolation quadrature sum *loses the invariant property* that holds for the field of real numbers. Second, *Bayesian inference* significantly improves the reliability of automated solutions. Third, *robust implementation of decision trees* is only possible using artificial intelligence tools.

A. S. Ayriyan, H. Grigorian, and V. Abgaryan, in collaboration with colleagues from BLTP, are solving computational astrophysics problems related to numerical modeling of the thermal evolution of neutron stars and analyzing the equations of the underlying dense matter state. This work is aimed at studying the microphysics of superdense matter at extreme temperatures and pressures. Particular attention is paid to hybrid equations of state with a possible transition to the quark phase. Calculations performed with developed parallel algorithms on the Govorun supercomputer and the HybriLIT platform made it possible to model the temperature evolution of hundreds of thousands of possible neutron star configurations on timescales of up to millions of years and compare the results with observations.

As part of a collaboration between E. A. Ayryan and staff members of the Institute of Physics, Academia Sinica, Taiwan (Prof. Hu Ch.-K. and Sh. Ayryan), with the participation of Slovak colleagues (J. Buša, J. Buša (Jr.), J. Džurina, J. Plavka, I. Pokorný, and J. Skřivánek), new methods for studying the geometric properties of complex proteins were proposed. The developed programs were applied to solve the nonlinear Poisson–Boltzmann problem for determining the electrostatic potential of proteins in a complex 3D region.

The work on the development and application of polynomial computer algebra methods, initiated by V. P. Gerdt in the early 1990s, has been very fruitful over these years. This activity included a wide range of applications of involutive methods in applied, engineering, and physical problems described by systems of underdetermined and overdetermined differential equations. In a large series of studies carried out by staff members of V. P. Gerdt's sector, together with colleagues from Bulgaria, Georgia, and Russia, an algorithm for finding a complete set of constraints (of the first and second kind) for polynomial mechanical systems with a degenerate Lagrangian function was developed and applied. It is based on the ideas of Gröbner basis theory and the involutive division of polynomials developed by V. P. Gerdt and others. A software implementation of computer algebra methods, actively developed under the supervision of V. P. Gerdt has received high praise and recognition from the world's leading professional computer algebra providers (Mathematica, MATLAB), which, in exchange for LIT developments, exceptionally provided free access to their software for LIT specialists. Among these, a special place was occupied by studies of mechanical systems, whose configuration and phase space are restrained by constraints and relationships, and whose evolutionary problems inevitably require involutive analysis (Yu. Palii, A. Khvedelidze).

Another important application of the Gröbner basis theory and involutive division of polynomials is related to O. V. Tarasov's work on the efficient calculation of

the Feynman integrals in various models of quantum field theory. Here, it is worth noting the wide range of problems, both in pure mathematics and in the theory of continuous Lie groups and finite groups, solved using analytical methods of computer algebra (V. V. Kornyak).

A. M. Raportirenko played a significant role in the correct and precise implementation of computer algebra software, including the error-free migration of developed products (REDUCE, AXIOM, MAXIMA, etc.) from 32-bit to 64-bit machines. His sudden death was a severe loss for the entire MLIT.

Computational problems related to the description of quantum systems have become another area of application of the Gröbner bases in research. Among the time-consuming computational problems, an important one is the classification of quantum systems in terms of their quantum resource, in particular, depending on the complete set of characteristics responsible for the phenomenon of entanglement of quantum states. It was precisely this range of problems that was the focus of the joint research of V. P. Gerdt, Yu. Palii, and A. Khvedelidze, conducted in Dubna from 2006 to 2016. These studies examined the algebraic structure of the ring of polynomial invariants of basic composite binary quantum systems, such as qubit–qubit and qubit–qutrit pairs. Further work in this direction (V. Abgaryan, M. Bureš, I. A. Rogozhin, A. G. Torosyan) on calculating quantum resource indicators showed that computer algebra methods allow for time-consuming computational calculations that are interesting for various applications, including quantum information theory.

The development and implementation of quantum algorithms and the application of quantum machine learning occupy a special place among modern computational methods in computer mathematics, both for modeling complex quantum systems and for efficiently processing large data sets. A. A. Bogolyubskaya, M. Bureš, and Yu. Palii are involved in research on simulating quantum computations and implementing machine learning schemes using the computing power of MLIT JINR.

L. A. Siurakshina and V. Yu. Yushankhai (BLTP) investigated the dynamics of the one-dimensional spin *XXZ* model in the quantum "hardening" mode using the Qiskit and LindbladMPO software on a classical computer.

DIGITAL ECOSYSTEM

Along with scientific research, MLIT also addresses the creation and support of scientific, information, and administrative systems. Year after year, work has been systematically carried out to maintain previously developed databases and information systems, and to create new ones based on user requests.

In the second half of the 1990s, CERN began actively using the Internet not only for file sharing or websites but also as an interface for corporate web applications. A web application differs from a website (even a dynamic one) in that it involves fairly complex data processing, typically performed on the server side (back-end). Various technologies were used for back-end development, such as CGI Script, PHP, Perl, ASP and ASP.NET, C#, and Java in its three varieties:

Servlet, Applet, and JSP. Since then, a number of higher-level technologies have been added to this list, but Java Servlet and, to some extent, JSP remain popular for creating complex web apps due to the power and development of the Java language and tools. The relatively high entry barrier is still a disadvantage of Java — the developer must thoroughly study the language and at least some of the numerous available tools based on it.

In the late 1990s and early 2000s, a group led by S. V. Kuniaev at JINR began developing a platform called WALT (Web Application Lego Toolkit)[50]. The goal was to create a Java toolkit that would allow developers to solve typical subtasks arising during web application development, even without any Java knowledge. WALT is a pattern language and an interpreter for that language. Since then, WALT has been used and continuously developed at JINR. Standard WALT services enable the solution of common problems without Java programming by preparing compact text templates with information about database queries, data processing algorithms, and the output HTML code. A specialized service (Java class) can be developed based on the standard services to solve a specific problem that cannot be solved by standard WALT services.

The basic principles of the Agile software development methodology were applied to achieve maximum results in the shortest possible time with a small team of one or two, sometimes three, programmers, in the development of all these applications, in addition to using WALT:

- Regular close communication between developers and end users. The primary method of information transfer is face-to-face conversation.
- Striving for maximum product simplicity to avoid unnecessary or excessive labor-intensive work. Particular attention was paid to a user-friendly and intuitive interface.
- Early phased implementation of functioning software, frequent software updates taking into account operating experience and feedback received from end users.

The WALT platform is an effective tool for creating web applications for a small team of developers, which is typical at JINR. The effectiveness of WALT is demonstrated by the large number and diversity of applications developed over the past 25 years with the participation of S. V. Kuniaev, S. V. Semashko, P. V. Ustenko, O. V. Belyakova, A. V. Prikhodko, I. A. Sokolov, and N. E. Belyakova. The most significant applications include:

- ADB2 — a system of management accounting and budget preparation at JINR;
- PIN, PIN-2.0 — PIN (Personal INformation) system for collecting and analyzing information on the results of scientific activities of employees;
- Document Database — an electronic database for the main paperwork management of JINR with elements of electronic document management;
- NICA EVM — NICA project management system: project structure, work and financing planning, progress of implementation according to the EVM methodology, financial reports, etc;
- Dubna EDMS — JINR electronic document management system;

[50] *Korenkov V. V., Kuniaev S. V., Semashko S. V., Sokolov I. A.* // WALT Platform for Web Application Development // CEUR Workshop Proc. 2021. V. 3041. P. 387–392.

- HR JINR — administrative information and reference system for JINR departments;
- GIS JINR is a geographical information system that includes multilayer interactive maps;
- Gateway — a multipurpose gateway for data exchange between various information systems;
- ISSC — information system for scientific certification for JINR Dissertation Councils;
- CERN DB — accounting of JINR employees' business trips to CERN (visits, accommodation, finances, reports);
- "Advance" — preparation of data for accounting reports on business trips, electronic queue in the accounting department;
- monitoring system shell for the Dubna Satellite Communications Centre;
- information system for grant proposal (IFA);
- Shell of the JINR Digital Ecosystem.

In preparation for the anniversary of JINR and MLIT, it is important to highlight the role of the digital repository created to preserve and disseminate the scientific achievements of the Institute. The repository has become an integral part of scientific communication, reflecting the evolution of technologies and the needs of the research community. The project's origins date back to the early 2000s, when the global scientific community was actively implementing the principles of open access to knowledge. JINR decided to create a repository of its employees' publications. In 2004, the Institute implemented the Invenio platform, developed at CERN, which provided digital resource management. This system became the basis for accumulating data — articles, dissertations, reports, and archival materials — which were made available to both internal and international scientific community. Later, the JOIN^2 system, an extension of Invenio, was tested as part of a joint project with German institutes.

In the 2020s, the JINR repository migrated to the new DSpace platform — one of the most powerful popular open-source publication repository solutions. The system, which entered trial operation at JINR in 2024, has improved scalability and integration with global databases. Automatic collection of publication information is performed from three main sources: ELibrary, Inspire HEP, and Scopus. Publications are linked to user profiles of JINR employees. Information about them is available both through the repository's web interface and in the new PIN-2. Publications not included in the main sources can be added by the user (all fields can be automatically filled in if DOI is available). A key achievement was the development and implementation of automated collection of publication metadata from various sources, which reduced the need for manual data entry. This made the publication addition process more efficient and reduced the risk of data duplication. The team headed by I. A. Filozova and consisting of G. V. Shestakova, T. N. Zaikina, A. S. Bondyakov, A. O. Kondratyev, I. K. Nekrasova, and Ya. I. Popova is working on the creation and development of publication repositories.

The repository has become an important tool for ensuring the transparency and accessibility of research results. It allows for the analysis of publication topics, tracking of citations, and assessment of JINR's contribution to various fields of

science. Furthermore, the repository facilitates the exchange of ideas, making the Institute's work accessible to students, researchers, and analysts worldwide. The creation and development of the repository is not only a technical achievement but also a symbol of JINR's openness and innovation. Today, it represents a modern ecosystem reflecting the Institute's mission: promoting fundamental research and transferring knowledge to future generations. In this anniversary year, its history serves as a shining example of how technology helps preserve scientific heritage and strengthen international collaboration.

To facilitate collaborative document processing, the SciDocsCloud software platform (I. A. Sokolov, N. A. Balashov) was developed to replace the outdated DocDB system. The platform's goal is to provide a centralized service for storing, managing, structuring, and collaborating on documents. A cloud service based on this platform was launched in 2024. It is accessed using JINR Single Sign-On (JINR SSO) accounts.

An important area, led by S. V. Semashko, is the development of the Institute's geographical information system. It addresses a wide range of tasks, from visualizing the locations of the Institute's buildings and facilities to detailed documentation of complex engineering infrastructure. It supports the development of building plans, accounting for personnel placement within rooms, searching for personnel and rooms, and analyzing departmental space usage (occupancy, average density, etc.). Building and territory plans can be imported from external sources (topographical maps, digital geodetic surveys, high-resolution satellite images), while utility network data can be imported from technical plans and site drawings of related departments (Technical Communication Service, Capital Construction Department, laboratory technical plans, etc.). The system is used for planning and executing maintenance and repair works on the territory of the Institute and in its buildings.

In 2022, work began on creating a digital ecosystem platform (JINR Digital Ecosystem). Its primary goal, in accordance with the Institute's Strategic Development Plan, is the digitalization of the Institute's core activities. The platform's primary objective is to provide a unified environment for the creation and development of digital services, their integration, and the analysis of information on all aspects of JINR's activities. It includes a wide range of services — from resources for users of basic facilities to travel arrangements, trip tickets, orders of certificates, etc. The main service groups are administrative (area of responsibility of the JINR Department of Digital Services Development) and scientific ones.

Today, the JINR Digital Ecosystem is a comprehensive digital environment based on the principles of mutually beneficial relationships, uniting existing information services and business processes, as well as a large number of newly developed ones. The system is accessed using the JINR Single Sign-On (SSO) authentication service — a single sign-on and access to all services through a single account. The system features a fast and convenient information search and allows seamless user switching between the various services within the digital ecosystem. The main developers of the Digital JINR portal are S. V. Kuniaev, O. V. Belyakova, A. V. Prikhodko, and N. E. Belyakova.

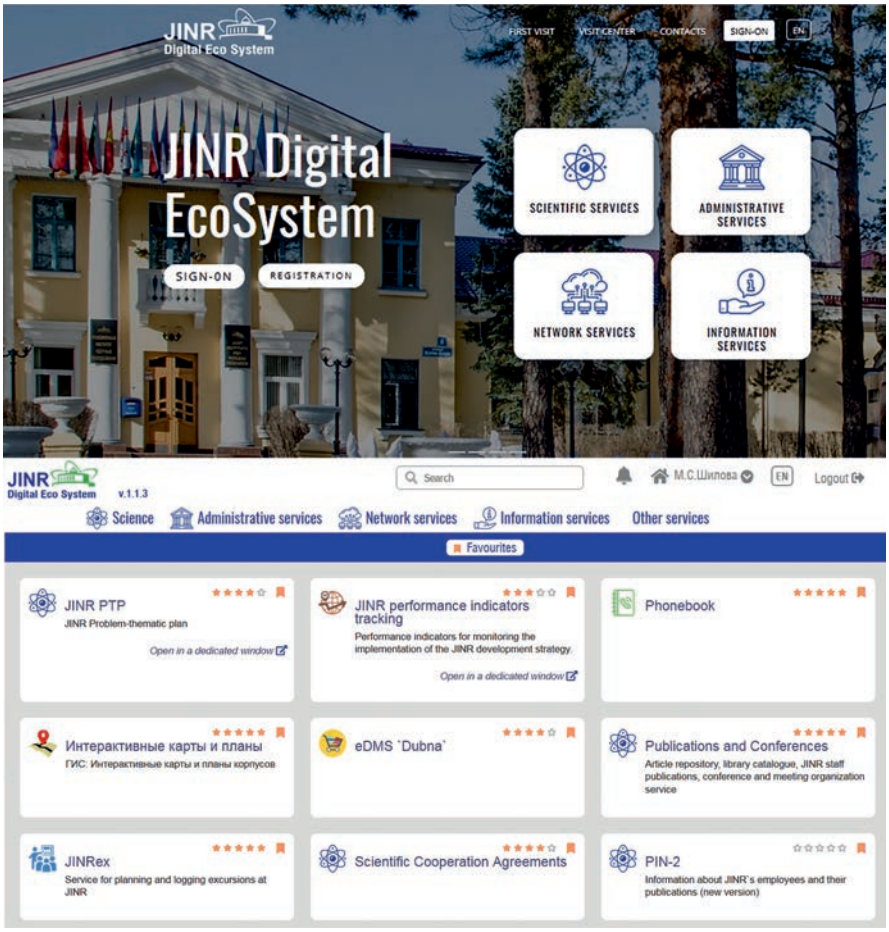


Fig. 17. JINR Digital Ecosystem interface

In 2024, several institute-wide digital services were launched: a thoroughly redesigned version of PIN-2 for managing information about JINR employees (S. V. Kuniaev, O. V. Belyakova, N. E. Belyakova, A. V. Prikhodko), a repository of scientific publications of JINR employees (I. A. Filozova's group), and a calendar for collaboration. A prototype of a corporate data bus for integrating digital services and managing information flows was created (D. V. Neapolitanskiy). An electronic user support system was implemented based on the application management service (E. V. Sheyko). Existing digital services are being developed actively, integrating with each other and with the core services of the DES. The launched services are accessible through the DES interface https://digital.jinr.ru; as for 2025, there are more than 50 of them.

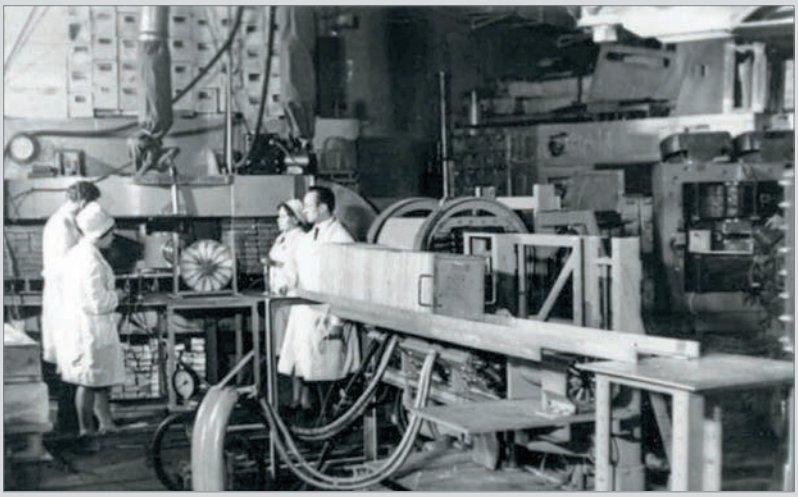
RADIATION RESEARCH IN LIFE SCIENCES

The necessity and effectiveness of using ionizing radiation with different physical characteristics in studying the mechanisms of the genetic effects of radiation were already emphasized by the classics of radiation biology. The Institute's Laboratory of Radiation Biology (LRB), which celebrated its 20th anniversary in 2025, addresses fundamental and applied issues related to the biological effects of ionizing radiation.

Radiobiology, as an interdisciplinary science, requires the support of physicists, and JINR, in this regard, offers unique opportunities, as it has highly qualified personnel, the necessary equipment, and a wide range of diverse radiation sources. In fact, there is no research center more convenient and physically equipped for radiobiological research than JINR among the Institute's Member States. Therefore, the Laboratory of Radiation Biology can with good reason claim leadership among scientific organizations in Russia and the JINR Member States in studying the effects of ionizing radiation with various physical properties.

The first radiobiological experiments in Dubna began back in 1959 at the 6-meter proton synchrocyclotron of the Laboratory of Nuclear Problems. Subsequently, specialists from various institutes of the USSR Ministry of Health successfully conducted research into the effects of protons of different energies on the human body and sought ways to protect cosmonauts from their negative effects during spaceflight. In 1967, at the initiative of Corresponding Member of the USSR Academy of Sciences V. P. Dzhelepov, Director of the Laboratory of Nuclear Problems, the first medical proton beam in the USSR was created at JINR using the same accelerator. Radiobiological experiments conducted on cell cultures and laboratory animals determined the key radiobiological parameters of accelerated protons, making it possible to begin radiation therapy for cancer patients just one year later.

Radiobiological research at the Institute's basic facilities subsequently began to be successfully developed by radiobiologists working directly at JINR, within the Biological Research Sector of the Laboratory of Nuclear Problems, established in 1978 (JINR Order No. 3388 of November 29, 1977). Doctor of Physics and Mathematics V. I. Danilov, Head of the Synchrocyclotron Department, was the initiator of the Biological Research Sector. Professor V. I. Korogodin was invited to lead the sector, and in 1986, Professor E. A. Krasavin took over.



The first radiobiological experiments at the LNP synchrocyclotron

Later, the expansion of the range of radiobiological research at JINR's basic facilities required a structural reorganization of the departments conducting this research. In 1988, the Biological Research Sector was transformed into the Biophysics Department (JINR Order No. 248 of March 25, 1988).

Following the establishment of the Biophysics Department, intensive radiobiological research was conducted using heavy charged particle beams from the U-300 and U-200 accelerators of the Laboratory of Nuclear Reactions. This work required specialized spectrometric and dosimetric studies of accelerated heavy ion beams. The staff of the JINR Department of Radiation Research and Radiation Safety had extensive experience in this field. The JINR Directorate, Corresponding Member of RAS V. G. Kadyshevsky and Professor A. N. Sissakian, supported the initiative to merge the Biophysics Department of the Laboratory of Nuclear Problems and the JINR Department of Radiation Research and Radiation Safety into a new structural unit of the Institute — the Division of Radiation and Radiobiological Research, DRRR (JINR Order No. 270 of April 27, 1995). Following successful acceleration of heavy nuclei to relativistic energies at the Nuclotron in the Laboratory of High Energies and the commencement of physics experiments at the new accelerator, the DRRR team planned radiobiological experiments using high-energy heavy ion beams. The division continued its previously initiated research into the mutagenic effects of radiation over a wide range of linear energy transfer values on microorganisms, mammalian cells, and human cells. The DRRR staff, together with radiochemists from DLNP, FLNR JINR, and the Institute of Biophysics of FMBA of Russia, conducted research into the biological effects of the isotope astatine-211. An innovative method for its use in targeted melanoma therapy was developed.



The founder of LRB — Corresponding Member of the Russian Academy of Sciences E. A. Krasavin

In 2005, at the initiative of Professor E. A. Krasavin and with the support of the JINR Directorate, a new, seventh laboratory of the Joint Institute — the Laboratory of Radiation Biology — was established based on the Division of Radiation and Radiobiological Research (JINR Order No. 403 of June 20, 2005). Professor E. A. Krasavin, Doctor of Biological Sciences, became the founding director of the laboratory. In 2009, at the 106th session of the JINR Scientific Council, he was elected the first director of the laboratory. This event marked a logical step in the development of interdisciplinary research at JINR and recognition of the high relevance of life sciences in the modern world.

Research conducted by the laboratory team using the Institute's basic facilities allowed addressing one of the central challenges of radiobiology: the relative biological effectiveness (RBE) of radiation of varying quality. This, as demonstrated, is determined not only by the physical characteristics of the radiation but also by a biological factor — the cell's ability to repair DNA damage. Based on these concepts, the mechanisms of radiation-induced mutagenesis in prokaryotic and lower eukaryotic cells exposed to heavy charged particles were studied in detail[1,2].

A new concept of radiation risk for manned interplanetary flights was proposed and substantiated for the first time in the world in collaboration with specialists from the Russian Academy of Sciences. According to this concept, radiation risk for astronauts is determined by the effect of heavy nuclei of galactic cosmic rays, primarily, on the structures of the central

[1] *Krasavin E. A.* The Problem of RBE and DNA Repair. Moscow: Energoatomizdat, 1989; 2nd ed. Dubna: JINR, 2025.

[2] *Krasavin E. A., Kozubek S.* Mutagenic Effect of Radiation at Different LET. Moscow: Energoatomizdat, 1991; 2nd ed. Dubna: JINR, 2025.

nervous system and the potential disruption of crew operator performance.

In pioneer experiments conducted by LRB JINR, together with colleagues from the University of Tuscia (Viterbo, Italy), in irradiating aqueous solutions of formamide with accelerated protons and multiply charged ions in the presence of meteorite material as a catalyst, the synthesis of a large number of prebiotic compounds was observed for the first time: amino acids, carboxylic acids, sugars, nucleic bases, and even nucleosides. These compounds had not previously been detected in experiments using other types of radiation.

In 2019, the laboratory staff first proposed and patented a fundamentally new approach to increasing the biological effectiveness of ionizing radiation with low linear energy transfer by converting non-lethal DNA damage into lethal damage in the presence of certain medicines — inhibitors of DNA synthesis. The method demonstrated high efficiency in experiments on various tumor cell cultures and laboratory animals with transplanted tumors, which makes it highly promising for radiation therapy using proton and gamma beams.

In 2022, the laboratory's first basic facility, the Small Animal Radiation Research Platform (SARRP) for precision X-ray irradiation of laboratory animals, was commissioned. The laboratory's infrastructure is not limited to this; research is conducted on all of the Institute's major accelerators — the ARIADNA applied beamlines of the NICA complex at the Laboratory of High Energy Physics, the U-400M cyclotron at the Laboratory of Nuclear Reactions, and the Linac-200 linear accelerator at the Laboratory of Nuclear Problems.



The resources of the Multifunctional Information and Computing Complex (MICC) of the Laboratory of Information Technologies are actively utilized. Research will soon begin on the new MSC-230 medical proton accelerator at the Laboratory of Nuclear Problems and on neutron beams at the Laboratory of Neutron Physics. Plans are underway to organize radiobiological research in radiochemical laboratories for applications in nuclear medicine.

RADIATION BIOLOGY

RESEARCH AREAS

LRB's scientific program includes the study of the molecular, genetic, and organismal effects of ionizing radiation with different physical characteristics, as well as radiation-biophysical and astrobiological research[3]. This program is implemented by two scientific departments.

The Department of Radiation Biology and Physiology at LRB comprises four sectors: Molecular Radiobiology Sector, Radiation Cytology Sector, Radiation Physiology Sector and Medical Radiobiology Sector, and a group for radiation genetics of lower eukaryotes. The department conducts research on a wide range of fundamental and applied radiobiological problems, including the development of new approaches to increasing the biological effectiveness of radiation for tumor radiation therapy and investigating the mechanisms of functional impairments in the brain caused by radiation. The department has a well-developed research infrastructure and qualified specialists capable of conducting scientific experiments using modern methods at the molecular, cellular, tissue, and organismal levels of biological organization.

The Radiation Research Department of LRB includes two sectors: Mathematical Modeling Sector and Sector for Radiation Research at Basic Facilities. The main areas of research in the Radiation Research Department include: developing a hierarchy of mathematical models to describe radiation-induced effects at different levels of biological organization and time scales (modeling the formation and repair of radiation-induced DNA damage, the induction of gene and structural mutations, and tissue effects caused by exposure to ionizing radiation with different physical characteristics); improving irradiation methods and precision dosimetry in radiobiological research at the Institute's nuclear physics facilities; and developing methods for automated processing of experimental data.

MOLECULAR RADIOBIOLOGY

Research in molecular radiobiology is aimed at:

— studying the induction and repair of various types of DNA damage, and especially clustered damage, in normal and tumor cells exposed to ionizing radiation with different physical characteristics *in vitro* and *in vivo*;

[3] *Krasavin E. A.* // Physics–Uspekhi. 2016. V. 186. P. 435–443.



Researchers of the Molecular Radiobiology Sector (left to right) I. S. Hramco, M. Lal, M. E. Krupnova, E. A. Kuzmina, and R. A. Kozhina at work

— the molecular and radiobiological aspects of radiation therapy associated with the use of radio modifier complexes that increase the yield of lethal radiation-induced DNA damage in tumor cells when exposed to ionizing radiation with different physical characteristics *in vitro* and *in vivo*.

Various molecular and biological methods are used for these purposes, including immunocytochemistry and immunohistochemistry. These approaches allow not only for quantitative analysis of the formation of genetic damage but also for visualization of the spatial distribution of damage within the genetic structures of cells. DNA double-strand breaks (DSBs) are the most severe type of damage. Induction of DSBs in specific regions of the genome leads to specific phosphorylation of H2AX histone in the chromatin surrounding the damage, resulting in the formation of so-called γH2AX foci. The internal structure of these ionizing radiation-induced foci (IRIFs) reflects the correlation of biochemical processes triggered in response to damage and aimed at restoring DNA integrity.

The studies use not only cell cultures of normal and tumor cells of mammals and humans, but also primary cultures of neuronal cells, as well as histological sections of tissues from various parts of the central nervous system of irradiated animals.

Researchers of the Molecular Radiobiology Sector studied the dose dependence of the frequency of IRIF formation in human cells exposed to radiation with different LET values. A higher formation efficiency was found with accelerated heavy ions compared to γ irradiation. It was found that heavy ions, compared to γ rays, produce a higher rate of maximum DNA foci formation and slower elimination kinetics. A detailed analysis of the structure of complex damage clusters in accelerated ion tracks was performed based on a differentiated analysis of individual DNA foci in three-dimensional images reconstructing the entire cell nucleus[4].

It was established that after exposure to accelerated heavy ions of low and intermediate energies, unlike γ irradiation, complex clusters containing up to six or more

[4] *Falk M. et al.* // J. Radiat. Res. 2014. V. 55. P. i79–i80.

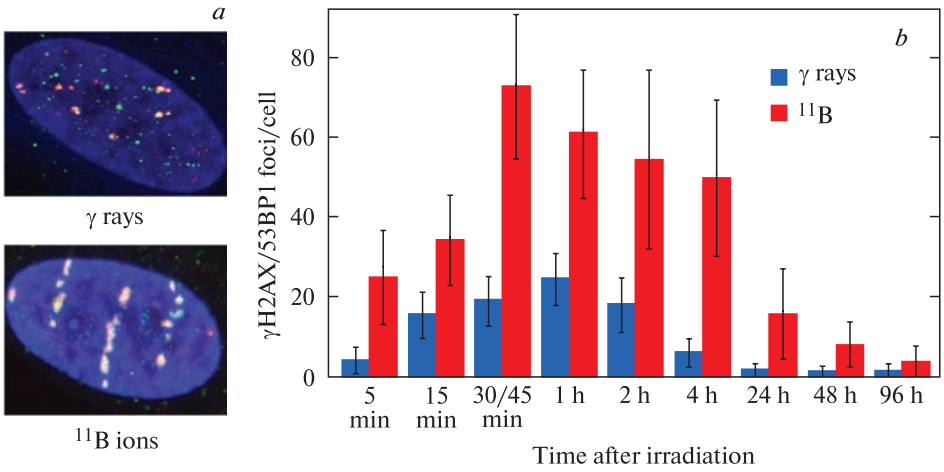


Fig. 1. Visualization of IRIF (a) and the kinetics of their repair (b) after exposure to γ rays and 50 MeV/nucleon ^{11}B ions

individual foci are formed[5]. The structure, size, and shape of clustered DNA damage depended on the particle LET. Slower elimination kinetics of radiation-induced foci in cells was demonstrated under heavy ion exposure compared to γ irradiation. Based on the results of this series of studies, the sector team was awarded the JINR First Prize for applied scientific and technical work in 2019.

A new method for analyzing the fine structure of clustered DNA damage with ultra-high resolution was developed in collaboration with Czech and German colleagues[6]. It is based on single-molecule localization microscopy. By using this method, the structure of clustered DNA DSBs was studied, and a comparative study of their repair kinetics in normal and tumor human cells exposed to accelerated ^{15}N ions was conducted. The proposed approach provides new insights into the nature of radioresistance in a number of tumors.

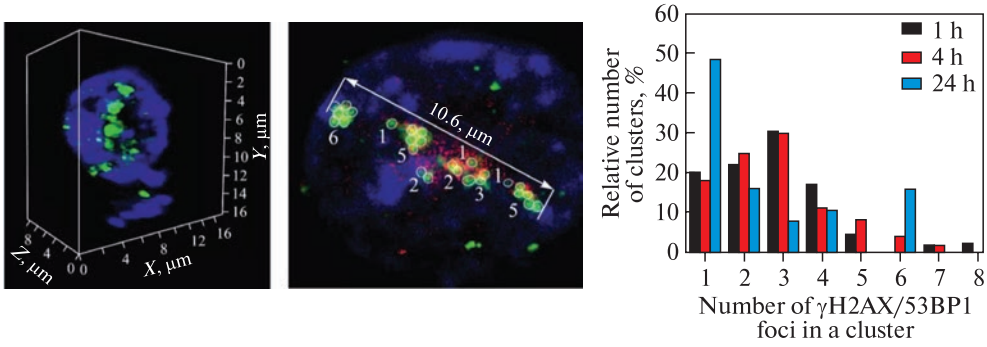


Fig. 2. Visualization and quantitative composition of IRIF in neurons of the rat brain irradiated with 2.58 GeV/nucleon ^{78}Kr ions

[5] *Jezkova L. et al.* // Nanoscale. 2018. V. 10. P. 1162.
[6] *Hausmann M. et al.* // Front. Phys. 2020. V. 8. P. 578662.

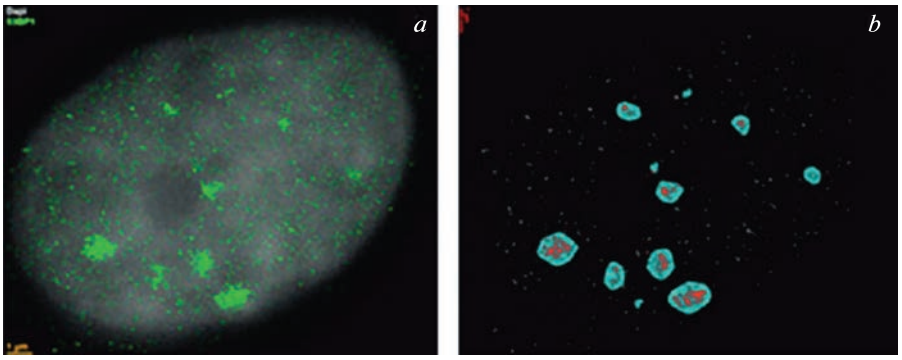


Fig. 3. Visualization of the structure of 53BP1 repair protein clusters in the nuclei of U87 human glioblastoma cells 24 hours after irradiation with accelerated ^{15}N ions (13 MeV/nucleon, 1.3 Gy): a) images in a microscope; b) software post-processing

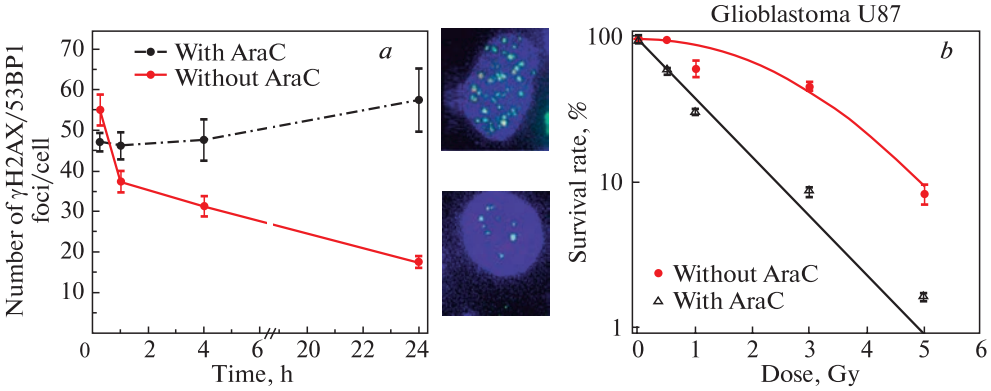


Fig. 4. Kinetics of formation and elimination of γH2AX/53BP1 foci in the nuclei of human glioblastoma U87 cells (a) and survival curves (b) under the combined action of AraC and spread-out Bragg peak protons at a dose of 1.25 Gy

DNA DSBs are either formed as a result of a direct break between two complementary regions — direct DSBs, resulting from the transfer of energy to a local DNA region, leading to a disruption of its integrity, or they are formed from other damage as "repair side effects" during the work of repair enzymes — this type of damage is classified as enzymatic DSB. The incidence of enzymatic DSBs during irradiation depends on many biological factors, and their frequency can be influenced by modifying DNA repair processes. It was shown that administration of the clinically approved drug 1-β-D-arabinofuranosylcytosine (AraC), a DNA synthesis inhibitor, prior to exposure of human cells to ionizing radiation transforms single-strand DNA breaks into lethal enzymatic DSBs[7]. The number of DNA DSBs in cells exposed to Bragg peak protons in the presence of modifiers increases more than 15 times by the 24th hour of observation due to an increase in the number of

[7] *Chausov V. N. et al.* // Phys. Part. Nucl. Lett. 2018. V. 15, No. 6. P. 700–710.

enzymatic DSBs, whereas in the absence of modifiers it decreases to a minimum by this time.

Based on this, a fundamentally new method for increasing the biological effectiveness of medical proton beams and gamma-therapeutic installations was developed and patented at LRB JINR[8], which, in the long run, makes it possible to bring the biological effectiveness of proton irradiation closer to that of carbon ion irradiation.

RADIATION GENETICS AND CYTOGENETICS

Molecular and genetic research aims to understand the spectrum of mutational events induced by exposure to ionizing radiation with different physical characteristics. Specially developed genetic systems and sequencing of specific DNA regions are used for mutation analysis. The genetic heterogeneity of cell populations and the radiosensitivity of various fractions, the mechanisms of cell aging and death, and the mechanisms of radioresistance are studied. The genetic control of mitochondrial DNA stability is also being explored, as is the role of mitochondria and mitochondrial DNA in the response to radiation exposure.

Studying the long-term effects and mutagenic action of ionizing radiation of varying quality, particularly accelerated heavy ions, on mammalian and human cells is a crucial task in modern radiobiology. Chromosome aberrations have been studied for over half a century, yet many unanswered questions remain. LRB conducts research on chromosomal damage, various types of gene and structural mutations depending on the dose and LET of radiation, and mechanisms of genetic stability. Complex radiation-induced chromosomal rearrangements are studied using the modern and advanced multicolor Fluorescent In Situ Hybridization (mFISH) method. The main advantage of this method is the ability to study complex chromosomal aberrations (three or more breaks in two or more chromosomes), which are a marker of densely ionizing radiation, reflecting the cluster distribution of DNA damage along the particle track.

An analysis of the spectra of gene mutations induced by gamma rays and accelerated heavy ions was carried out. The mutation spectra were dominated by base pair substitutions, single nucleotide deletions, and complex mutations, which are combinations of substitutions and deletions within a single DNA strand. Heavy ions were shown to induce complex mutations more effectively. A plasmid system was used to analyze structural rearrangements. The size and location of the induced damage were determined using genetic, electrophoretic, and restriction analysis. Sequencing of plasmid DNA in nine mutants that had lost DNA sections affecting two (eight mutants) and three (one mutant) genes revealed the precise location and size of the deletions.

The mutational process patterns in mammalian cells exposed to accelerated ions (^{11}B, ^{20}Ne, and ^{18}O) with varying LET values and ^{60}Co γ rays at various times

[8] A Method of Increasing the Formation Frequency of Ionizing Radiation-Induced DNA Double-Strand Breaks in Human Cells in the Presence of Radiomodifiers / Krasavin E. A., Boreyko A. V., Bulanova T. S., Chausov V. N., Kulikova E. A., Timoshenko G. N. RF Patent 2699670. Publ. 09.09.2019. Bull. No. 25.

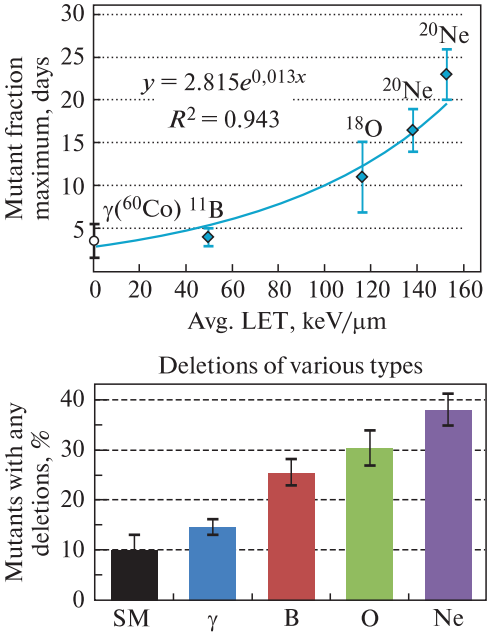




Fig. 5. Maximum level of radiation-induced mutagenesis in Chinese hamster cells and structural changes in the hprt gene depending on the expression time and LET of accelerated ions. In the photo: N. A. Koshlan (left) and M. D. Isakova

after radiation exposure were studied. The maximum yield of mutant subclones was found to depend on the LET of accelerated ions. A shift in the maximum mutant yield was observed at higher LET values with increasing expression time of irradiated cells. The dependence is exponential, which may indicate qualitative differences in damage to genetic structures at different LET values, which are responsible for this shift. Long-term cultivation of mutant subclones revealed unusual growth patterns in some mutants. Such signs may indicate the initiation of cell transformation processes, including malignant ones[9,10].

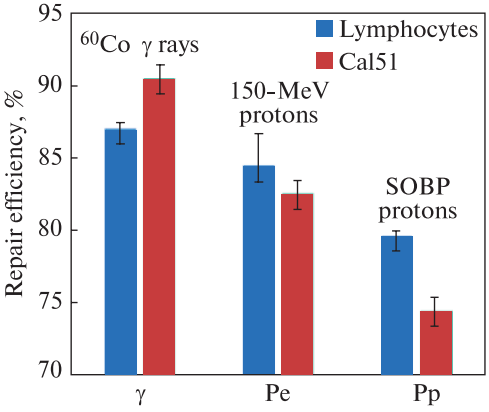


Fig. 6. Efficiency of chromatin break repair in normal human lymphocytes and Cal51 carcinoma cells

A metaphase analysis of the formation of chromosomal aberrations was performed in human Cal51 carcinoma cells and normal human peripheral blood lymphocytes irradiated with photons and protons (150 MeV and at

[9] *Bláha P. et al.* // Mutat. Res. 2017. V. 803–805. P. 35–41.
[10] *Bláha P. et al.* // Front. Phys. 2021. V. 8. P. 584326.

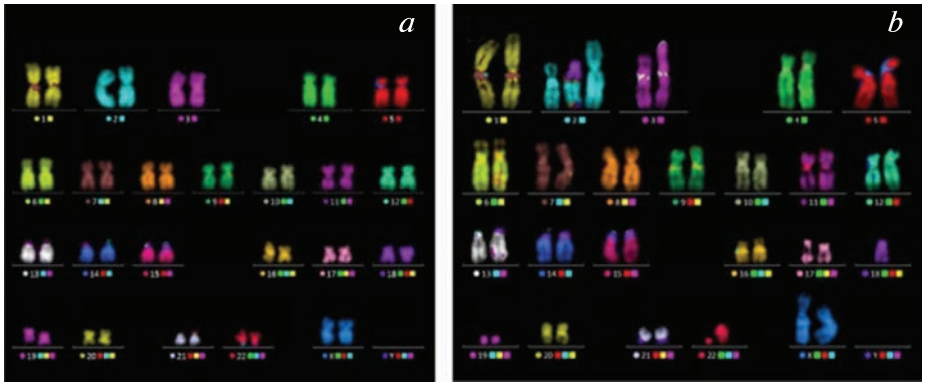


Fig. 7. a) Normal karyogram of human blood lymphocytes obtained by the mFISH method; b) karyogram with complex chromosomal aberrations long after exposure to iodine-131 radiopharmaceuticals

the Bragg peak). The proportion of successfully repaired chromatin breaks 12 hours after irradiation was assessed using the premature chromosome condensation method. Gamma-ray exposure in tumor cells revealed more effective chromatin break repair compared to normal cells than proton irradiation. The results indicate that proton beams are preferable for radiation therapy of breast carcinoma[11].

A cytogenetic study was conducted in collaboration with the Tsyb MRRC (Obninsk) on the side effects of radioiodine therapy for thyroid tumors. Using the mFISH method, it was demonstrated for the first time that exposure to iodine radiopharmaceuticals induces predominantly unstable chromosomal aberrations in blood cells, while the level of stable chromosomal aberrations, which are a possible trigger for secondary carcinogenesis, increases only slightly[12].

RADIATION PHYSIOLOGY

Radiation physiological research is aimed at studying behavioral response disorders, brain electrical activity, and pathomorphological changes in critical organs and systems of laboratory animals exposed to ionizing radiation with different physical characteristics. Video tracking and machine learning software systems are used for behavioral analysis. Electrical activity in various parts of the rodent central nervous system is recorded after implantation of microelectrodes using wireless sensors. Morphological changes in tissues are analyzed with modern histological and immunohistochemical methods using light and fluorescence microscopy.

One of the key tasks of radiation physiology is assessing radiation risks during deep space exploration. The galactic cosmic rays (GCRs) consist of high-energy protons and ions with high charge and energy. The latter, despite their low fluence, contribute significantly to the radiation risk for astronauts due to their high biological effectiveness. Most of our knowledge about the effects of GCRs is limited to

[11] *Kowalska A. et al.* // Radiat. Environ. Biophys. 2023. V. 62. P. 151–160.
[12] *Khvostunov I. et al.* // Int. J. Mol. Sci. 2023. V.24, No. 6. P. 5128.

ground-based experiments at particle accelerators. From this perspective, JINR's basic facilities offer extensive opportunities for modeling the biological effects of cosmic radiation on highly organized living organisms.

LRB's specialists were the first to propose and substantiate a new concept of radiation risk for manned interplanetary flights, linking the radiation risk for astronauts to the effects of GCR heavy nuclei on the central nervous system[13]. Such effects during flight can lead to changes in the higher integrative functions of the brain and impair the crew's operator performance. This new paradigm defines new research areas in the field of space radiobiology and indicates the need to develop new regulatory documents to ensure radiation safety during manned deep space flights.

In conjunction with the developed concept, radiation physiological studies were conducted to determine the relationship between morphological and functional changes in the retina and various brain regions of rodents. High retinal radioresistance was identified based on criteria for morphological and functional impairments in the postradiation period.

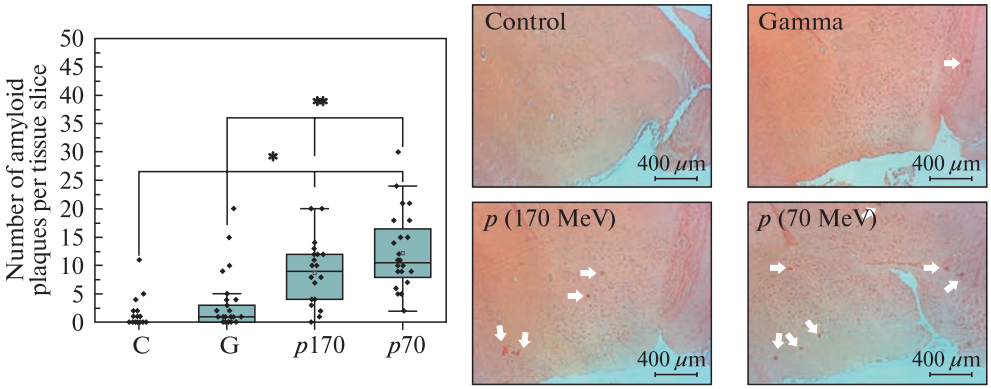


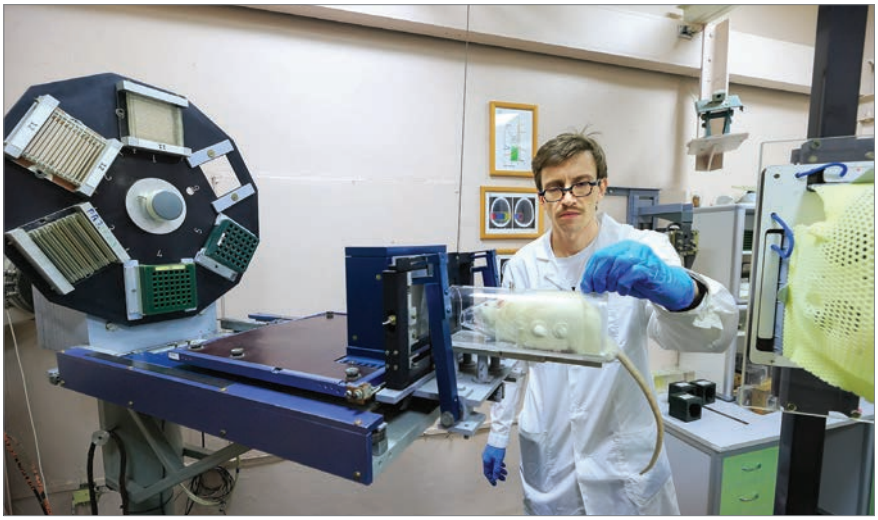
Fig. 8. Amyloid plaques in the forebrain of rats 30 days after irradiation (marked with white arrows on the sections). C — control group; G — ^{60}Co γ rays; p170, p70 — protons with energies of 170 and 70 MeV

Behavioral disorders in irradiated animals in the postradiation period were studied using various test systems. Quantitative patterns of development of morphofunctional disorders in various brain regions exposed to protons and accelerated carbon ions were investigated. A correlation analysis of behavioral responses and morphological changes in various brain regions of rats after exposure to gamma radiation and accelerated charged particles of multiple energies was performed for the first time[14,15]. Changes in stereotypy, exploratory activity, and motivation of animals were studied during total body irradiation and localized head irradiation.

[13] *Grigoriev A. I., Krasavin E. A., Ostrovsky M. A.* // Herald Russ. Acad. Sci. 2017. V. 87, No. 1. P. 65–69.

[14] *Severyukhin Yu. S. et al.* // Cell. Mol. Neurobiol. 2023. V. 43, No. 1. P. 339–353.

[15] *Kolesnikova I. A. et al.* // Cell. Mol. Neurobiol. 2023. V. 43, No. 7. P. 3723–3741.



Conducting an experiment with animals on the DLNP medical proton beam. Yu. S. Severyukhin

The development of amyloidosis in the forebrain of rats and dystrophic changes in the cortex, hippocampus, and cerebellum was observed in irradiated animals over a period of 1 to 3 months. A computer-aided morphometric analysis of brain neurons was made, demonstrating the presence of brain regions with greater radiosensitivity. Pathomorphological changes and a reduction in the cell population of the ependymal cells of the brain after exposure to Bragg peak protons were identified for the first time.

The effects of high-energy carbon ions (500 MeV/nucleon) on the metabolism of key neurotransmitters in the rodent brain were studied together with specialists from the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences (RAS) and the Institute of Biomedical Problems of RAS. The areas of the brain most sensitive to irradiation were identified, in which metabolism changed in the early and late stages after radiation exposure[16].

In collaboration with the Institute of Biomedical Problems of RAS, the Institute of Primatology of RAS, and the Institute of Higher Nervous Activity and Neurophysiology of RAS, pioneering experiments were conducted and data obtained on the effects of high-energy protons and accelerated carbon ions on the cognitive functions of monkeys and the levels of monoamines and their metabolites in peripheral blood. It was shown that irradiation of the monkeys' heads with protons at a dose of 3 Gy does not cause significant changes in their cognitive functions. However, a significant decrease in cognitive functions and serotonin metabolite concentrations in the blood of monkeys[17] was observed after exposure to carbon ions at a dose of 1 Gy.

[16] *Belov O. et al.* // Eur. J. Med. Phys. 2016. V. 32, No. 9. P. 1088–1094.
[17] *Belyaeva A. G. et al.* // Neurochemistry. 2017. V. 34, No. 1. P. 1–9.

Subsequent studies revealed delayed neurological, biochemical, cytogenetic, and hematological disorders in *Macaca mulatta* monkeys that persisted for more than 5 years after localized head irradiation with 2.58 GeV/nucleon ^{78}Kr ions. The irradiated animals, characterized by marked deviations from standard behavior, exhibited lower ratios of lymphocytes, thrombocytes, neutrophils, and monocytes, altered liver function tests, and higher levels of chromosomal aberrations[18].

MEDICAL RADIOBIOLOGY

The main research area in this field is studying the properties of radiomodifying agents to identify new compounds capable of increasing tumor radiosensitivity (radiosensitizers), as well as compounds that can protect normal tissues during radiotherapy (radioprotectors). LRB's Medical Radiobiology Sector utilizes methods for screening various medicines for their toxicity and radiomodifying effects in cell culture, *in vivo* models of transplantable tumors to study the pharmacological and radiobiological properties of potential radiosensitizers, and analytical methods using liquid chromatography to study the pharmacokinetics and pharmacodynamics of the compounds being studied.

The elaboration of a new approach to enhancing the biological effectiveness of medical proton beams, developed at LRB, was continued through preclinical studies in small laboratory animal models[19,20]. Specialists from LRB and the Tsyb MRRC investigated the patterns and molecular and cellular mechanisms of the combined effects of AraC and proton radiation at a focal dose of 10 Gy on the growth of B16 melanoma cells and a number of processes associated with the tumor's radiation response *in vivo*. Control, non-irradiated animals died on the 30th day due to tumor development. The average tumor volume with the combined treatment, compared with proton irradiation without a modifier, decreased 1.7–3.4 times at different observation times ($p < 0.05$). It was shown at the molecular level that the number of DNA DSBs in tumor cells 2 days after completion of irradiation sessions significantly exceeded the level of DNA DSBs observed during radiation exposure without a modifier. The proportion of cancer stem cells (CSCs) in the animal groups was determined. It was found that 9 days after proton irradiation the proportion of CSCs remained at the control level, but with combined exposure it decreased 3.1 times compared to proton irradiation alone.

Simulation of fractionated therapy with five weekly proton irradiations with a total focal dose of 50 Gy in the presence of AraC resulted in more pronounced growth inhibition of B16 melanoma than irradiation in the same regimen without AraC. Thirteen percent of animals of the combined treatment group showed regression of the primary melanoma lesion, and prolonged survival was observed until the end of the observation period.

A series of experiments demonstrated that administration of AraC enhances the antitumor effect of proton radiation through several mechanisms, including a

[18] *Koshlan N. A. et al.* // Aerosp. Environ. Med. 2024. No. 2. P. 105–112.
[19] *Boreyko A. V. et al.* // Part. Nucl., Lett. 2023. V. 20, No. 4. P. 698–708.
[20] *Zamulaeva I. A. et al.* // Phys. Part. Nucl. Lett. 2023. V. 20, No. 1. P. 63–75.

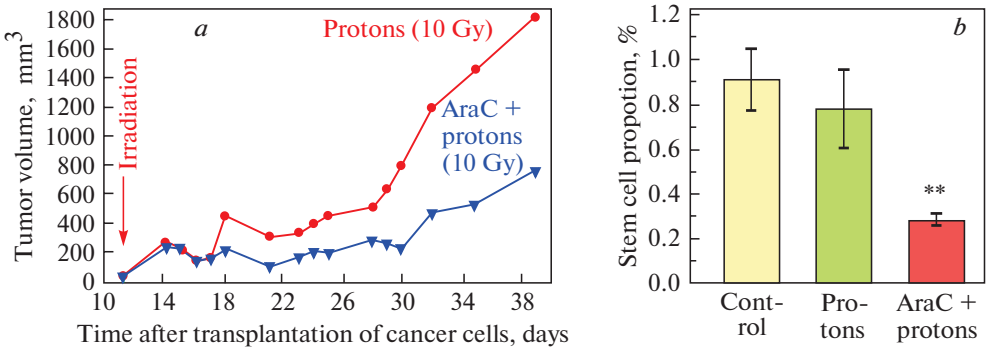


Fig. 9. a) Inhibition of B16 melanoma tumor growth in mice after proton irradiation and combined exposure to AraC and protons at a dose of 10 Gy; b) the proportion of cancer stem cells in the primary lesion of B16 melanoma 9 days after proton irradiation and combined exposure to AraC and protons

reduction in the number of CSCs, inhibition of cell proliferation and angiogenesis in the tumor, and altered immune response in the primary lesion and its infiltration by lymphocytes. Several patents were issued based on these studies[21,22].

A number of nootropic medicines were tested to study the modification of impairments to higher integrative functions of the central nervous system by pharmacochemical protection following total body irradiation with 170 MeV protons. Behavioral testing revealed that Cerebrolysin significantly restored motor activity and had a positive effect on working memory in irradiated animals. Semax was found to normalize the emotional impact index on the seventh day after exposure to accelerated protons. The level of recovery of skeletal muscle strength in exposed animals was determined before control measurements. The morphological pattern in the sensorimotor cortex of the irradiated animals that received Semax was close to normal.

MATHEMATICAL MODELING

The research in LRB's Mathematical Modeling Sector is focused on the creation of a hierarchy of models that systematize experimental data and study the pathways by which radiation-induced pathologies develop at different levels of organization (from molecules to cell populations) and over time (acute and long-term effects). The research utilizes a wide range of computational methods from various fields of knowledge (modeling the transport of charged particles through matter, molecular dynamics, polymer biophysics, genetic regulatory networks,

[21] A Method for Increasing the Efficiency of Ionizing Radiation on Melanoma / Zamulaeva I. A., Boreyko A. V., Bugay A. N., Kaprin A. D., Koryakin S. N., Krasavin E. A., Matchuk O. N., Mosina V. A., Selivanova E. I., Chausov V. N. RF Patent 2774032. Publ. 14.06.2022. Bull. No. 17.

[22] A Method for Increasing the Effectiveness of Proton Therapy on Melanoma Stem Cells / Matchuk O. N., Boreyko A. V., Bugay A. N., Zamulaeva I. A., Kaprin A. D., Koryakin S. N., Krasavin E. A., Mosina V. A., Selivanova E. I., Solovyov A. N., Chausov V. N., Yakimova A. O. RF Patent 2798733. Publ. 23.06.2023. Bull. No. 18.

models of cell population dynamics, and processing and transmission of information in neural networks), as well as computational resources, including the JINR supercomputer.

The sector staff have proposed a novel modeling method for microdosimetric calculations of radiation damage in neurons and their subcellular structures exposed to accelerated charged particles with different physical characteristics[23,24]. A radiation transfer model was implemented for the first time using detailed geometric models of nerve cells to study the damaging effects of accelerated charged particles on the central nervous system structures. It was demonstrated that the developed neuron models can be used not only for dosimetric analysis but also for studying the electrical activity of neural networks. The developed algorithms were implemented as the NEURON application, which is included in the GEANT4-DNA software package. It was found that most of the absorbed dose and radiolysis products in a nerve cell are localized in dendrites and depend strongly on cell geometry and particle type. An original biophysical model was developed that allows for calculating the probabilities of impact and induction of possible radiation damage in nerve cells. New calculated data on DNA damage induction in nerve cell nuclei were obtained, taking into account the direct and indirect effects of radiation when exposed to accelerated charged particles over a wide range of LET values. It was established that after accelerated heavy ion exposure, most of DNA strand breaks occur due to direct interaction with the particle, and more than 80% of DNA DSBs are found in clusters containing base damage. Calculations showed that the largest number of damaged neurons occurs in the granular zone when the hippocampus is irradiated with accelerated charged particles. The survival rate of radiosensitive cells in the subgranular zone of the hippocampus was calculated after irradiation with protons and carbon and iron ions with physical characteristics similar to the spectrum of galactic cosmic rays. Agreement was found between the experimental data and the results of modeling radiation-induced DNA damage and the survival of neural stem cells.

A series of works were carried out on the development of theoretical models for the generalization and formalization of large amount of experimental data on radiobiological experiments with bacterial, mammalian and human cell cultures[25,26]. A detailed mathematical model of the radiation-induced mutagenesis in *E. coli* bacterial cells was built. The influence of defects in various genes controlling damage repair and the level of mutagenesis was analyzed. A mathematical model was developed that describes the main mechanisms of DNA DSB repair under exposure to ionizing radiation of varying quality. The proposed computational approach allows for reproduction of the kinetics of the formation and elimination of γH2AX foci, the level of which correlates with the number of DNA DSBs in the cell. The constructed model captures the key temporal characteristics of DSB repair following irradiation across a wide range of LET values, from ^{137}Cs γ rays to ^{56}Fe ions.

[23] *Batmunkh M. et al.* // J. Radiat. Res. Appl. Sci. 2015. V. 8. P. 498–507.
[24] *Batmunkh M. et al.* // Phys. Med. 2019. V. 57. P. 88–94.
[25] *Bugay A. N. et al.* // J. Theor. Biol. 2015. V. 364. P. 7–20.
[26] *Belov O. V. et al.* // J. Theor. Biol. 2015. V. 366. P. 115–130.

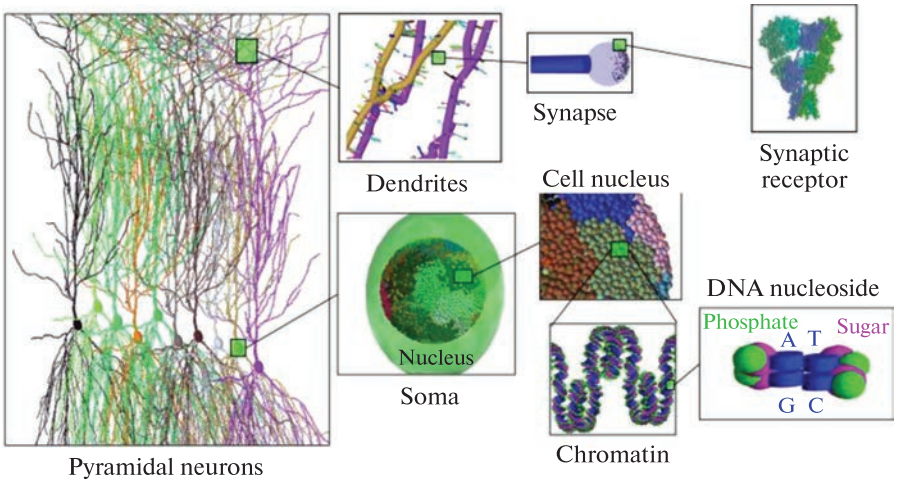


Fig. 10. An example of a model hierarchy for studying brain damage in rats. Elements of the pyramidal neuron layer and key targets at the cellular level are shown

It was shown that the model can be applied to describe the kinetics of DNA DSB repair in cells containing defects in the repair system. The developed models are consistent with a large volume of experimental data.

A novel approach was developed using molecular dynamics methods to predict structural and functional damage in mutant protein structures. The obtained data were used to model the activity of brain neural networks, and the potential impact of radiation exposure on their functioning was analyzed. A mathematical model of the CA3 region of the hippocampus was constructed using the NEURON software environment. This model was used to calculate the occurrence of synchronous oscillations that contribute to the formation of γ- and θ-rhythms, which

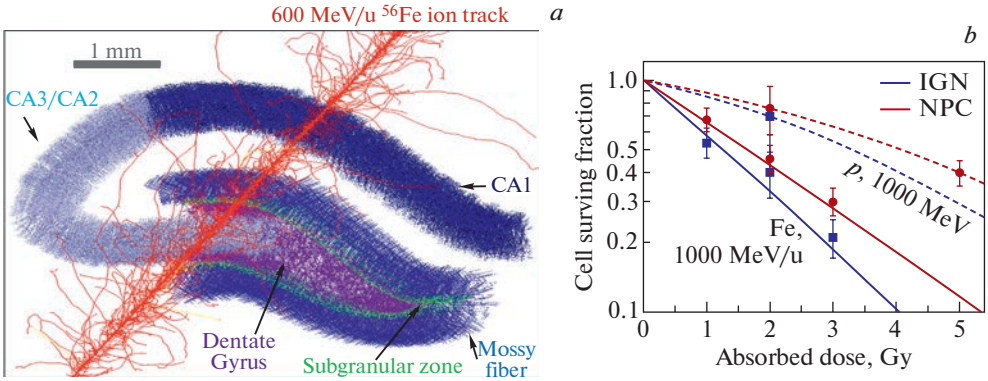


Fig. 11. a) Monte Carlo simulation of the structure of a 600 MeV/nucleon ^{56}Fe ion track in a three-dimensional model of the rat hippocampus; b) calculation of the survival of neural progenitor cells (NPCs, red lines, • — experiment) and immature granular neurons (IGNs, blue lines, ■ — experiment) when irradiated with protons (dashed lines) and iron ions (solid lines) with an energy of 1 GeV/nucleon

play an important role in memory and learning mechanisms. Taking the ionotropic glutamate receptor NMDA, which plays a key role in the regulation of synaptic plasticity, learning, and the formation of various types of memory as an example, molecular dynamics simulation of the activation process of the full-atom structure of the NMDA receptor was performed using the NAMD package. The effects of single and double point mutations, as well as a structural mutation (deletion), on the structure of the ion channel and the functioning of the neural network as a whole were examined. The macroscopic effect of a specific type of mutation can be assessed by the nature of neural network activity and the corresponding electroencephalogram. As a result, an approach was developed to establish the association between certain types of gene mutations and neurodegenerative diseases, such as various types of epilepsy and autism, and diagnostic methods were proposed using EEG signal analysis[27].

RADIATION RESEARCH AT JINR'S BASIC FACILITIES

Radiation research covers a wide range of topics, from radiation biology and space medicine to radiation protection of accelerator complexes. Unique experiments are conducted at JINR's basic facilities, including the Nuclotron and U-400M, to study the effects of ionizing radiation on biological objects under conditions simulating deep space. Specialized facilities are being developed, such as the mixed radiation simulator for space radiobiology at the NICA complex. Monte Carlo programs for calculating radiation fields are actively used, and new instruments for neutron dosimetry are being developed. The LRB staff manage the operation of the multifunctional SARRP (Small Animal Radiation Research Platform) complex for medical radiobiology research, as well as the compact CellRad X-ray irradiator for cell culture exposure.

A number of major upgrades were completed in collaboration with the FLNR staff to the Genom facility for automated irradiation of biological samples at the U-400M cyclotron[28]. The Genom-M version (2013) features an improved beam diagnostics system and updated software and hardware for process automation. The current Genom-3 version (2025) features a complete replacement of the vacuum equipment at the beam exit, a biological sample changer, a window for beam extraction into the atmosphere, devices for measuring the transverse beam density distribution, radiation dose, and beam position control, as well as the dosimeter calibration.

The LRB staff, together with a VBLHEP team, actively participated in the development of a method for irradiating the brains of rodents and primates using extracted beams from the Nuclotron[29]. This paved the way for LRB's pioneering monkey irradiation experiments and the subsequent development of the ARIADNA applied research beamlines at the NICA complex, especially the SIMBO station. The LRB team also played an active role in calculating the radiation environment

[27] *Batova A. S. et al.* // J. Bioinform. Comput. Biol. 2019. V. 17, No. 1. P. 1940003.
[28] *Bezbakh A. A. et al.* // Part. Nucl., Lett. 2013. V. 10, No. 2(179). P. 274–280.
[29] *Baldin A. A. et al.* // Part. Nucl., Lett. 2019. V. 16, No. 4(223). P.302–309.



From left to right: N. V. Lomakin, E. E. Pavlik, I. S. Gordeev, and D. V. Davydov at LRB's basic facility SARRP



Changing the disk with samples at the Genom-M facility, U-400M accelerator, FLNR. Yu. G. Teterev (left) and G. N. Timoshenko

and personnel safety at various NICA facilities, including the collider and applied research beamlines[30]. Systems for neutron dosimetry and spectrometry are being developed together with the Radiation Safety Department.

A monograph by G. N. Timoshenko was published, examining the main issues related to the formation of ionizing radiation fields in high-energy proton and heavy ion accelerators, the activation of equipment, coolants, air, and shielding, and the development of radiation monitoring equipment[31].

A series of studies aimed at assessing the radiation risk to astronauts during long-term interplanetary flights was completed[32]. Detailed calculations of the spectra of all components of the radiation field inside the spacecraft's habitation module from galactic cosmic rays were performed for minimum and maximum solar activity. The calculations were verified using the only available experimental data from the RAD and Liulin-MO instruments and demonstrated good agreement with the experiment. Adjusted fluence-to-effective dose conversion coefficients were calculated for all components of the radiation field inside the spacecraft.

A test bench was created in collaboration with FLNP and the Space Research Institute of the Russian Academy of Sciences for testing nuclear planetary science instruments on planetary soil models. These instruments are designed to analyze the elemental composition of extraterrestrial soil. The search for free and bound water in the near-surface regolith layers of Mars and the Moon is central to studies in this field. LRB staff participated in the development of several instruments used to confirm the presence of water ice on Mars and the Moon, the DAN instrument mounted on the Curiosity rover, and several other instruments for future Roscos-

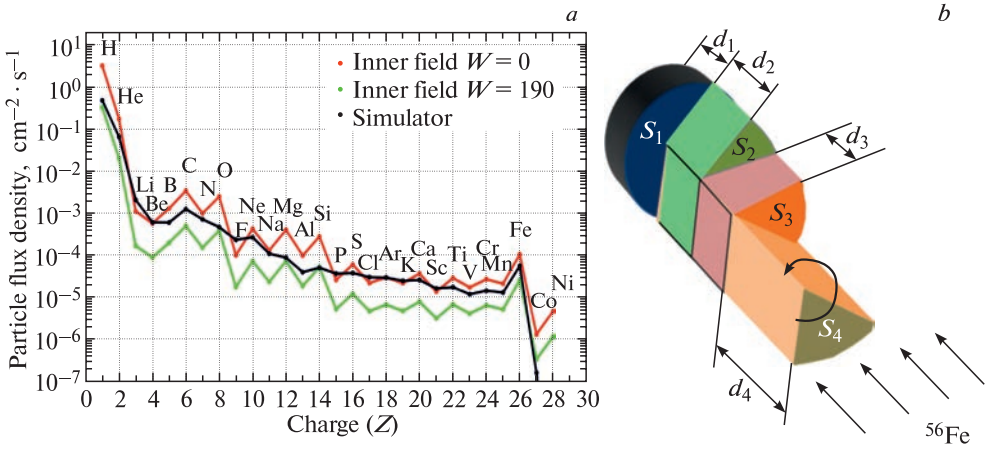


Fig. 12. a) Comparison of the calculated charge distributions of particles in the internal radiation field of the spacecraft at minimum and maximum solar activity and the calculated charge distribution of particles in the field behind the simulator; b) schematic view of the simulator converter

[30] *Butenko A. V. et al.* // Phys. Part. Nucl. Lett. 2022. V. 19, No. 2. P. 123–128.

[31] *Timoshenko G. N.* Radiation Protection of High-Energy Accelerators. Dubna: JINR, 2022. 111 p.

[32] *Timoshenko G. N., Gordeev I. S.* // J. Astrophys. Astron. 2020. V. 41. P. 5.

mos, NASA, and ESA missions. The bench was used for extensive testing of the DAN, MGNS, ADRON-LR, ADRON-RM, and FREND instruments.

A unique simulator of the radiation field inside a spacecraft's habitation module under deep space conditions was proposed to develop experimental methods for assessing the radiation risk of spaceflights in ground-based environment[33]. The developed simulator accurately reproduces all components of the spacecraft's radiation field, averaged over solar activity. The cosmic radiation simulator can be installed on a 1 GeV/nucleon beam of ^{56}Fe nuclei at the Nuclotron's radiobiology channel, which is being developed as part of the applied innovative research program at the NICA complex. A patent was granted for the invention[34]. Based on the results of this series of studies, the team was awarded the JINR First Prize for applied scientific and technical work in 2021.

ASTROBIOLOGY

Astrobiological research aims to acquire new insights, or refine existing ones, regarding the origin of life, the occurrence of life across the Universe, the survival limits of organisms, and the likely conditions for their transfer through space.

LRB's Astrobiology Sector searches for and analyzes microfossil remains in meteoritic material. Research is also conducted to model possible pathways and conditions for abiogenic prebiotic synthesis, and the interactions of biotic com-

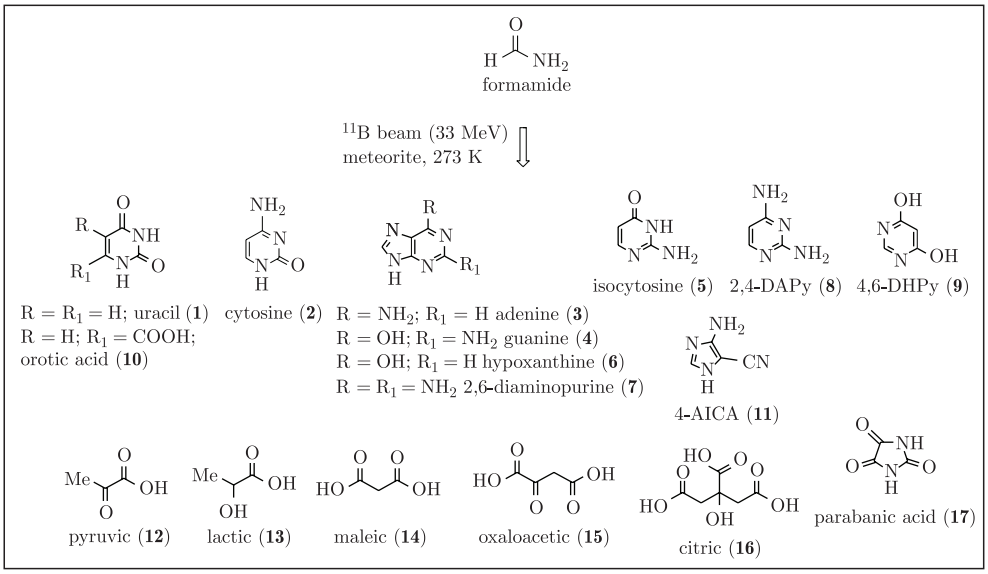


Fig. 13. Compounds formed from formamide after irradiation with ^{11}B ions in the presence of meteorite matter

[33] *Gordeev I. S., Timoshenko G. N.* // Life Sci. Space Res. 2021. V. 30. P. 66–71.

[34] Device for Modeling Mixed Radiation Fields Using High-Energy Heavy Ion Beams for Experimental Radiobiology Purposes / Timoshenko G. N. (RF), Gordeev I. S. (RF). RF Patent 2761376. Publ. 07.12.2021. Bull. No. 34.

pound precursors with various types of geological rocks are studied. These studies expand current understanding of the early Earth's biosphere and suggest the possibility of life originating beyond Earth.

In pioneering experiments, conducted by LRB JINR together with colleagues from Italy, on irradiation of aqueous solutions of formamide with protons and accelerated ions in the presence of meteorites as catalysts, the abiogenic synthesis of a large number of prebiotic compounds — amino acids, carboxylic acids, sugars, nucleic bases, and even nucleosides — was observed for the first time[35]. These compounds had not previously been detected in experiments with other types of radiation. Subsequent experiments pointed to a new mechanism facilitating the formation and processing of insoluble organic matter in meteorites and during prebiotic processes[36].

A series of studies of fossilized microorganisms (microfossils) in over 30 meteorites were conducted using scanning electron microscopy and energy-dispersive X-ray microanalysis. Forms interpreted as the remains of bacteria and single-celled eukaryotes were discovered. The world's first illustrated atlas of microfossils in the Orgueil meteorite was published[37].

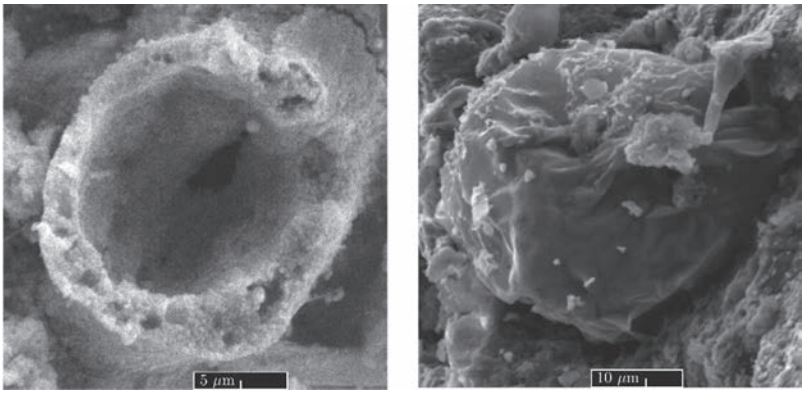


Fig. 14. Images of fossilized microorganisms from the Orgueil meteorite

The monograph "Astrobiology" was published[38]. This work is the first attempt to summarize the accumulated knowledge in astrobiology. Experts from various scientific organizations and fields contributed to its preparation. The book presents the history of the development of views on the origin of life, the stages in the development of astrobiology as a science, describes the facts and models on which these worldviews are based, and outlines a range of unresolved questions and promising research areas.

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[35] *Saladino R. et al.* // PNAS. 2015. V. 112, No. 21. P. E2746–E2755.

[36] *Bizzarri B. M. et al.* // RSC Adv. 2021. V. 11, No. 31. P. 19258–19264.

[37] The Orgueil Meteorite (Atlas of Microfossils) / Ed. A. Yu. Rozanov. Moscow: PIN RAS, 2020. 130 p.

[38] Astrobiology / Eds. A. Yu. Rozanov, E. A. Saprykin. Dubna: JINR, 2024. 199 p.

SPECIALIST TRAINING; COLLABORATION AND CONFERENCES

The LRB staff has been actively working on the training of specialists in the fields of radiobiology, health physics, and dosimetry for more than 30 years. The first steps in organizing the JINR University Centre included establishing the Department of Radiobiology as a branch of the MEPhI department and opening postgraduate courses in radiobiology. In 1998, the first JINR-affiliated department, the Department of Biophysics, was opened at Dubna University, headed by Professor E. A. Krasavin. Since then, more than 200 specialists in radiobiology have been trained, many of whom work at JINR. Plans are underway to open a department at the Dubna branch of Moscow State University, which will train specialists in radiochemistry and radiobiology.



Graduates of the Department of Biophysics of Dubna University with E. A. Krasavin, Head of the Department (in the center). 2010

As of 2025, the Laboratory of Radiation Biology actively collaborates with more than 50 research centers and universities from 16 countries. Projects are being implemented under collaboration programs with Belarus, Bulgaria, Egypt, Serbia, South Africa, and Vietnam. The Laboratory employs staff from Russia, Belarus, Cuba, Egypt, India, Kazakhstan, Mongolia, Uzbekistan, and Vietnam.

In 2019, LRB joined an international biophysical collaboration, bringing together scientists conducting radiobiological, biophysical, and medical research at world-class facilities such as NICA, FAIR, RAON, ELIMED, FRIB, among others.



Practical training in radiobiology under the guidance of E. A. Nasonova (second from right) at the SAINTS Summer Student School at iThemba LABS. South Africa, 2025



Meeting of the International Biophysical Collaboration. GSI/FAIR, Darmstadt, 2019

In 2021, LRB, as part of JINR, joined the ARIADNA collaboration, which brings together researchers working on the applied channels of the NICA complex. The LRB radiobiologists also participate in the FLAP collaboration, conducting research at the Linac-200 facility at DLNP. The LRB researchers are active members of the GEANT4-DNA collaboration, developing tools for Monte Carlo radiobiological modeling. The LRB scientists have represented the Institute at the IAEA and IUPAP at various times.

For many years, Dubna hosted meetings of the Scientific Council on Radiobiology of the Russian Academy of Sciences, chaired by E. A. Krasavin. The annual



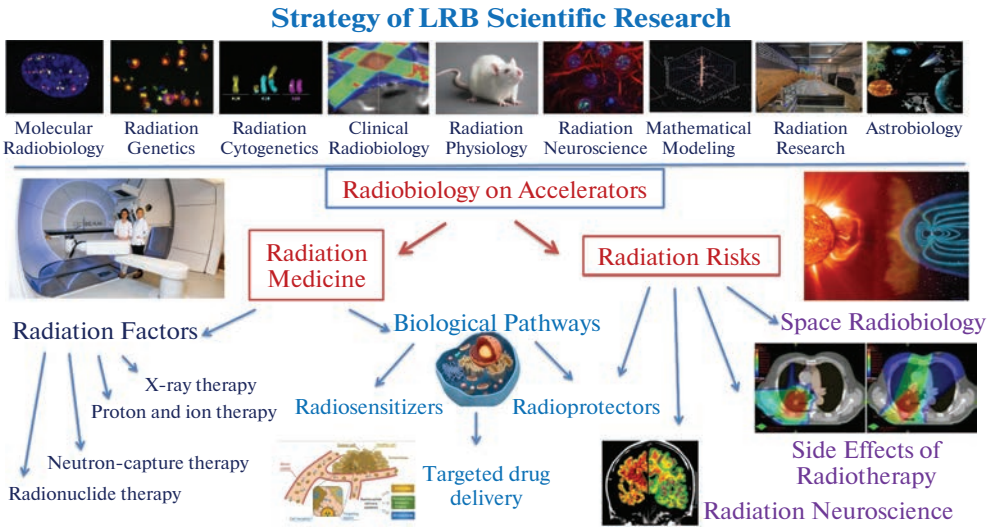
International conference "Modern trends in radiobiology and astrobiology. Molecular, genetic, cellular, and tissue effects, their modification, and late effects". 2015



NUMAR-2025 international school. Cuba, 2025

international conference "Current Issues in Radiobiology" is held under the auspices of the Council, bringing together leading radiobiologists from around the world.

The International School on Nuclear Methods and Applied Research in Environmental, Material and Life Sciences (NUMAR) was established at the initiative of LRB Director A. N. Bugay and is held in JINR Member States, including Cuba, Mongolia, and South Africa.



Today, the Laboratory of Radiation Biology feels confident about the future. It has become a magnet for young and mature scientists from various countries, representing international collaborations. New horizons lie ahead, as radiobiologists seek solutions to fundamental problems, such as establishing integrative relationships between radiation-induced effects at various levels of biological organization — molecular, cellular, tissue, and organismal — after exposure to radiation with different characteristics, as well as identifying the mechanisms of effects of radiation on the higher integrative functions of the central nervous system and the development of neurodegenerative diseases. Particular attention will also be paid to practical applications — the development of new methods for increasing the effectiveness of radiation and radionuclide therapy for malignant tumors, radiation risk assessments for various crewed spaceflight scenarios, and for work in mixed radiation fields.

APPLIED RESEARCH AND DEVELOPMENT

One of JINR's priority tasks beyond its main scientific agenda is to maximize the potential for the economic and social application of the Institute's results in its Member States. When discussing JINR technologies, promising applied results, and innovations emerging at the Institute, it's worth noting several distinct, although closely intertwined, tracks through which they emerge and mature.

First and foremost, the emergence of innovation at JINR is linked to the technological level of its scientific infrastructure, large unique facilities developed and modernized both within the Institute itself and with the participation of its specialists in other global centers. JINR's accelerator complexes, detector systems, information infrastructure, research reactor and its extracted beamline facilities, and other major research infrastructures are all examples of the development and implementation of cutting-edge innovative technologies by the Institute's specialists and their partners from research centers and leading global technology companies. JINR's facilities are always both challenges for their creators, who develop and manufacture systems that are often unique, and a display of the most striking innovations that have emerged in response to these challenges. The solutions implemented in these facilities become the objects of effective technology and knowledge transfer for the benefit of other research centers, industrial partners, medicine, and other sectors, including cryogenic technology, magnetic systems, various types of accelerators, ion sources, beam diagnostic systems, detectors, sample environment systems, modern neutron guides and other extracted beam equipment, various types of neutron scattering spectrometers, vacuum and high-voltage systems, and information and computing systems.

A striking example of JINR's innovative technologies is the results of the work of a team of VBLHEP specialists and the Magnet Factory created by them under the leadership of G. V. Trubnikov and H. G. Khodzhibagiyan. Even a single facility like NICA uses 493 different types of magnets. The NICA collider magnets are cooled by a flow of boiling helium at a temperature of 4.6 K. The operating temperature of the energy storage system made of high-temperature cuprate superconducting material is approximately 30 K (the boiling point of neon), and the temperature of the magnets at the

new Nuclotron will be 50–70 K. For the first time in the world, JINR developed the design and manufacturing technology for a unique cable, enabling the manufacture of windings with a bending radius of 40 mm and a current of tens of thousands of amperes. The critical current of HTS tapes was increased up to three times in magnetic fields at a temperature of 50–80 K due to the creation of pinning centers through irradiating the tapes with protons and ions. A design was developed for connecting the ends of HTS cables with a transition resistance of only a few nanoohms at a current of 10–15 kA and a temperature of 30–65 K. An epoxy compound composition was selected that ensures long-term stability and optimal cooling conditions for the winding, etc.

HTS magnets for accelerators are planned for use in the modernization of the Nuclotron magnetic system and in future cyclotrons for cancer therapy. A powerful energy storage device based on an HTS magnet will find application not only in high-energy physics, but also in current and future vehicles, renewable energy facilities, and other areas.

The contribution of the JINR scientific team to the implementation of breakthrough technologies that opened the possibility of developing high-temperature superconducting magnets for charged particle accelerators and megawatt energy storage devices was highly appreciated by the Scientific Committee of the Vyzov Prize for Future Technologies, the winner of which in the nomination “Engineering Solution” was H. G. Khodzhibagiyan (co-authors: G. V. Trubnikov, M. S. Novikov).

The second track includes examples of the Institute’s targeted solutions to major scientific, technical, and technological challenges relevant to the economies and social spheres of the Member States, such as the development of track-etched membrane technology for microelectronics and biomedical applications, proton therapy at the DLNP phasotron, the recent history of proton therapy at JINR using a specialized superconducting cyclotron, and the development of infrastructure and methodological support for testing the resistance of electronic components to the effects of heavy-ion cosmic radiation… Many times throughout the history of the Institute, demand for a solution to a problem relevant to society, the willingness of JINR specialists to address it and the appearance of a scientific leader who decided to focus their efforts on it gave rise to a productive applied research project, despite its scope extending beyond the fundamental research agenda. Thus, since the USSR’s first proton beam with parameters suitable for radiation therapy was produced at the synchrocyclotron in 1967, the use of protons in cancer treatment has come a long way at JINR. Hundreds of patients have received therapy, a three-dimensional conformal proton radiation therapy technique has been developed, and

accelerator technology for hadron therapy centers has been perfected in partnership with leading global manufacturers.

Today, the Institute continues this work at a new level. A specialized medical superconducting cyclotron for proton therapy MSC-230 is being developed in partnership with State Atomic Energy Corporation Rosatom. The facility is designed for proton beam therapy and biomedical research, including the development of FLASH therapy, which delivers a therapeutic radiation dose to the tumor at an ultra-high beam dose rate, several orders of magnitude higher than that typically used in standard radiotherapy. This irradiation regimen reduces damage to normal tissues surrounding the tumor and exposed to the radiation, while maintaining virtually the same level of impact on cancer cells, improving the prospects for local tumor control with a lower incidence of side effects.

The MSC-230 will become a key infrastructure component for the joint project with the Federal Medical-Biological Agency of Russia to establish a Scientific and Clinical Center for Proton Therapy and, in the future, a specialized machine ready for mass production.

JINR, as a center for innovative development, is primarily a specialized infrastructure for applied research and a competence center for its use. The development of a user infrastructure segment for applied research and development at JINR facilities has become another area which stimulates innovation. The flagship initiative in this area is the creation of an Innovative Center for Nuclear Physics Research in the fields of life sciences, biomedical technologies, radiation biology and radiation materials science, ecology, and information systems. This center provides researchers and developers with access to new facilities and user infrastructure that offer significant potential for obtaining applied results and developing new technologies, such as:

- ARIADNA — a user infrastructure based on NICA extracted beams (beams with energies from MeV/nucleon to GeV/nucleon): life sciences, biomedical applications, research into the radiation resistance of semiconductor electronics, nuclear physics data for new energy;
- an infrastructure for developments in the field of omics technologies and neuroradiobiology: developments aimed at increasing radiosensitivity, creating transgenic systems, new solutions in the field of targeted delivery (molecular vectors) and the use of radionuclides;
- a complex based on the superconducting proton cyclotron MSC-230 for R&D in the field of beam therapy: the use of radiomodifiers, FLASH therapy, irradiation planning; a pilot facility for medical centers;
- a complex based on the DC-140 cyclotron for testing electronic components, for radiation materials science, for

the development of track-etched membrane technologies and their production;
- a first-class radiochemical laboratory and a specialized accelerator (40 MeV) for R&D in the field of radioisotope production technologies (^{225}Ac, ^{99m}Tc) for nuclear medicine.

This initiative is progressing well. Application work has begun at ARIADNA user stations (detailed information on the project's status is provided below).

The development of a complex based on the DC-140 cyclotron for work in the field of track-etched membrane technologies, radiation materials science, and for testing electronics for radiation resistance is in the final phase.

This project includes two large infrastructure units: a prototyping and characterization laboratory (NanoLab), which is fully equipped and is in intensive use, and a specialized DC-140 accelerator under construction, the launch of which will significantly expand the capabilities of the FLNR cyclotron complex for applied research and innovative development.

Along with the above-mentioned units, the ecosystem of the Innovative Center for Nuclear Physics Research also includes the applied segment of the IBR-2-based user program, which is a bright and dynamically developing success story, and new capabilities being developed on the basis of Linac-200 and other JINR facilities.

Innovations, development and implementation of new technologies always involve working in high-risk environments. Success in this field largely depends on the effective use of systemic government support measures for innovation. JINR has not only devoted and continues to devote significant attention to the analysis of current information on such instruments, but has also actively participated in their development and piloting, as well as in creating the architecture of an innovative economy and innovation financing instruments. JINR organized a mutual investment fund management company, which received the number one license in Russia, and the first interval mutual fund focused on high technology. It was also one of the initiators and participants in the approval process by the Russian Government of the decision to establish the Dubna Special Economic Zone for technology and innovation, which subsequently ensured the training of its first residents, forming part of the Institute's so-called "innovation chain". Other similar examples include winning the first competition for the establishment of nanotechnology centers and the establishment of the International Innovative Nanotechnology Center in partnership with high-tech businesses, as well as the establishment by the Institute, together with scientific and educational organizations of the CIS and with the support of Intergovernmental Foundation for Educational, Scientific and Cultural Cooperation, of the CIS International Innovation Center for Nanotechnology in 2009,

which became the basic scientific and technical organization of the Commonwealth.

Business-oriented projects sometimes require participation of a scientific organization in formats that don't fully align with its fundamental science priorities. Nevertheless, participation in these projects yields significant results for JINR. For example, the Dubna Special Economic Zone and its resident companies are now effective partners of the Institute in the field of innovation. The development of the special economic zone has provided a powerful impetus for developing Dubna and improving its quality of life. Participation in the nanotechnology center project has enabled a new step in the development of the R&D program at FLNR's Center of Applied Physics, as well as the applied research and development infrastructure it has established.

Another track where JINR innovation is born is targeted collaboration with industrial partners and industry-specific research to develop JINR's R&D infrastructure as an open space for creativity and cutting-edge research (Open Research Space @ DUBNA) and for integration between big science and business. This work has resulted in a great variety of business-initiated projects in a wide range of fields, often quite distant from fundamental nuclear and particle physics, where the Institute's expertise, research and development infrastructure, and specific results have proven to be in demand by the real sector. These areas include the use of artificial intelligence in agricultural applications, the development and application of detector systems for cutting-edge medical tomographs, the creation of materials for ophthalmological implantation, water purification technologies, materials for hydrogen energy, equipment for environmental monitoring and climate projects, and other areas.

An important component of JINR's innovative development policy is the search for and implementation of its own systemic measures and tools to stimulate the generation of innovative projects. The origins of innovative projects at the Institute are varied. They often originate within user programs at JINR facilities, when participating teams from applied, industry-specific science initiate experiments that are of interest to representatives of the relevant industry. In some cases, they are inspired by the Institute's partners, who are involved in the construction of its new facilities or who express interest in the Institute's established competencies and R&D infrastructure.

Nevertheless, JINR considers it essential to go beyond these capabilities and seek systemic tools for proactive generation of results that are significant for the economies and social spheres of its Member States. Applied innovation has been included as a separate area in the Institute's Topical Plan. The JINR Advisory Committee on Innovation has been established. A mechanism has been implemented for selecting

proposals for developments in applied and innovative fields with high potential for implementation in industry, scientific instrumentation, and the social sphere. In 2025, this selection, which is planned to be made regular and held at least every two years, received over 30 applications from young development teams, five of which received financial support for up to three years.

Below is more detailed information on some of the research areas being implemented by the Institute's laboratories and on new infrastructure opportunities for innovation development.



APPLIED RESEARCH AT THE NICA COMPLEX

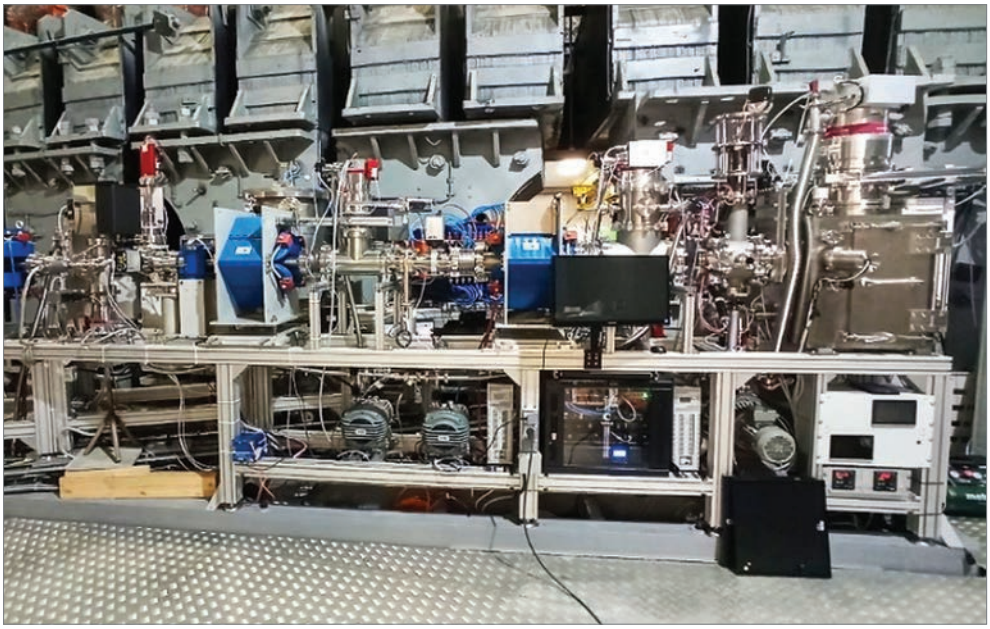
A new milestone in the development of JINR's scientific potential was to create an infrastructure for applied research at the NICA complex. This infrastructure, called ARIADNA (Applied Research Infrastructure for Advanced Developments at NICA fAcility), includes charged particle beam transport channels, magnetic optics, power supplies, beam diagnostics systems, experimental areas with irradiation stations, and support infrastructure, including areas for deploying user equipment, sample preparation, and rapid analysis of samples after exposure. The opportunities of the NICA complex enable applied research in life sciences, radiation materials science, radiation resistance of electronics, and the development of advanced technologies for accelerator-driven subcritical reactor systems.

Applied research areas are an integral part of the NICA project in its concept from the very beginning. Five facilities were made during the development of the ARIADNA infrastructure, designed to address a wide range of tasks: the Station Of CHip Irradiation (SOCHI), the Irradiation Station of Components of Radioelectronic Apparatus (ISCRA), the Station for Investigation of Medical Biological Objects (SIMBO), the station for nuclear power technology research (SHINE), and the long-term irradiation station.

The first facility commissioned within the ARIADNA infrastructure was the station of chip irradiation (SOCHI), designed for research and irradiation of promising semiconductor micro- and nanoelectronics products with low-energy heavy ion beams at the exit from the heavy ion linear accelerator (HILAC).

The equipment for the SOCHI station was developed within a collaboration between JINR and ITEP, with the participation of SPELS/MEPhI, GIRO-PROM, and VST. During the development of the station, detectors for the diagnostics and control system for low-energy ion beams in vacuum were constructed, as well as station components used in testing semiconductor micro- and nanoelectronics products for their resistance to the effects of low-energy heavy charged particles in vacuum. A system to monitor test object parameters, equipment to connect control and measuring instruments to the test object, a vacuum chamber, a positioning system, a temperature setting system, and operator workstations for the control room were developed. Radiation protection calculations were performed for the station's equipment and site.

Table 1 shows the main parameters of the ion beam delivered to the SOCHI station. The diagnostics system consists of the following detectors: an ionization



The SOCHI station and the ion beam transfer line from HILAC

Table 1. Parameters of the ion beam at the SOCHI station

Parameter	Value
Ion types	$^{12}C^{4+}$, $^{40}Ar^{8+}$, $^{131}Xe^{22+}$, $^{84}Kr^{14+}$, $^{169}Tm^{21+}$, $^{197}Au^{31+}$, $^{209}Bi^{35+}$
Ion energy at the exit from HILAC, MeV/nucleon	3.2
Ion flux density, $cm^{-2} \cdot s^{-1}$	10^3–10^5
Maximum irradiation area, mm	∅29
Beam diameter on target, mm	∅73

detector based on microchannel plates, a system for online diagnostics and control of the ion flux density and halo beam fluence (four scintillation detectors), a fast scintillation detector with optical readout, a detector based on the Faraday cup, and a fast phosphor detector with optical readout. Signals from the beam diagnostics detectors are integrated into the general data acquisition system[1,2]. The mounting of the SOCHI applied station was completed in October–November 2021. In December 2021, the first experiment with C^{4+} ion beams was carried out at the station. The ion beams were transported through a new beamline to the applied station,

[1] *Slivin A. et al.* Construction of Stations for Applied Research at the NICA Accelerator Complex // Part. Nucl., Lett. 2022. V. 19, No. 5(244). P. 421–425 (in Russian).

[2] *Slivin A. et al.* Description of the Beam Diagnostics Systems for the SOCIT, SODIT and SODIB Applied Research Stations Based on the NICA Accelerator Complex // Proc. of the 12th Intern. Part. Accel. Conf. (IPAC'21). 2021. P. 946–948.

where they were recorded by the SOCHI detectors. Subsequently, commissioning work continued at the SOCHI station.

The ISCRA station is designed to study and test semiconductor micro- and nanoelectronics products for resistance to long-range heavy charged particles. The ISCRA equipment was also developed as part of the collaboration between JINR and ITEP, with the participation of ENPO SPELS JSC, NRNU MEPhI, and GIRO-PROM LLC. Proposals for the ion beam characteristics at the station's entrance were carefully prepared, taking into account the specifics of research and testing of semiconductor micro- and nanoelectronics products for resistance to high-energy heavy charged particles. The characteristics of the beam extracted to ISCRA allow research and testing of semiconductor micro- and nanoelectronics products over a linear energy loss (LEL) range from 0.1 to 60 MeV·cm^2/mg. Long-range high-energy ion beams will enable irradiation of microchips in Bragg peak mode, eliminating the need to decapsulate the microchips prior to irradiation. Detectors have been developed for the ion beam diagnostics and monitoring system for beam parameter adjustment and for certification, testing, and experimental study of semiconductor micro- and nanoelectronics products for resistance to long-range heavy charged particles. The design and development of the components of the station took into account current requirements for resistance to heavy charged particles, the design features of modern semiconductor micro- and nanoelectronics products, their functional diversity, the capabilities of localized irradiation of individual products, and other factors.

Table 2. Parameters of the ion beam at the ISCRA station

Parameter	Value
Ion types, MeV/nucleon	$^{197}Au^{79+}$, 150–350 $^{131}Xe^{54+}$, 150–367 $^{12}C^{6+}$, 150–392
Ion energy at the exit from HILAC, MeV/nucleon	3.2
Ion flux density, cm$^{-2}\cdot$s^{-1}	10^3–10^5
Maximum irradiation area, mm	∅29
Beam diameter on target, mm	∅73

The diagnostics system of the ISCRA station consists of the following detectors: an ionization chamber, a proportional wire ionization chamber, a miniature gas-filled ionization chamber, a scintillation-fiber detector, a semiconductor detector, and an online particle flux density detector based on four scintillators (or four semiconductor detectors). Absolute measurements of ion flux density can be performed using 0.1 mm thick polymer films installed at specified points.

The SIMBO station has been designed for life science research in order to study the biological effects of ions across a wide range of LET values. Specifically, one of the main tasks to be solved using the developed irradiation station is to simulate in ground conditions the effects of heavy charged particles from galactic and solar



The positioning system (a) and energy attenuator (b) of the ISCRA station; a general view of the station (c)

cosmic rays on laboratory animals. The equipment of the station allows the irradiation of various biological objects, from cell cultures to small laboratory animals and primates. The equipment for the SIMBO station was developed in the collaboration between JINR and VST LLC, with the participation of Ostec Corporate Group. The diagnostics system consists of the following detectors: four ionization chambers, a thin scintillation counter, a diamond detector, and a system based on four scintillation detectors for online diagnostics of the halo-beam particle flux density.

Research into the effects of heavy charged particles on biological objects has recently been intensively pursued due to ambitious long-term interplanetary spaceflight programs. The main sources of radiation exposure to humans in space are ga-

lactic cosmic rays, the Earth's radiation belts, and solar radiation. During periods of high solar activity, the proton flux is 10^8–10^9 cm^{-2}. The dose rate from galactic cosmic rays reaches 1 μGy/min. These rays consist of protons (85%) with energies up to 10^{11} MeV, alpha particles (12%), heavy particles (1%), and electrons (2%). The heavy particles include carbon, nitrogen, and oxygen atoms (0.83%), lithium, beryllium, and bromine atoms (0.23%), and iron atoms (0.05%). The heavy component of galactic cosmic rays consists mainly of nuclei with Z up to 26. The near-Earth radiation belt is represented by 100-MeV protons and 10-MeV electrons.

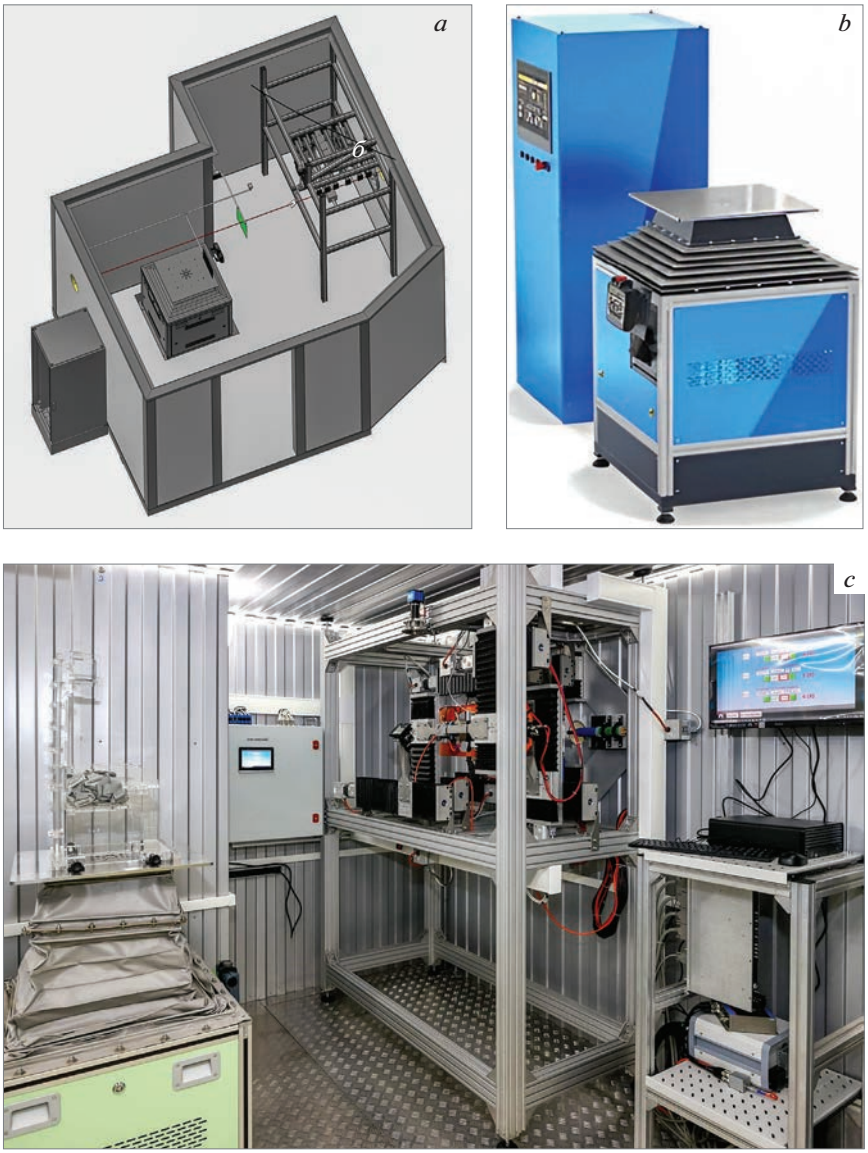


Fig. 1. A 3D model of the SIMBO station (a), a device for positioning objects exposed to the ion beam of the NICA complex (b), and a general view of the station (c)

Table 3. Parameters of the ion beam at the SIMBO station

Parameter	Value
Ion types	$^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{56}Fe^{26+}$, $^{84}Kr^{36+}$
Ion energy at the exit from the Nuclotron, MeV/nucleon	500–1000
Ion flux density, $cm^{-2} \cdot s^{-1}$	10^3–10^6
Radiation dose, Gy	1–3
Irradiation area in the scanning/nonscanning mode, mm	100 × 100/∅ 10

Radiation doses on a space station are approximately two orders of magnitude higher than the human exposure limits under normal conditions on the Earth. During a one-year mission to the International Space Station (ISS), an astronaut can receive a dose exceeding the dose limits for nuclear industry workers (effective dose < 20 mSv/year). During an average "exit" lasting approximately 5 hours under undisturbed conditions, an astronaut receives additional 0.3–0.5 mSv, which is close to the average daily dose inside the station. Cosmonaut landings on the surface of celestial bodies should also be taken into account. For example, cosmic radiation on the surface of the Moon is more severe than on the Mars. The radiation load on the surface of the Mars averages 0.7 mSv/day. This is comparable to an average daily dose on the ISS of 0.3–0.8 mSv/day. It is impossible in the near future to protect the body from the damaging effects of cosmic rays in space using physical protection methods.

Studies are being performed on the effects of various types of radiation on living organisms to assess the effects of cosmic rays on the human body under earth conditions. In the 1960s and 1970s, specialists from various institutes across the country, primarily the Institute of Biomedical Problems (IBMP), carried out extensive experiments on irradiation of laboratory animals, plant specimens, mammalian cells, and human cells with 25–645-MeV protons, generated by the JINR synchrocyclotron (Dubna). The patterns and mechanisms of gene and structural mutation induction under exposure to radiation of broad-spectrum linear energy transfer (LET) were studied in bacterial cells at JINR, and the high mutagenic effectiveness of accelerated charged particles was discovered. Irradiation of mammalian cells with heavy ions also revealed their high mutagenic activity. More recently, studies have been conducted on morphological and functional damage in the retina of experimental animals, disorders in neurotransmitter levels in various brain regions under heavy charged particle irradiation, and behavioral disorders.

Experiments on mice were performed to predict the effects of cosmic radiation on the visual system. The experiments involved irradiation with accelerated ^{15}N ions with LET values of 71 and 160 keV/μm *in vitro* and with ^{60}Co gamma rays for several hours. Individuals of different ages were also irradiated with gamma rays *in vivo* for several weeks. Based on these experiments, conclusions were drawn about the nature and extent of DNA damage.

An interesting result of the effect of ionizing radiation on the central nervous system (CNS) was obtained by a group of Russian scientists in 2019. Rodents were exposed to a combination of heavy charged particles and gamma rays, equivalent in composition and dose to an 860-day interplanetary mission. It has been found that ionizing radiation causes profound remodeling of nervous tissue, but functionally, this has a positive effect on the CNS. In experiments of American scientists who irradiated rats with iron-56 ions for several seconds, it was found that even at the smallest doses, the rats' spatial orientation was completely impaired. To study the effects of ionizing radiation on the human CNS, experiments were conducted on more closely related organisms – primates. At JINR, monkeys were irradiated with high-energy protons and carbon ions. Both positive and negative effects were observed. However, irradiation with heavy ions in monkeys revealed a significant decline in cognitive function. This is a very serious result, which may cast doubt on the possibility of long-distance missions. Researchers irradiated the brains of primates and rats with a beam of 2.58 GeV/nucleon ^{78}Kr nuclei extracted from the Nuclotron. The experiments were performed to simulate the effects of heavy nuclei emitted by galactic cosmic rays on the cognitive functions of astronauts.

Currently, research in this area is being carried out or planned to be done in such major Russian scientific centers as the Joint Institute for Nuclear Research (Dubna), the State Scientific Center of the Russian Federation — Institute of Biomedical Problems of the Russian Academy of Sciences (Moscow), the National Research Center "Kurchatov Institute" (Moscow), and others.

The SIMBO station is compatible with the applied beamline infrastructure in the Measurement Hall of Building 1 at VBLHEP and includes the following main components: an area for experimental physicists to sit during irradiation sessions and a climate chamber for irradiated biological samples. The SIMBO facility itself consists of a beamline to transport and shape the ion beam into the station and a positioning chair to arrange the irradiated samples.

The design and development of ion beam transport channels for applied research and irradiation stations SOCHI, ISCRA, SIMBO were fulfilled by a team led by E. A. Syresin with the active participation of A. A. Slivin, A. V. Agapov, A. A. Baldin, G. A. Filatov, K. Shipulin, A. V. Tuzikov, T. V. Kulevoy, Yu. Titarenko, D. Bobrovsky, A. Chumakov, S. Soloviev, G. N. Timoshenko, A. Kubankin, I. Glebov, P. Chernykh, and V. Luzanov.

On February 15, 2024, the grand opening of two applied research stations at NICA, SIMBO and ISCRA, took place. Members of the JINR Scientific Council attended the opening, visited VBLHEP, and viewed the NICA accelerator complex under construction.

By the end of 2025, the work on the SHINE station, a facility for irradiating heavy targets with relativistic beams of 0.3–4.5 GeV/nucleon protons and light ions at the Nuclotron's slow beam extraction channel, entered the active phase. The team headed by A. A. Baldin has made significant progress in installation works in the SHINE area, preparing design documentation and beam handling equipment. The research planned for the station is a logical continuation of the work done at VBLHEP over the past 30–40 years.



The grand opening of the SIMBO and ISCRA stations for applied research at the NICA complex, which took place during the 135th session of the JINR Scientific Council on February 15, 2024

In 2024–2025, the VBLHEP Department of Scientific and Methodological Research and Innovation, led by O. V. Belov, developed and commissioned a long-term irradiation station within the BM@N facility. A. V. Agapov, V. A. Artiukh,

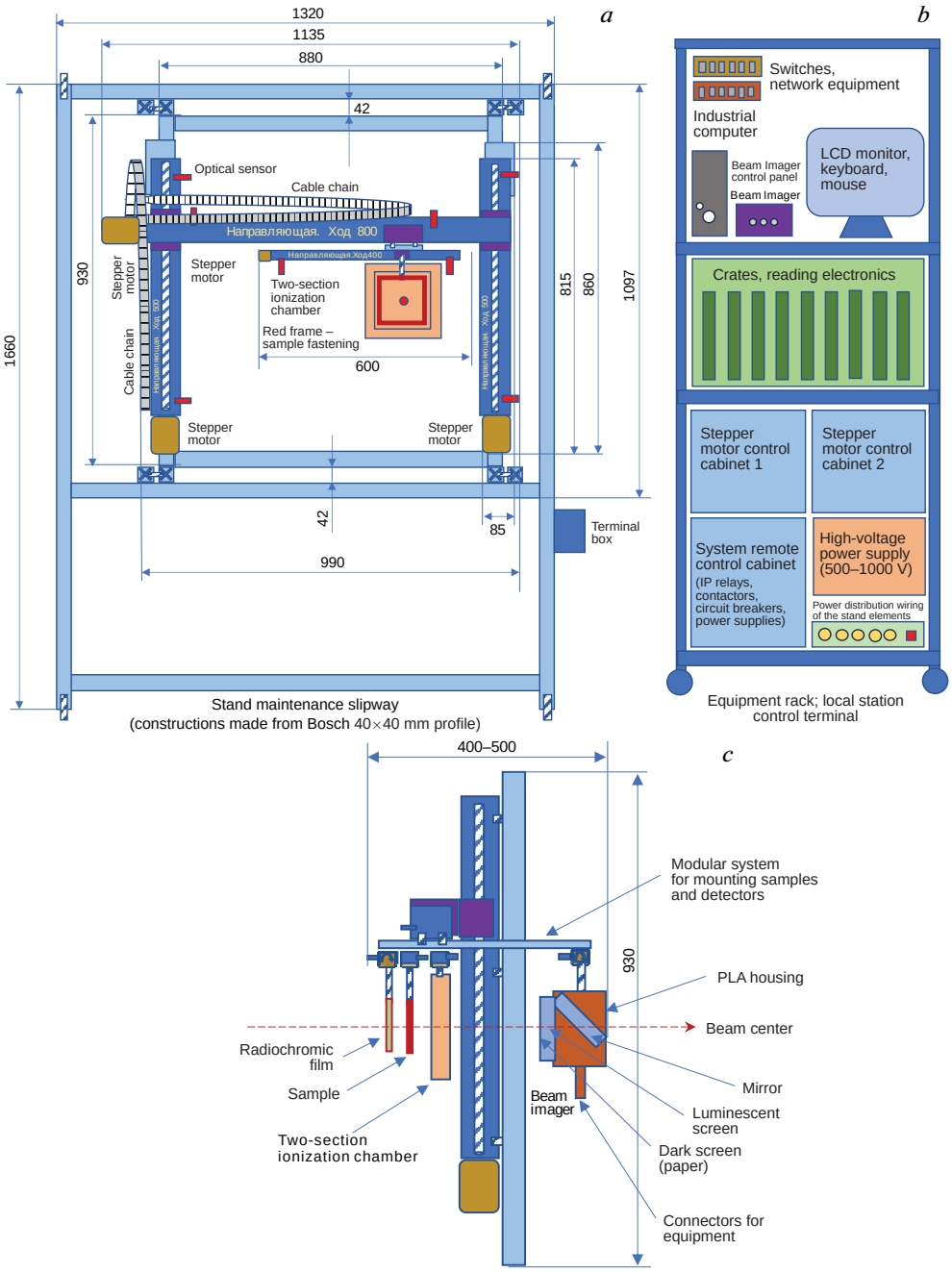


Fig. 2. a–c) Configuration of the ARIADNA long-term irradiation station (working title: Station for Long-Term Exposure, SLTE)

I. A. Kryachko, G. V. Mytsin, and V. N. Shalyapin actively participated in the construction of the station.

The long-term irradiation station allows using the residual ion beam between the forward hadron calorimeter (FHCal) and the trap for applied research[3] and significantly improving the efficiency of the NICA complex beams, substantially increasing the amount of the beam time for the ARIADNA scientific program. The station enables a unique mode of long-term irradiation of samples with high-energy ion beams in the 1–4 GeV/nucleon range for periods of up to several months, which was previously tested on a prototype irradiation facility during a setup session in December 2022 – January 2023.

In the current configuration, the ARIADNA long-term irradiation station includes the following elements (Figs. 2–4): 1) an electromechanical section, represented by systems for linear movement of samples and detectors, two control cabinets with stepper motor controllers, a network interface, and power supplies; 2) a modular system of detector and sample holders that allows for supplementing the station's detector system with new elements; 3) a local control terminal based on an industrial computer; 4) a remote control unit for the station's elements based on a multi-contact IP relay; 5) a video monitoring system for the position of samples and detectors, consisting of four video cameras, two laser modules, and a local lighting system; 6) a Beam Imager optical monitoring system based on a fluorescent screen with a coordinate field and optical signal output via a fiberscope fiber optic channel to a highly sensitive video camera; 7) a two-section ionization chamber; 8) a high-voltage power supply, electronics for reading and converting a signal from a two-section ionization chamber; 9) network equipment to switch station elements into a single subnet; 10) a station operator's workstation in the control room, designed on the basis of two computers, five monitors and peripheral computer equipment; 11) equipment to install and secure the stand at the operating site as part of a lifting device (winch), a bracket with block mechanisms and stand position locks, 12) a slipway for servicing and moving station elements.

The design of the long-term irradiation station was developed to meet the requirements for compact placement within the space allocated for it between the FHCal and the trap. To reduce the weight of the suspended structures, additive technologies (3D printing) with polylactide (PLA) and polyethylene terephthalate (PETG) filaments were extensively used in the development of the station's components.

Between September and November 2025, 38 test cycles of all the station's equipment and devices were performed, and the normal and edge operating modes of the facility's main subsystems were determined. On January 17, 2026, during a run at the NICA complex, the long-term irradiation station underwent its physical startup, and the first measurements of the parameters of the 1.7 GeV/nucleon xenon ion beam delivered to the station were made.

The principal possibility to use the residual beam in parallel operation with the BM@N facility was previously demonstrated in the 4th setup run of the NICA complex, with xenon ion acceleration and beam extraction with energies up to

[3] *Belov O. V.* Long-Term Irradiation Station // JINR News. 2024. No. 2. P. 21–23.

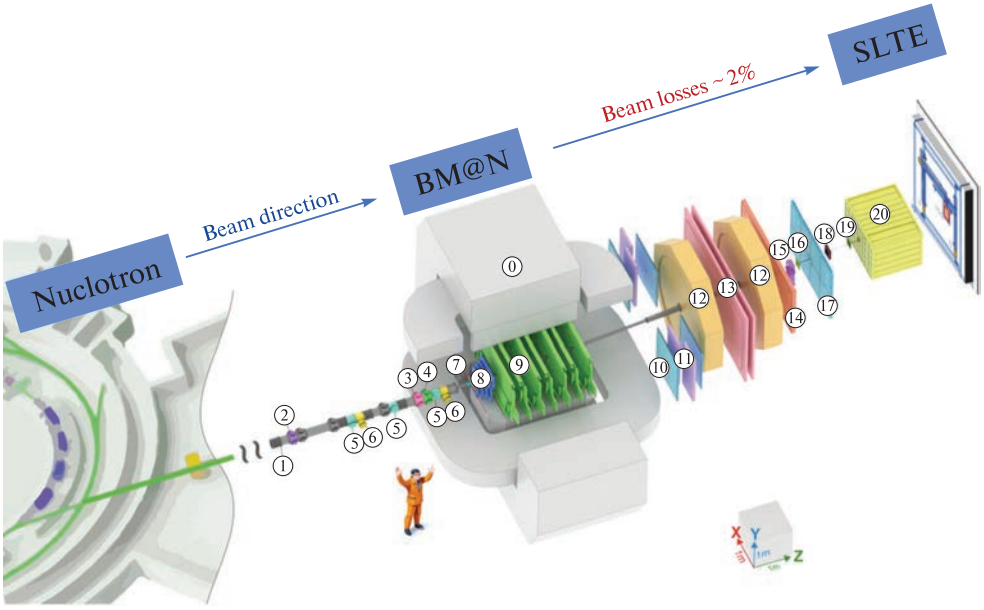


Fig. 3. Location of the SLTE station in the BM@N facility site

3.8 GeV/nucleon. The beam in the target area was elliptical in shape with axes of 3.42 and 2.93 cm; the irradiation area was 7.87 cm^2, with the most uniform field in the central part, over an area of 1.08 cm^2, also elliptical with axes of 1.2 and 0.9 cm (Fig. 5). The residual beam parameters were recorded using an OCTAVIUS 1500XDR PTW detector, used in clinics for precise irradiation planning in radiotherapy sessions, as well as a TM30010-1 calibration ionization chamber and an EBT-3 radiochromic film plate.

Regarding the alignment of the completed work with the latest knowledge in this field, it should be noted that, at the scale of major scientific centers such as CERN, GSI-FAIR, BNL, GANIL, etc., the availability of long-term high-energy ion irradiation for applied research is limited compared to other sources of ionizing radiation, primarily due to the high cost of accelerator complex operation time. In this respect, diverse methods for enabling the operation of applied research stations in parallel with physics facilities designed to solve fundamental problems are of particular importance. Therefore, the development of a long-term high-energy ion beam irradiation station at the NICA complex, operating in parallel with the BM@N facility, should be considered a result comparable to the achievements of leading accelerator centers offering high-energy ion beam opportunities.

The development of the ARIADNA long-term irradiation station has become one of the key elements of the planned research program under the JINR topic "Applied research at the NICA complex for radiation materials science, life sciences, and new energy generation methods". Long-term irradiation modes are particularly important for the task of radiation processing of materials addressed within this topic, enabling significant exposure and the study of radiation resistance, as

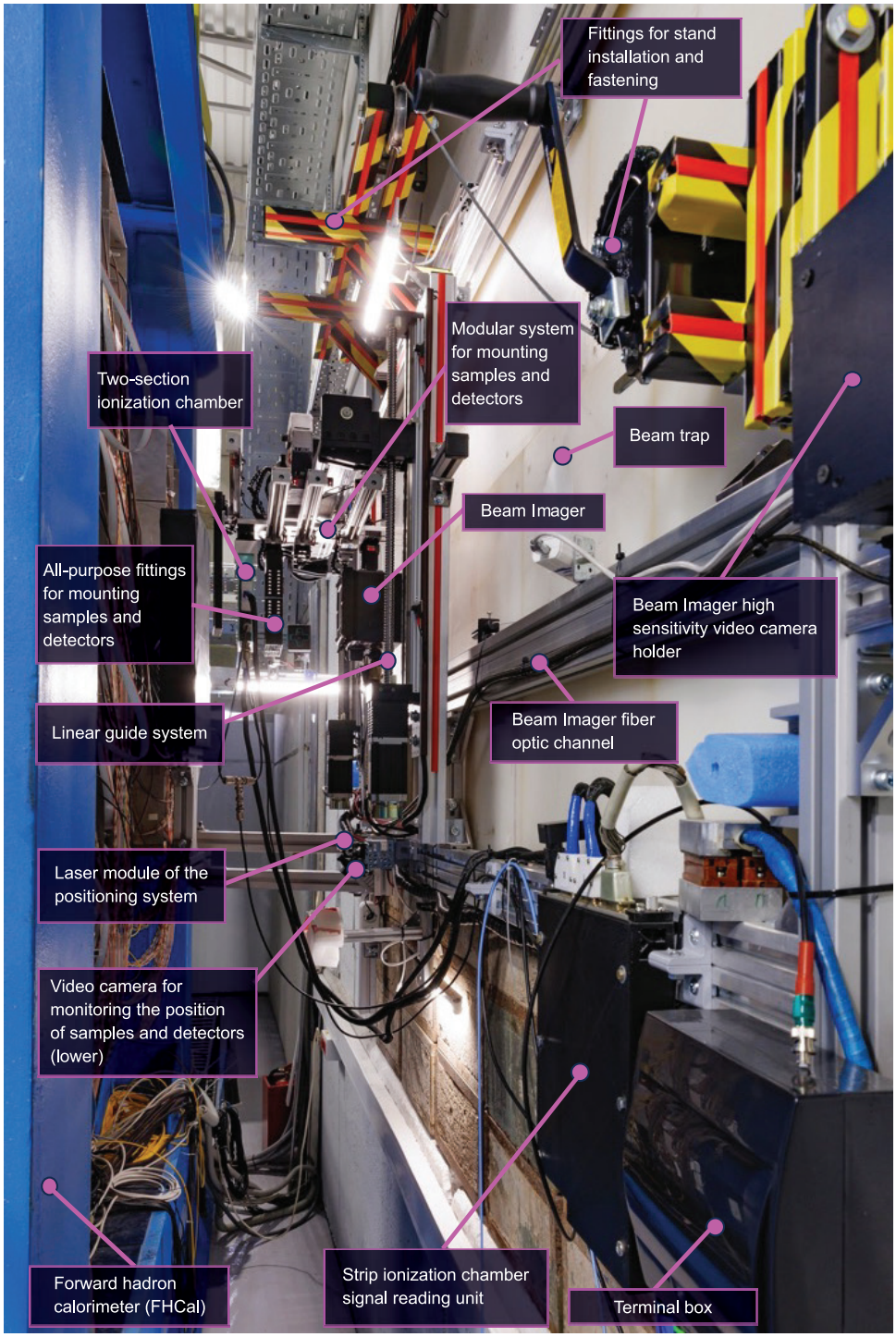


Fig. 4. Configuration of the suspension system of the ARIADNA long-term irradiation station at the BM@N facility site in the beam path between the FHCal and the trap

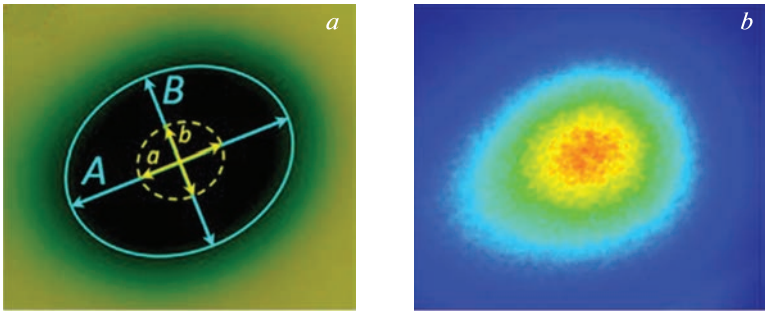


Fig. 5. a) Trace of the 3.8 GeV/nucleon $^{124}Xe^{54+}$ beam on radiochromic film; b) beam profile on the OCTAVIUS 1500XDR detector. Geometric parameters of the irradiation region: A = 3.42 cm, B = 2.93 cm; the most uniform region: a = 1.2 cm, b = 0.9 cm

well as targeted modification with ionizing radiation to produce materials with desired properties.

Long-term irradiation is of great interest in regard to the research into the effects of ionizing radiation on living systems due to the study of radiobiological effects based on the superposition of processes of induction and repair of biologically significant damage. Such irradiation modes, particularly when using ion beams of relatively low intensity or beams delivered in a fractionated mode, make it possible to approximate the actual radiation conditions of deep space missions, which involve prolonged exposure of biological objects to ions contained in galactic cosmic rays.

Long-term irradiation with high-energy ions also has practical relevance for space applications in studying the reliability of microelectronics used on spacecraft. Long-term irradiation modes allow addressing radiation resistance issues in deep-submicron very large scale integration circuits (VLSI) both in terms of the accumulated dose of ionizing radiation and in terms of single errors caused by the impact of individual particles present in galactic cosmic rays. Furthermore, the significant penetrating power of accelerated high-energy ions helps address the increasing integration of modern microchips, which often hinders proper chip decapsulation and radiation resistance testing using low-energy ion beams. Technologies of long-term irradiation with high-energy ions allow not only for selective testing of a limited number of microchips from a production batch, eliminating them during testing, but also for continuous non-destructive reliability testing of products that subsequently receive a radiation resistance certificate.

The development of the ARIADNA long-term irradiation station has significantly expanded the capabilities of the infrastructure of the NICA complex for applied research using high-energy heavy ion beams. It offers users unique opportunities for long-term sample exposure to high-energy (up to 4 GeV/nucleon) heavy ion beams and increases the total beam time available for applied tasks in parallel operation with the BM@N facility. The capabilities of the newly developed station have attracted considerable interest from representatives of many research centers in JINR Member States and partner organizations in other countries which perform applied research by using ionizing radiation sources. This irradiation station

will be one of the core infrastructure elements supporting the implementation of the ARIADNA scientific program in the coming years.

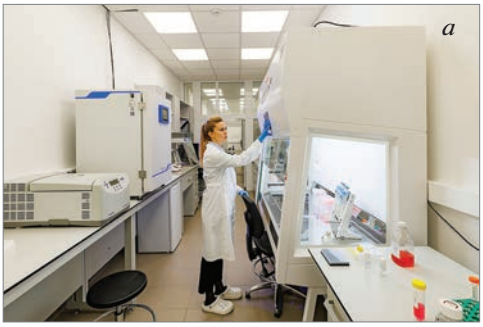
In 2025, the first phase of the ARIADNA auxiliary user infrastructure was completed under the leadership of O. V. Belov and with the active participation of K. P. Afanasyeva, V. Javadova, S. Yu. Anisimov, and M. Yu. Meshenkov. This infrastructure consists of a sample preparation area in room 203 of building 205 at VBLHEP. This area is a 37.7 m^2 laboratory space divided into zones to work with material samples and biological objects, as well as to house users' own equipment. These zones are equipped primarily with general laboratory equipment for sample preparation and rapid sample analysis, sample storage devices, and 3D printing infrastructure. The facility was equipped with supply and exhaust ventilation, power supply for a total load of up to 10 kW, low-current networks, zoned lighting, gas handling equipment (CO_2 with the ability to expand for inert gases), an analytical-grade water treatment system, bactericidal lamps, and remote process control systems.

In its current configuration, the sample preparation area provides the most commonly used sample preparation capabilities in close proximity to the irradiation stations for applied research, eliminating the need to transport samples between buildings. The equipment available at the site allows working with solid and powdered material samples, non-toxic non-flammable chemical agents, liquid media, and biological samples such as cell and tissue cultures. The area also offers opportunities to work in sterile conditions. A structured sample storage system is provided for users from organizations participating in the ARIADNA collaboration, and space has been allocated on the newly commissioned network storage system. Two general-purpose workstations with computers and a printer have been equipped for temporary use.

The ARIADNA sample preparation site will be used for work in virtually all areas of applied research at the NICA complex. By the end of 2025, the opportunities to prepare biological samples in the form of cell cultures, to load sample cassettes into fixing devices of the irradiation station, and methods to prepare powdered samples for irradiation were successfully tested. In 2025, the sample preparation area provided low-temperature (–40 and –86°C) storage for a number of samples from the BION-2M experiment, in which several research groups from the ARIADNA collaboration have been actively involved.

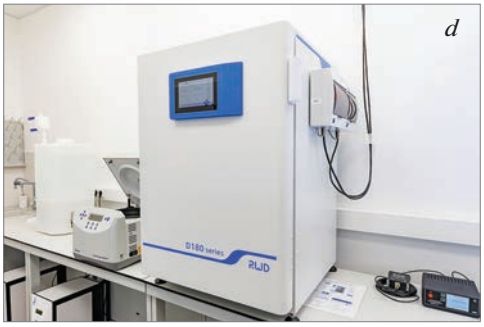
In 2025, the SMM-2000 scanning probe microscope was commissioned at the ARIADNA sample preparation site. It is designed to measure the geometric and physical parameters of material samples' surface topography. Basic measurement techniques were tested on the surfaces of HTS tapes and a number of other objects. The microscope enables measurements in the following ranges: the lower and upper limits of lateral measurements are from 0.0003 to 20 μm, and the lower and upper limits of high-dimensional measurements are from 0.0002 to 2 μm. Frame fields are $15 \times 15 \times 2.5$ and $2.5 \times 2.5 \times 0.5$ μm. The multi-mode SMM-2000 microscope has three basic modes: STM (scanning tunneling microscopy), AFM (atomic force microscopy), and VAFM (vibrating atomic force microscopy).

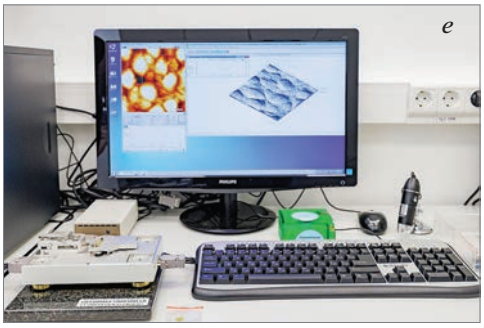
The 3D printing equipment available in the sample preparation area was actively used to develop structural elements for the ARIADNA long-term irradiation

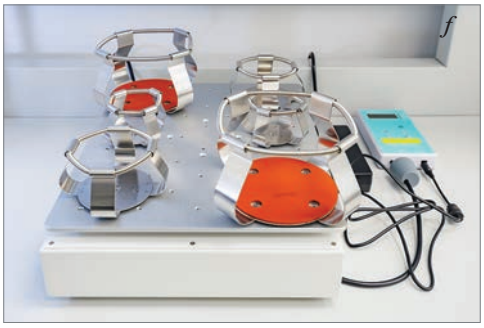

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Equipment of the ARIADNA sample preparation site: a), b) a general view of the room sections; c) low-temperature sample storage system; d) CO_2 thermostat; e) scanning probe microscope SMM-2000; f) shaker; g) steam sterilizer; h) ultracentrifuge with refrigeration; i) wide-aperture 3D printer; j) draft hood; k) muffle furnace; l) CO_2 gas storage and supply system with redundancy, sensors for monitoring pressure and CO_2 content in the air

station in the BM@N facility area and to manufacture sample holders of various configurations compatible with applied research irradiation stations at the NICA complex.

The global experience of establishing sample preparation and analytical research sites in close proximity to irradiation facilities demonstrates the high efficiency of this approach, both in laboratory standard compliance for handling various types of samples and in unique studies involving rapid sample analysis after irradiation (within minutes after exposure). Similar experience of organizing such a site exists at BNL (NSRL laboratory complex at the beamline of the AGS booster) and at GSI-FAIR, where analytical laboratories are located at a short distance from the irradiation sites and sample transport routes are provided without exiting the premises. Therefore, setting up a similar area at the NICA facility should be considered a significant step in improving standards for applied radiation research, consistent with the world experience in this field.

The requirement for such a site in close proximity to the irradiation stations for applied research was determined by the high number of requests from ARIADNA collaboration participants planning to visit JINR to carry out experiments at the NICA complex. The newly prepared site meets the primary needs of the first run participants on its own scale, while there remains a need for its further development as the number of experiment participants increases.

A wide range of scientists and specialists were provided with access to the applied research infrastructure of the NICA complex. In this regard, the memorandum of the international roundtable "Applied Research and Innovation at the NICA Complex", held in Dubna on September 15–16, 2021, formalized the initiative to establish the ARIADNA international collaboration in areas corresponding to the purpose of the experimental zones. A primary objective of the collaboration is to develop a research program using accelerated charged particle beams of the NICA complex. The work planned within the ARIADNA channels will include ensuring radiation safety for long-term manned spaceflights, research related to cancer radiation therapy, radiation biophysics, general radiobiology, studying the mechanisms of radiation damage in microelectronics, radiation materials science, and laying the foundation to develop new radioactive waste disposal technologies.

To implement the proposed initiative, the NICA project management organized a process to coordinate the foundation documents of the ARIADNA collaboration with partner organizations wishing to join. The process of establishing the collaboration included signing by each interested organization in sequence of a Letter of Intent and a Memorandum of Understanding (MoU), which implied each party's agreement to the Bylaws of the Collaboration. The foundation documents of the new collaboration were prepared with the extensive use of the experience of the successful BM@N, MPD, and SPD collaborations for NICA fundamental physics experiments.

In 2022, the collaboration's governing bodies and key work areas were established. O. V. Belov took the duty of the head of the collaboration. S. I. Tyutyunnikov, as well as M. S. Novikov and M. Paraipan, responsible for key areas of collaboration, made significant contributions to establish and strengthen ties with the organizations which have become part of the collaboration.



The ARIADNA collaboration meeting. Dubna, May 31, 2024



The workshop "Applied Research at the NICA Complex: Prospects for RNO–Alanya–JINR Cooperation". Vladikavkaz, June 17–19, 2023

By the end of 2025, 30 organizations became members of the ARIADNA collaboration, including academic institutes, universities, and research and production companies from seven JINR Member States. In anticipation of regular experiments, a user policy for the NICA complex is being developed, covering rules of using the equipment, issues of bioethics, access to beam transport channels and

associated user infrastructure. Financial support programs were launched for organizations participating in the ARIADNA collaboration. ARIADNA collaboration conferences, seminars, and meetings on current areas of joint work among collaborating organizations are held. An important aspect to build collaboration on applied research at the NICA complex is the combination of the analytical infrastructure of major specialized institutes with the sample irradiation opportunities in Dubna.

The status of the development of the applied research infrastructure and information about the ARIADNA collaboration were regularly reported at various major international conferences, seminars, and other scientific events. These included the IUPAP conference "Heaviest Nuclei and Atoms" (Yerevan, April 25–30, 2023), the meeting of the Presidium of the National Academy of Sciences of the Republic of Belarus (Minsk, November 13, 2024), JINR Days in Uzbekistan (Tashkent, April 21–25, 2025), the conference "Nucleus-2025. Nuclear Physics, Elementary Particle Physics, and Nuclear Technologies" (St. Petersburg, July 1–6, 2025), and the RAS Council on Heavy Ion Physics (St. Petersburg, June 27 – July 2, 2025).

AREAS OF APPLIED RESEARCH AT DLNP

LINAC: NEW ACCELERATOR COMPLEX FOR FUNDAMENTAL AND APPLIED RESEARCH

February 13, 2025 marked a ceremonial opening and successful test launch of the first stage of the LINAC Linear Accelerator at the Joint Institute for Nuclear Research (JINR). It is a facility for R&D in the field of elementary particle detectors, scientific and methodological work on the search for new methods and the construction of equipment for electron beam diagnostics, applied work in radiation materials science, radiobiology and radiochemistry, nuclear physics experiments, and educational projects.

In its final design, the LINAC facility will have six dedicated experimental channels enabling a wide range of research. Its key feature is fine tuning of the beam parameters, allowing the production of electron beams ranging from 10^{13} electrons to single particles, which is essential to test and calibrate various types of particle detectors.

Design and parameters of the first run

At the first stage of accelerator commissioning, the operation at an electron energy of 200 MeV will be enabled. The facility includes an injector and four accelerator stations equipped with rotating magnets and experimental beam extraction channels for operation at energies of 24, 60, 133, and 200 MeV. It is planned to expand the accelerator complex and put the accelerator structures into operation at 400 and 800 MeV at the second and the third stage, respectively.



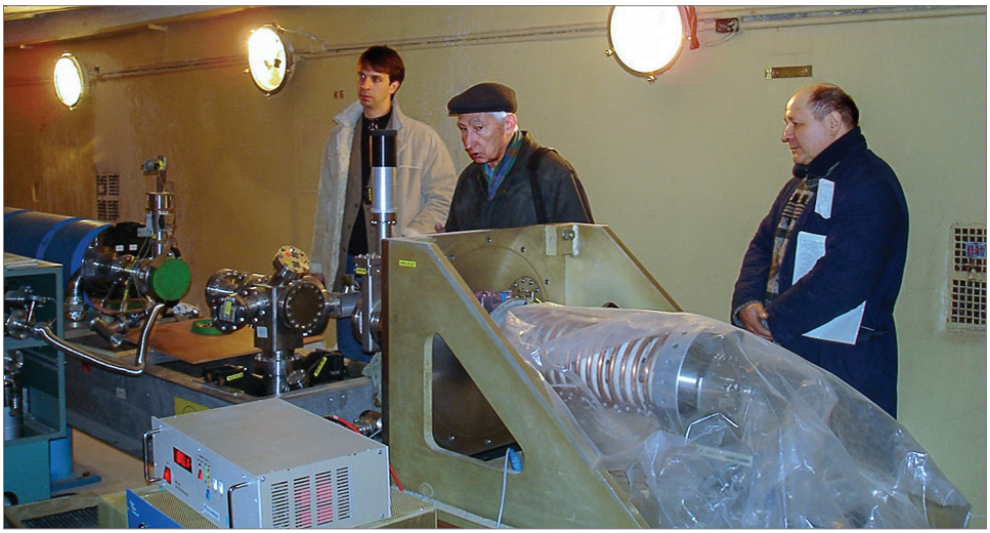
A ceremonial opening of the LINAC facility by the JINR Directorate representatives and the Scientific Council members. February 13, 2025



In the LINAC control room. Left to right: V. V. Glagolev, V. V. Kobets, S. D. Nadgerieva, M. E. Acosta, A. E. Brukva, D. S. Shokin, A. A. Ulankin, D. L. Demin

History of the accelerator: from NIKHEF to JINR

Initially, the accelerator was used as a storage ring injector for synchrotron radiation experiments at the National Institute for Subatomic Physics (NIKHEF) in the Netherlands. However, in the late 1990s, it was decided to transfer the accelerator research to CERN, whereupon the facility was decommissioned. By the agreement between NIKHEF and JINR, the accelerator was dismantled and transported to Dubna in 2000. After this, assembly and extensive modernization of the accelerator got started. It included the replacement of electronic and engineering systems, the upgrade of klystron modulator control units, and the overhaul of the building and its engineering infrastructure.



Start of LINAC assembling in DNLP JINR building No. 118. Left to right: G. V. Trubnikov, I. N. Meshkov, V. F. Minashkin

Scientific potential and cooperation

LINAC is a platform for research in nuclear spectroscopy, radiobiological processes, materials science, and radiochemistry. The project is being implemented at DLNP in cooperation with other JINR laboratories and its Member States. Research groups from VBLHEP, LRB, FLNR, and FLNP plan to participate in the experiments at LINAC. An Organizational and Program Committee has been established to review user proposals.

A User Program for research at the accelerator is already being developed primarily targeted at the requests of JINR laboratories and scientific groups from the JINR Member States. The extracted beams of LINAC-200 will be used to test the prototypes of electromagnetic calorimeters and tracking detectors for the MPD and SPD experiments at the NICA collider; for applied research in radiation materials science, radiobiology, and radiochemistry; to carry out experiments in nuclear physics; as well as to organize the internships for students and specialists from the Member States provided by the JINR University Centre. Specialists from Vietnam

are planning to implement a scientific program to study photonuclear reactions at the 133- and 207-MeV beam extraction channels.

An international Fundamental & Applied Linear Accelerator Physics collaboration (FLAP) has already been formed around LINAC. It brings together 19 research centres from seven countries and is aimed at studying the interactions of accelerated electrons with matter and external fields, as well as developing new experimental techniques.

The commissioning of the first stage of the accelerator is expected to be completed in 2026, and it is planned to obtain the operating license from the Federal Medical and Biological Agency of Russia.

Further development of the LINAC accelerator complex will provide new opportunities for fundamental research and for testing experimental methods in nuclear physics, materials science, and biomedical technologies.

LASER METROLOGY: FROM PARTICLE PHYSICS TO MONITORING OF THE SEISMIC OSCILLATIONS OF THE EARTH'S SURFACE

Modern laser technologies enable precision measurements across a wide range of scientific fields. This is the reason why the laser metrology research has emerged at the Dzhelepov Laboratory of Nuclear Problems at JINR, initially intended for alignment of the barrel modules of the ATLAS hadronic calorimeter at CERN.

While constructing the ATLAS hadronic calorimeter, the DLNP scientists developed techniques that made it possible to control the positions of 64 "wedges" of the central hadronic calorimeter barrel with an accuracy of 300 μm, with their subsequent assembling into the barrel of the hadronic calorimeter. Later, a completely new application for these laser technologies was found: the monitoring of microseismic oscillations in the area of the Large Hadron Collider (LHC). In particular, inclinometers developed at DLNP are installed in the shafts of the CMS and ALICE experimental facilities[4].

The luminosity of a collider is a key parameter determining its efficiency. It depends on the accuracy of the particle beam alignment at the interaction point. Even minimal displacements of accelerator units caused by seismic or industrial impacts can reduce luminosity and affect the results of experiments.

Correlations between the LHC luminosity and seismic noise recorded by the DLNP precision laser inclinometer (PLI), located in the LHC transfer tunnel, have been found.

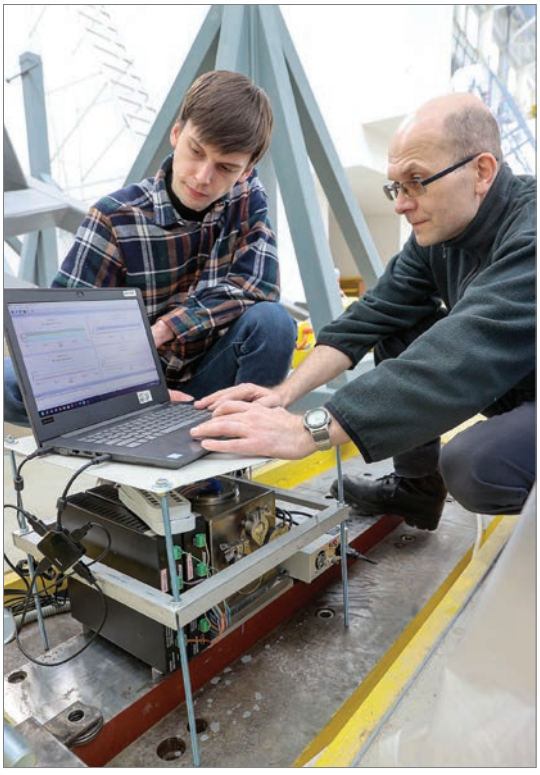
PLIs are also used at NICA, the "home" collider of JINR. Monitoring of the MPD hall bases and the ones under the collider units is performed before the beams are extracted into the collision zone of the MPD experiment.

The technology of high-precision angular measurements by means of the nanoradian inclinometer of DLNP attracted the attention of scientists working on the VIRGO Gravitational-Wave Antenna project. Two laser inclinometers are installed near the antenna's mirror suspensions, and the data obtained from them are used to suppress high-frequency noise.

[4] *Azaryan N. et al.* The Seismic Angular Noise of an Industrial Origin Measured by the Precision Laser Inclinometer in the LHC Location Area // Phys. Part. Nucl. Lett. 2019. V. 16, No. 4. P. 343–353.



M. V. Lyablin and Yu. A. Budagov (the constructors of the precision laser inclinometer) take measurements in CERN transfer tunnel No. 1



Employees of the Laser Metrology Sector of the Research and Innovation Department at DLNP K. D. Polyakov and A. M. Kuzkin adjusting the laser inclinometer in the MPD NICA hall



A. V. Krasnoperov and R. V. Ni installing the inclinometer at the Kamchatka Branch of the GS RAS

Further refinement of the PLI design led to the development of a compact precision laser inclinometer (CPLI), which was protected by a number of Russian Federation patents[5].

High measurement accuracy and the ability to measure very low-frequency signals with periods of hours and days, and potentially months, have captured their interest, so DLNP scientists and geophysicists from the JINR Member States proposed using CPLIs in geophysical observations.

Nowadays, CPLIs operate at observatories in Armenia, Belarus, and Kamchatka, transmitting data to Dubna for analysis and monitoring.

The development of laser metrology, which began with application to particle physics, is now opening new prospects for geophysics, engineering research, and the study of Earth's crust dynamic processes. Modern laser technologies still can find new applications and, therefore, expand the capabilities of fundamental and applied sciences.

Colleagues from the Geophysical Monitoring Centre of the National Academy of Sciences of Belarus have proposed that JINR open a new station to test laser inclinometers, particularly in the low-frequency range, and to carry out comparative analysis with the measurement results of "standard" geophysical instruments.

[5] Device for Measuring Angles of Inclination of Surface / Budagov Yu. A., Lyablin M. V. Patent for invention RU 2 734 451. Publ. 16.10.2020. Bull. No. 29.

PROTON THERAPY

In 1986, construction of the multi-room Medico-Technical Complex (MTC) based on the Phasotron (DLNP JINR) was completed, where research on hadron therapy of malignant tumors was continued. In 1987–1989, radiobiological experiments with high-energy proton and neutron beams were carried out, and clinical trials on irradiation of patients (in collaboration with the All-Union Cancer Research Center of the USSR AMS) were initiated. Proton beams were used in irradiation, by means of recently-developed methods of shaping dose fields and rotational-scanning irradiation of deep-seated tumors. During this period, a set of unique equipment was created: a full-scale positron emission tomograph (PET); an X-ray computed tomograph (CT) combined with a therapeutic chair for topometry of a patient in a sitting position; and a proton computed tomograph (pCT), providing topometric information in units of proton beam path in tissue.

Between 1986 and 1996, the Medico-Technical Complex included:

— five medical proton beam channels for irradiating tumors in various locations with wide and narrow proton beams within the energy range from 70 to 660 MeV;

— a medical pi-meson beam channel for radiotherapy with negative pi-meson beams with energies from 30 to 80 MeV;

— a medical neutron beam channel (average neutron energy in the beam was approximately 350 MeV) for irradiating large radioresistant tumors;



A chair for proton treatment

— a Rokus-M gamma-therapy unit as a backup radiation source and for remote gamma therapy with a combination of irradiation methods.

By early 1987, all beam transport channels were adjusted and all necessary physical and dosimetric characteristics of the medical beams were obtained.

In 1999, a new important stage in the development of proton therapy at JINR began. Thanks to the persistence and efforts of V. P. Dzhelepov, a specialized 25-bed radiology department was opened at Medical Unit No. 9 in Dubna, which allowed to carry out regular proton therapy sessions. At the same time, it was decided to focus on the work in the first treatment room of MTC.

The TPN 3D computerized proton irradiation planning system developed at the first hospital proton therapy centre in the world (Loma Linda, USA)

was adjusted to the equipment and proton beams of the Phasotron. After dosimetric studies, the system was successfully used in regular proton therapy sessions at the Medico-Technical Complex. It was the first time when the technique of 3D conformal proton radiotherapy at the JINR Phasotron was implemented in the post-Soviet territory.

However, the American program was not amenable to any modernization, so that it could not be used with other emerging irradiation techniques.

Due to the need to develop alternative irradiation techniques, the DLNP Medico-Technical Complex developed its own computed planning system.

The first MTC treatment room was refurbished to meet the requirements for implementing 3D conformal proton radiotherapy for deep-seated tumors. During the session, a patient is placed in the treatment room in a special chair-like positioner with four degrees of mechanical movement: two orthogonal horizontal positions, one vertical position, and a rotational one.

In 1999–2019, MTC staff have treated nearly 1300 patients with various tumors.

It was proved ineffective to continue using the Phasotron for proton therapy sessions due to its excess in particle energy, that led to increased energy consumption. Moreover, when slowing the proton beam from 660 to 150 MeV (usual energy of a therapeutic beam for irradiating head and neck tumors), a large portion of the



Employees of the Medico-Technical Complex of the Phasotron Department (DLNP JINR) who have been performing regular proton radiotherapy sessions for cancer patients using the therapeutic beam of the DLNP Phasotron for many years. G. V. Mytsin, Head of the Phasotron Department, is on the left

particles was lost, which made it impossible to shape a proton beam with the best parameters for radiotherapy in the treatment room.

The Phasotron is currently shut down. Staff of New Accelerators Department of DLNP have developed a project of a new MSC230 superconducting cyclotron for medical applications. This accelerator is expected to be the basis for a new Proton Therapy Centre in Dubna, which will consist of two treatment rooms. The first room will utilize a wide horizontal proton beam and a therapeutic chair, while the second one is planned to be equipped with a gantry system for a pencil proton beam dynamic scanning and a positioner for supine patient position. The new centre will also house diagnostic equipment (for CT and MRI) and a standard linear accelerator for combined radiotherapy.

RADIOCHEMICAL RESEARCH AT DLNP JINR

In recent years research at the Radiochemistry Sector of DNSR at DLNP JINR has been aimed at the advancement of radiochemistry for nuclear medicine and low-background experiments. Its activities include the development and improvement of methods for producing radionuclides and low-background materials, radiochemical extraction and separation of elements, and the analysis of radiopharmaceuticals and their precursors[6].

The department's staff members participated in the development of advanced methods for producing medical radionuclides with generators, such as $^{44}Ti \rightarrow {}^{44}Sc$, $^{68}Ge \rightarrow {}^{68}Ga$, $^{90}Sr \rightarrow {}^{90}Y$, $^{238}U \rightarrow {}^{234}Th$, $^{237}Np \rightarrow {}^{233}Pa$, $^{229}Th \rightarrow {}^{225}Ra \rightarrow {}^{225}Ac$, $^{227}Ac \rightarrow {}^{227}Th \rightarrow {}^{223}Ra$, $^{202}Pb \rightarrow {}^{202}Tl$, $^{194}Hg \rightarrow {}^{194}Au$, $^{32}Si \rightarrow {}^{32}P$, etc., as well as ^{225}Ac, ^{223}Ra, ^{44}Sc, ^{119}Sb, etc. from irradiated targets [7,8,9,10,11,12,13,14,15]. The researchers are also actively involved in studying new candidates for targeted diag-

[6] *Filosofov D. V. et al.* Radiochemical Investigations for Radiopharmaceutical Nuclear Medicine at JINR Laboratory of Nuclear Problems // Phys. Part. Nucl. 2023. V. 54, No. 2. P. 321–363.

[7] *Filosofov D. V., Loktionova N. S., Rösch F.* A $^{44}Ti/^{44}Sc$ Radionuclide Generator for Potential Application of ^{44}Sc-Based PET-Radiopharmaceuticals // Radiochim. Acta. 2010. V. 98, No. 3. P. 149–156.

[8] *Pruszyński M. et al.* Post-Elution Processing of $^{44}Ti/^{44}Sc$ Generator-Derived ^{44}Sc for Clinical Application // Appl. Rad. Isotopes. 2010. V. 68, No. 9. P. 1636–1641.

[9] *Baimukhanova A. et al.* Production of the Positron-Emitting Radionuclide ^{68}Ga: The Radiochemical Scheme of Radionuclide Generator $^{68}Ge \rightarrow {}^{68}Ga$ // Chem. Bull. of Kazakh Nat. Univ. 2018. V. 89, No. 2. P. 20–26.

[10] *Grimm W. et al.* Ein $^{90}Sr/^{90}Y$-Generator auf basis eines 3-säulensystems des kationenaustauschers Aminex-A6. Mainz, 1999. 42 p.

[11] *Tsoupko-Sitnikov V., Norseev Y., Khalkin V.* Generator of Actinium-225 // J. Radioanal. Nucl. Chem. 1996. V. 205, No. 1. P. 75–83.

[12] *Khalkin V. A., Tsupko-Sitnikov V. V., Zaitseva N. G.* Radionuclides for Radiotherapy. Actinium-225: Properties, Production, Application // Radiochemistry. 1997. V. 39, No. 6. P. 481–490.

[13] *Baimukhanova A. et al.* An Alternative Radiochemical Separation Strategy for Isolation of Ac and Ra Isotopes from High Energy Proton Irradiated Thorium Targets for Further Application in Targeted Alpha Therapy (TAT) // Nucl. Med. Biol. Elsevier BV, 2022. V. 112–113. P. 35–43.

[14] *Kurakina E. S. et al.* Improved Separation Scheme for ^{44}Sc Produced by Irradiation of ^{nat}Ca Targets with 12.8 MeV Protons // Nucl. Med. Biol. 2022. V. 104–105. P. 22–27.

[15] *Kurakina E. S. et al.* Production of ^{111}In and Radioisotopes of Te and Sn from an Antimony Target Irradiated with High-Energy Protons // Radiochemistry. 2020. V. 62, No. 3. P. 393–399.

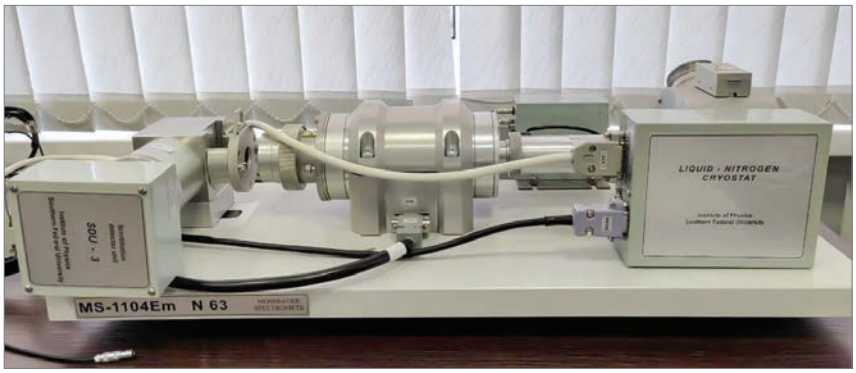
nostics (^{44}Sc and ^{90}Nb) or targeted therapy (^{119}Sb), as well as other promising radionuclides. In addition to methods of radiochemical extraction, the department is focused on studying decay processes of radionuclides contained in radiopharmaceuticals using hyperfine interaction methods. In particular, this includes development of techniques for determining the thermodynamic and kinetic constants of radiopharmaceuticals and their precursors using the perturbed angular correlation (PAC) method. This makes it possible to gain deeper insight into decay mechanisms and to enhance the efficiency of developing new radiopharmaceutical agents.



Sources for low-energy electron and α-particle spectrometry

To a large extent, these achievements stemmed from the access to a wide range of radionuclides used in nuclear medicine and produced at JINR facilities, such as the Phasotron (DLNP), the IBR reactor (FLNP), the U-200 cyclotron (FLNR), and others. An important factor of the successful implementation of new methods in nuclear medicine is also the international status of JINR, and the DNSR group, owing to its international composition, occupies the leading position. This is driven by the high interest of many countries in research on radionuclides and nuclear medicine in general.

Initially, the main objective of the group was to study the properties of atomic nuclei with nuclear spectroscopy and radiochemistry methods. The unique opportunity to irradiate targets at the Phasotron (Synchrocyclotron) of DLNP and to produce almost any radionuclide enabled a vast number of studies to be carried out, owing to the high purity and specific activity of the produced radionuclides. It should be emphasized that spectrometric sources and radioactive preparations supplied by the department were distributed to many countries worldwide. The department considers it crucial to leverage this experience for the development



A two-channel Mössbauer spectrometer operating in coincidence mode with a gamma detector



Working in a clean room on separating elements. A. V. Rakhimov, D. V. Karaivanov



Time differential perturbed angular correlation spectrometer. Left to right: A. Velichkov, G. Marinov, and D. Karaivanov



The staff members of DNSR of DLNP JINR participating in the radiochemical research (left to right): G. Yu. Magomedov, D. A. Salamatin, D. V. Karaivanov, K. V. Antokhina, A. V. Salamatin, A. V. Rakhimov, A. H. Inoyatov, N. T. Temerbulatova, D. V. Filosofov, M. Vorobyova, Kh. Dadakhanova, Zh. Dadakhanov, Yu. K. Khusenova, A. Baimukhanova, H. M. Alshubaki, E. S. Kurakina, Naomi Dikeledi Mokhine, M. V. Mukhina, B. E. Kalinova. Dubna, 2025

of techniques and methods for producing various radionuclide preparations and sources at the LINAC-800 electron accelerator, the new basic facility of DLNP.

In recent years, the department has focused on the application of nuclear spectroscopy and radiochemical methods to the study of rare events, such as double beta decay, the search for dark matter particles, and other rare-event experiments that require the use of unique materials — samples with extremely low levels of radionuclide impurities. So, the department is developing efficient techniques for the production and purification of low-background materials, as well as advanced analytical methods for working with such samples, in particular, the purification and analysis of enriched ^{82}Se and ^{96}Zr for the search for the particular neutrinoless mode of double beta decay[16,17,18,19], as well as the preparation of ultra-high-purity

[16] *Kurakina E. S. et al.* Perturbed Angular Correlation as a Tool to Study Precursors for Radiopharmaceuticals // Inorg. Chem. 2020. V. 59, No. 17. P. 12209–12217.

[17] *Rakhimov A. V. et al.* Development of Methods for the Preparation of Radiopure ^{82}Se Sources for the SuperNEMO Neutrinoless Double-Beta Decay Experiment // Radiochim. Acta. 2020. V. 108, No. 2. P. 87–97.

[18] *Rakhimov A. V. et al.* Purification of Selenium from Thorium, Uranium, Radium, Actinium and Potassium Impurities for Low Background Measurements // Radiochim. Acta. 2013. V. 101, No. 10. P. 653–659.

[19] *Temerbulatova N. T. et al.* Production of Tin-Lead Solder Based on Archaeological Lead for Low-Background Experiments // J. Instrum. 2025. V. 20, No. 07. P. P07021.

fluxes and solders for use in low-background electronics, and the development and implementation of techniques and methods for analysis of low-background materials, including a new method for determining low activities — the oxythermography method.

A number of doctoral and candidate theses based on this research were defended. V. Halkin, N. Zaitseva, I. Yutlandov, A. Novgorodov, A. Rösch, F. Rösch, G. Bayer, Yu. Norseev, N. Lebedev, V. Rybakov, N. Korolev, Z. Akselrod, D. Filosofov, V. Tsupko-Sitnikov, G. Bozhikov, P. Ivanov, G. Bonchev, M. Milanov, D. Karaivanov, A. Velichkov, J. Velichkova, M. Tsvetkov, G. Varot, V. Radchenko, A. Belozub, R. Severyanova, L. Angel, V. Karaush, A. Fuer, E. Kurakina, G. Marinov, A. Marinova, N. Mirzaev, I. Ostrovsky, K. Belikov, R. Mysiak, Shin Soo Bok, Chon Sun Chin, Chan Kim Hung, A. Rakhimov, N. Temerbulatova, A. Baimukhanova, Zh. Dadakhanov, M. Mukhina, M. Vorobyova, Yu. Khusenova, Kh. Alshubaki, K. Antokhina, D. Salamatin, G. Magomedov, Naomi Dikeledi Mokhine, E. Denisova, V. Sobolev, R. Stolupina, E. Kulikov, O. Bochko and others have participated in the work at different stages.

THE POSITRON ANNIHILATION SPECTROSCOPY

The Positron Annihilation Spectroscopy (PAS) setup consists of three main components: a slow monochromatic positron injector, a transport channel, and a dedicated experimental station. The positron injector is based on a cryogenic source of slow monochromatic positrons (CSSMP). The transport channel consists of a set of coils that generate a longitudinal magnetic field. The main element of the dedicated experimental station is an automated isolated input. Space for detectors is provided within the station.

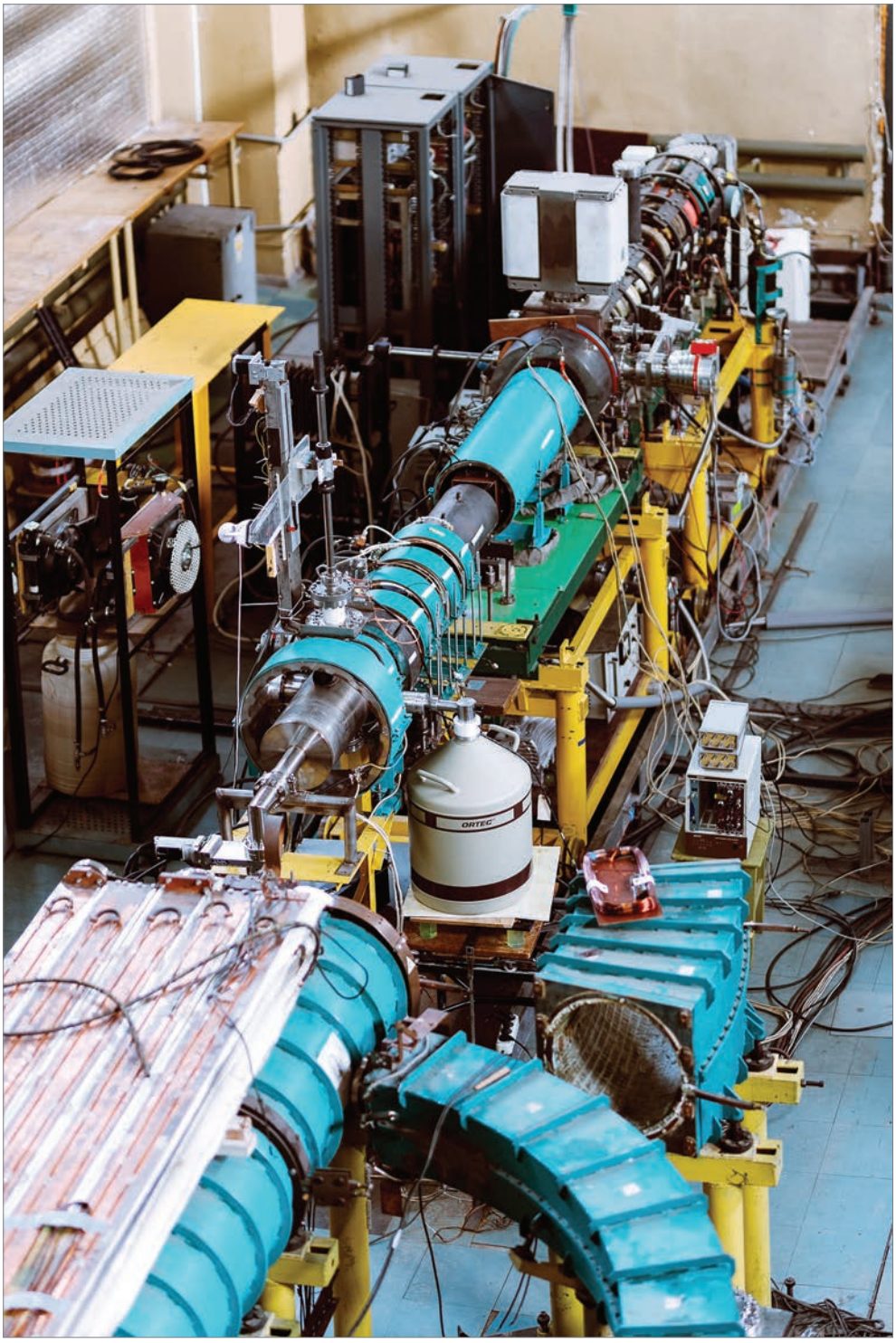
The automated isolated input has a holder for samples that allows additional elements to be inserted into the positron beam. Control is performed remotely from the control room. When measurements are being taken, the required potential (up to 30 kV) is applied to the holder.

The setup conducts flaw-detective studies on various materials from research institutes and laboratories of Russia and JINR Member States. Unique opportunities of non-destructive control, extreme sensitivity to defect detection, and the ability to scan samples for defects deeply inside them with high accuracy make positron annihilation spectroscopy one of the most relevant and rapidly gaining popularity methods of materials science in Russia and worldwide[20,21].

The first method implemented at the PAS setup using a monochromatic flow of slow positrons is Doppler Broadening of Annihilation Line (DBAL) of a gamma

[20] *Samadov S. F., Abiyev A. S., Asadov A. G., Trung N. V. M., Sidorin A. A., Samedov O. A., Popov E. P., Demir E., Vershinina T., Aliyev Y. I., Hasanov K. M., Mirzayev M. N.* Investigating the Crystal Structure of ZrB_2 under Varied Conditions of Temperature, Pressure, and Swift Heavy Ion Irradiation // Ceramics International. 11 Nov. 2023. (Impact factor 5.2). DOI: 10.1016/j.ceramint.2023.11.125.

[21] *Eseev M., Kuziv I., Kostin A., Meshkov I., Sidorin A., Orlov O.* Investigation of Nitrogen and Vacancy Defects in Synthetic Diamond Plates by Positron Annihilation Spectroscopy // Materials. 2023. V. 16. P. 203; https://doi.org/10.3390/ma16010203.



The PAS setup, top view



The staff members of Sector No. 4 of RID (left to right): A. A. Sidorin, O. S. Orlov, E. P. Popov, Nguyen Vu Minh Trung, and S. F. Samadov at the PAS setup

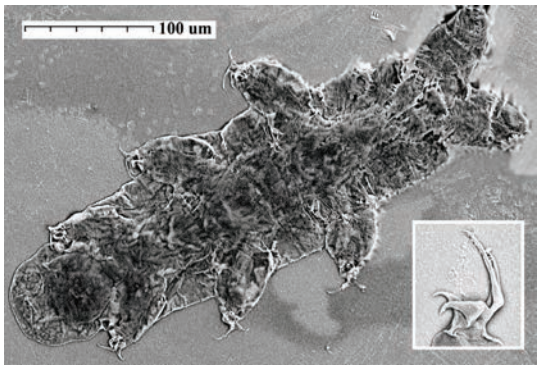
quantum. It is used to detect vacancies and vacancy clusters, and to determine their concentration.

The second method — PALS (Positron Annihilation Lifetime Spectroscopy) — is based on measuring the lifetime of positrons in a substance. It enables studying the microstructure of materials, in particular, crystal lattice defects, pores, and voids, at the nanometer scale.

THE TARDISS PROJECT

The TARDISS project, implemented at the Sector of Molecular Genetics of Cell of DLNP JINR, has been ongoing since 2021 and is dedicated to fundamental and applied research of the molecular mechanisms of extreme resistance of living organisms (extremophiles) to various physical and chemical stresses. The project focuses on tardigrades, underground microbial community of hydrothermal springs at the Baksan Neutrino Observatory (BNO) of INR RAS, deep-sea organisms from anchors of the Baikal Neutrino Telescope, and inhabitants of the IBR-2 reactor zone.

Tardigrades are among the animals most resistant to physico-chemical stresses on the Earth. The TARDISS project is studying the tardigrade protein Dsup (Damage suppressor), which efficiently protects DNA from radiation and reactive oxygen forms. It has been demonstrated for the first time on the *Drosophila melanogaster* model object and the human cell culture that Dsup can be used as a radioprotector in complex organisms, including for protection of healthy tis-



Scanning electron microscopy of a tardigrade Bertolanius markevichi



Participants in the expeditions to the Baksan Neutrino Observatory in the BNO tunnel 4000 m from the entrance. Left to right: A. M. Gangapshev (BNO INR RAS), M. P. Zarubin, K. A. Tarasov, E. V. Kravchenko (DLNP JINR)

sue from radiation during proton radiotherapy sessions. The effect of this protein was assessed by means of transcriptome sequencing. Small-angle X-ray scattering (SAXS) and circular dichroism spectroscopy were applied to determine the structural characteristics of Dsup and important parameters of its complex with DNA[22].

The first biological studies at BNO INR RAS (Neutrino settlement, Kabardino-Balkaria) were performed within the TARDISS project in 2021. They en-

[22] *Zarubin M., Azorskaya T., Kuldoshina O., Alekseev S., Mitrofanov S., Kravchenko E.* The Tardigrade Dsup Protein Enhances Radioresistance in *Drosophila Melanogaster* and Acts as an Unspecific Repressor of Transcription // iScience. 2023. V. 26, No. 7.

abled characterizing the genomes of one of the deepest microbial communities in Russia and the Caucasus and discovering new genera and species of extremophilic bacteria[23]. They launched a series of genome-wide studies of extremophile organisms and ecosystems, including the microbial community of the IBR-2 reactor core, deep-sea planarians from the Baikal Gigaton Volume Detector (Baikal-GVD) moorings, and extremophilic organisms from a number of locations in the JINR Member States. The results will be of great importance for fundamental molecular biology, radiation genetics, astrobiology, medicine, and biotechnology.

ARTIFICIAL INTELLIGENCE METHODS IN APPLIED PROBLEMS

Environmental safety and pollution control are always pressing issues. According to the Global Burden of Disease Study (GBD 2021), air pollution causes approximately 8 million deaths annually and is among the top ten leading causes of premature mortality. It is not surprising that there are numerous programs to analyze air quality. A significant one is the ICP Vegetation program of the UN Commission on long-range transboundary air pollution. It brings together hundreds of scientists carrying out research in more than forty countries in Europe and Asia. Since 2014, the Frank Laboratory of Neutron Physics at JINR has been responsible for project coordination. To increase the level of automation, a joint project between FLNP and LIT JINR was initiated. The project was led by M. V. Frontasyeva and G. A. Ososkov.

In 2016, development of the data management system (DMS) for the project was launched at LIT by A. V. Uzhinskiy. Initially, the system was planned to simplify and partially automate routine data operations and enable the rapid creation of pollution maps. Over time, the system evolved, incorporating new technologies and approaches, and today it can be considered an intelligent environmental monitoring platform[24].

As part of the ICP Vegetation project, participants collect moss samples, recording metadata about the collection locations, and use various techniques, such as neutron activation analysis, to obtain data on the contents of heavy metals, nitrogen, persistent organic compounds, and radionuclides. Naturally, errors are possible during the metadata acquisition process, which negatively impact the obtained results. To minimize these errors, a mobile app was developed that allowed most required fields to be filled in from drop-down lists, while some data, such as latitude, longitude, and altitude, were automatically entered. Furthermore, the app included the ability to photograph collection locations and moss samples and send them to the platform for recognition. This significantly simplified the process

[23] *Tarasov K. et al.* Cytobacillus Pseudoceanisediminis sp. nov., A Novel Facultative Methylotrophic Bacterium with High Heavy Metal Resistance Isolated from the Deep Underground Saline Spring // Curr. Microbiol. 2023. V. 80. P. 31; https://doi.org/10.1007/s00284-022-03141-8.

[24] *Uzhinskiy A.* Intelligent Environmental Monitoring Platform // Open Syst. DBMS. 2021. No. 2. P. 21–23.



Working meeting of representatives of FLNP, LIT and Ostrava Technical University (Czech Republic). 2018

of moss type identification, an important part of collecting metadata and, in some cases, challenging even for experts. Several deep learning models were tested using the system to solve recognition problems on a limited sample.

One of the key objectives in implementing the data management system was to minimize the need for third-party systems. Participants can manage data, create pollution maps, run forecasts, and generate analytical reports. Tools for cluster analysis, principal component analysis (PCA), time trend analysis, and cross-regional comparisons are available. Coordinators have extended permissions, including the creation of global maps.

Forecasting is an important stage of environmental monitoring, allowing data gaps to be filled. A. V. Uzhinskiy, as part of the DMS, proposed and implemented a forecasting mechanism based on the application of machine learning in conjunction with remote sensing data[25]. This approach has demonstrated very encouraging results for a number of chemical elements. Imagery from various satellite programs is used to obtain the so-called indices, which serve as additional data to train the model and as primary data to generate forecasts. The Google Earth Engine platform, which contains data from dozens of different satellite programs and products, is used to obtain these indices. The current implementation utilizes statistical machine learning models or neural networks, depending on the amount of source data. The accuracy of the models reaches 90–95% when constructing global and regional maps of some elements.

Thus, the developed platform made it possible to automate various data management processes and provided new opportunities for analysis and forecasting.

[25] *Uzhinskiy A., Vergel K.* Central Russia Heavy Metal Contamination Model Based on Satellite Imagery and Machine Learning // Comput. Opt. 2023. V. 47(1). P. 137–151; DOI: 10.18287/2412-6179-CO-1149.

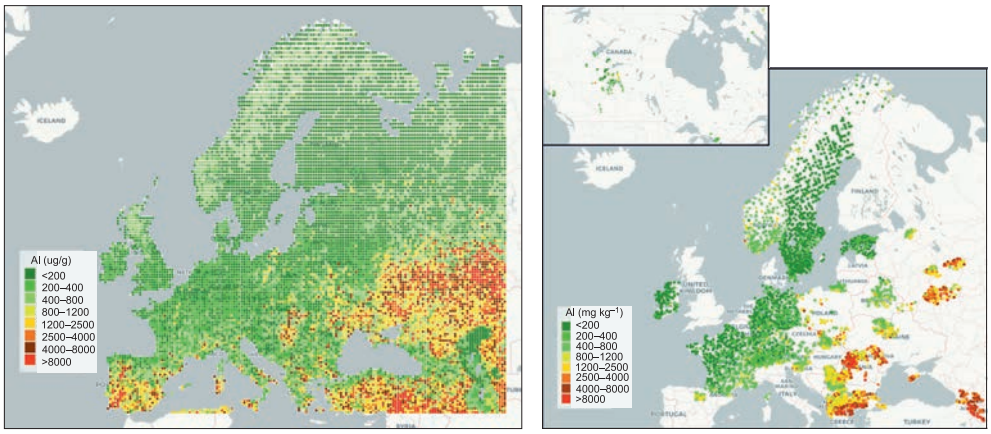


Fig. 6. Left: the model's forecast for aluminum pollution. Right: a map created using the platform and real data

Another interesting area being developed at MLIT JINR is the use of AI in plant cultivation. In 2017, a group of LIT researchers, including G. A. Ososkov, A. V. Uzhinskiy, A. V. Nechaevskiy, and P. V. Goncharov, a student at Gomel State Technical University, won a grant from the Russian Foundation for Basic Research (RFBR) to develop a comprehensive system for diagnosing plant diseases using images and text descriptions.

Drones with hyperspectral cameras flying over fields; robots with conventional cameras in greenhouses; high-resolution cameras installed in vertical farms; smartphone apps that can identify plant diseases from photographs — all of this has become a reality today. The use of various devices in conjunction with artificial intelligence technologies allows for increased yields and minimized losses in agriculture. The availability of experienced specialists in neural networks and machine learning, as well as modern computing resources, make MLIT an attractive candidate for joint agricultural projects.

A platform (pdd.jinr.ru) and a mobile app, DoctorP, were developed to solve problems of diagnosing and identifying diseases in house plants and crop plants by using modern methods for processing graphic and text information on high-performance computing infrastructures[26]. Currently, the platform includes models for 30 agricultural and decorative crops: barberry, grapes, cherries, blueberries, strawberries, corn, cucumbers, peppers, wheat, currants, tomatoes, cotton, apples, orchids, roses, etc. A common model for all plant species recognizes 68 classes of diseases and pests. The database contains over 6 000 images. To determine optimal approaches to model training, the development team is constantly testing various modern neural network architectures, data augmentation policies, and loss minimization functions. All this allows for a statistical accuracy of 97% for the

[26] *Uzhinskiy A. V.* Artificial Intelligence against Plant Diseases // Open Syst. 2022. No. 3. P. 29–31.

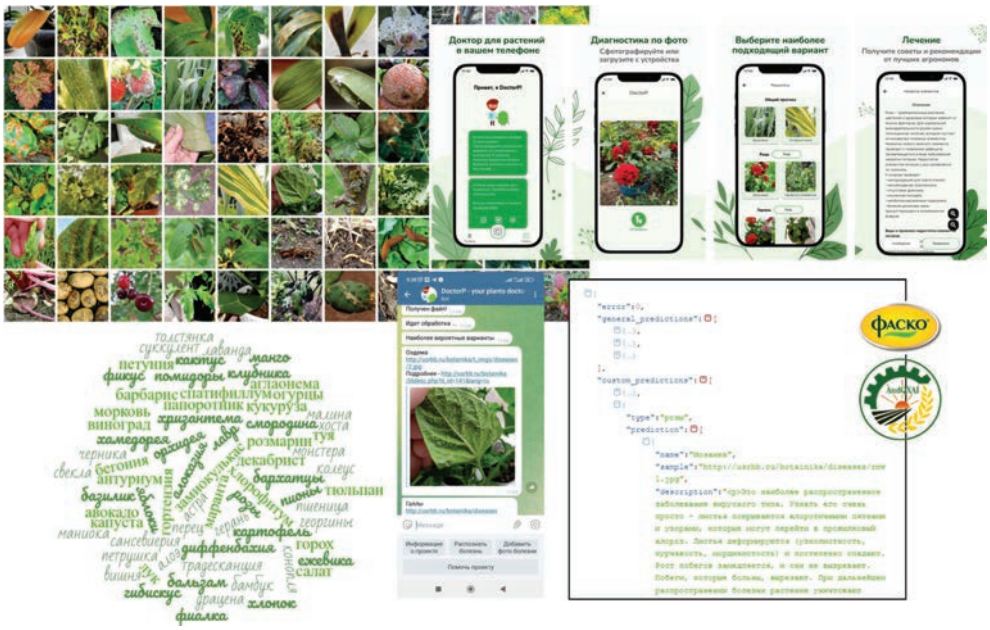


Fig. 7. Examples of DoctorP platform interfaces

models[27,28]. The platform's interface is accessible to everyone, from agricultural holding specialists to beginning gardeners, for whom a key feature of the program is its plant treatment recommendations verified by professional agronomists.

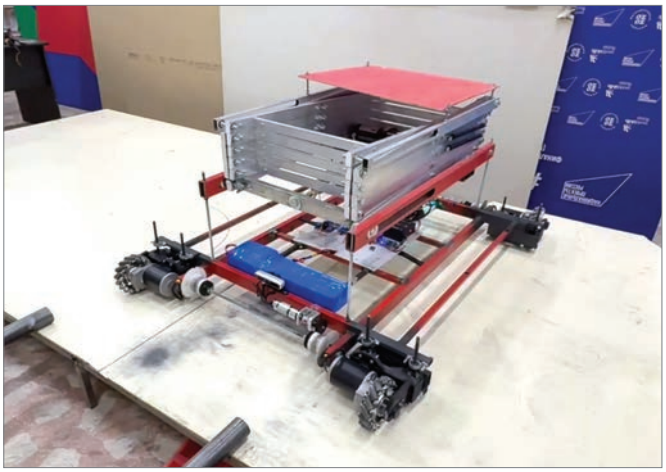
The obtained results attracted the interest of teams from various organizations. For example, similar classification algorithms were used in a joint project with the "Agrotechnologies for Future" research center at Moscow Timiryazev Agricultural Academy. It investigated the influence of light of various spectra on crop at specific stages of growth. Neural network models developed by the MLIT staff were used to assess the stage of development and weight groups of plants.

In addition to classification tasks, detection tasks are of great interest to agriculture. While the former requires identifying the specific disease in an image, the latter needs determining the coordinates of objects in the image and their classes. Initial experiments in this area utilized RCNNs (region-based convolutional neural networks), and later, networks based on well-known architectures designed for object detection, such as YOLO (You Only Look Once), were used. Network architectures were modified to optimize accuracy for specific types of objects and performance.

Mechanisms for detecting various potato diseases are being developed in a joint project between MLIT and Doka-Gene Technologies LLC. Hardware and soft-

[27] *Uzhinskiy A., Ososkov G., Goncharov P., Nechaevskiy A., Smetanin A.* Oneshot Learning with Triplet Loss for Vegetation Classification Tasks // Comput. Opt. 2021. V. 45(4). P. 608–614; DOI: 10.18287/2412-6179-CO-856.

[28] *Uzhinskiy A.* Evaluation of Different Few-Shot Learning Methods in the Plant Disease Classification Domain // Biology. 2025. V. 14. P. 99; https://doi.org/10.3390/biology14010099.



A fully functional prototype of a robotic complex

ware systems with high-resolution cameras mounted on agricultural equipment were used to identify problems in the fields. Detection and segmentation tasks are of particular interest. The former involves identifying image regions containing the object of interest — a plant with signs of disease. The latter allows for detecting regions of objects and all the pixels within them.

The research not only identified the most promising approaches to training models but also tested options for visualizing data on cases of plant disease detection in fields, and prepared recommendations for the software and hardware components of the complex.

Another area of research is analyzing hyperspectral images to identify patterns that can help detect diseased plants before visible symptoms appear. During the project, approaches to data labeling were developed to train and validate various models; multiple data preprocessing options were developed and tested, and the most promising were identified, along with spectral channel combinations that yield a vegetation index that most clearly reveals disease signs. Reliable class separation was achieved under controlled conditions.

Another rapidly developing area of research is the automation of monitoring and accounting in greenhouse complexes. The project's primary objective is to automate routine agronomist operations. It involves the development of an autonomous robotic platform capable of navigating various surfaces, recording relevant data, and performing high-altitude surveys. The resulting digital twin of the greenhouse complex will display up-to-date information on the number of plants per row and their characteristics, detected problems, data on various parameters (temperature, humidity, illumination), etc. The project combines various technical challenges related to the design and development of the platform's hardware components, robotic tasks (mapping, localization, autonomous movement, and route-based tasks), organizational tasks (image processing and displaying results on a map), and neural network tasks (tracking and counting, classification, localization, and identification of diseases and pests).

Currently, a fully functional prototype of a robotic platform, a prototype of a control and accounting system, and a number of models for plant counting, plant condition assessment, pest detection, and detection of signs of certain diseases have been developed.

Students from various institutes and universities, including Dubna State University, are actively involved in the projects. Students P. Goncharov, A. Smetanin, M. Gerasimchuk, E. Rezvaya, and A. Dorokhin have contributed to the research at various times.

In 2019, the joint interdisciplinary project BIO-HLIT was launched, implemented by staff from LIT and LRB JINR with the aim to create an information system for radiobiological research. The primary goal of the information system (IS) is to automate the analysis of experimental data obtained at LRB. This, in turn, will accelerate and simplify the work with this data by various research groups, simplify and accelerate the diagnosis of central nervous system (CNS) pathologies, and, in particular, the development of effective methods for the prevention and protection against ionizing radiation. The information system contains algorithmic modules that, using unified algorithmic approaches and IT solutions, support research into the influence of various factors on biological objects at the organismal, tissue, cellular, and molecular levels. One set of IS modules is aimed at studying morphofunctional changes in the CNS during physically induced neurodegenerative changes studied at LRB, specifically the effects of exposure to various types of ionizing radiation on small laboratory animals. In terms of data analysis, these studies involve collecting and analyzing video data reflecting the behavioral responses of laboratory animals during experimental testing using specialized setups. It should be noted that behavioral tests are a proven and widely accepted method for assessing cognitive function in laboratory animals, allowing for the identification of

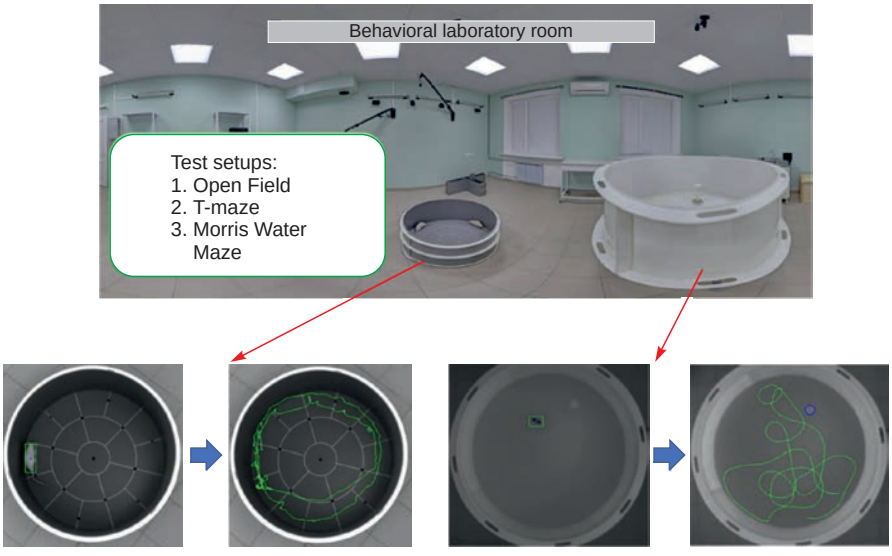


Fig. 8. The specialized laboratory behavioral room of LRB JINR and examples of the operation of the developed algorithms for tracking small laboratory animals in the Open Field and Morris Water Maze test systems

aspects of neural activity such as memory and learning impairments. This makes them an indispensable tool in the study of neurodegenerative diseases and the testing of treatment medications aimed at improving cognitive function and reversing brain disorders. However, despite the wide range of potential applications, the use of these tests is complicated by the time-consuming analysis of the resulting video data.

Algorithms based on computer vision and neural network approaches were developed, along with web services, to analyze experimental data obtained using the Open Field and Morris Water Maze test systems. The newly created information system also integrated a set of services and tools for storing and analyzing experimental data, as well as algorithmic blocks based on machine and deep learning methods and approaches, enabling the analysis of video data obtained during behavioral testing and images collected in DNA repair experiments.

The first version of the BIO-HLIT IS was developed in 2020 and continued to evolve with the active participation of LIT employees Yu. A. Butenko, M. I. Zuev, D. M. Marov, A. V. Nechaevskiy, D. V. Podgainy, and O. I. Streltsova, and LRB employees I. A. Kolesnikova, Yu. S. Severyukhin, M. G. Lalkovičová, K. N. Lyakhova, and D. M. Utina. LIT employees A. V. Stadnik, O. I. Streltsova, A. I. Anikina, T. Zh. Bezhanyan, S. Shadmehri, as well as A. I. Streltsov (Germany) and M. Yu. Bondarev from Dubna State University, contributed to the development of the algorithmic modules.

The information system is implemented as a web application and provides convenient, authorized, and secure access to the HybriLIT platform, including the Govorun supercomputer, and the ML/DL/HPC ecosystem, which includes a large number of frameworks and tools. A common interface for users is implemented using web technologies, allowing the interaction with the HybriLIT platform's database and file storage to edit and add data obtained during experiments[29].

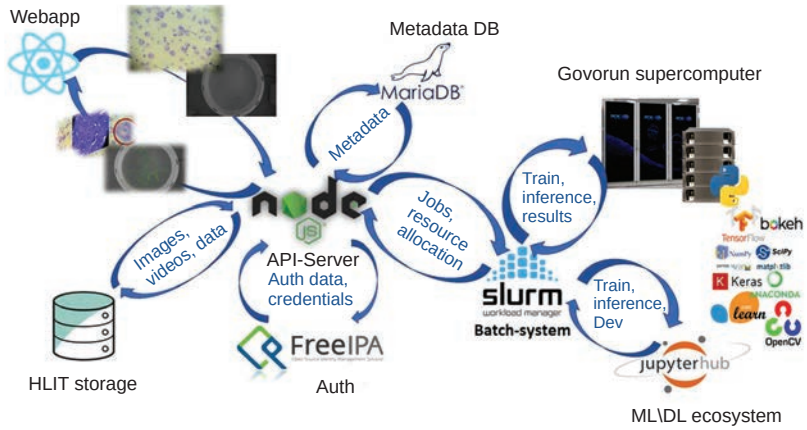


Fig. 9. Architecture of the BIO-HLIT Information System

[29] Information Systems for the Radiation Biology Tasks // Proc. Workshop on Information Systems for the Radiation Biology Tasks, Dubna, Russia, June 18, 2020; https://ceur-ws.org/Vol-2743/.

As part of the ongoing collaboration between MLIT and LRB, in 2024, the MOSTLIT web service was developed using the HybriLIT platform's ML/DL/HPC ecosystem — a tool for automating the detection of radiation-induced foci (RIF) in cell nuclei and for a subsequent analysis of their parameters. The service is designed to optimize the processing of experimental data obtained during radiobiological research, providing researchers with a convenient and effective analysis tool.

MOSTLIT uses a two-stage algorithm based on computer vision and deep learning to detect RIF in fluorescence images. This approach significantly accelerates data processing, minimizes human error, and produces images of individual cells with identified foci. Furthermore, the web service provides source images with numbered cells and analytical information, such as cell area, the number of RIF in each cell, etc. All results are available for download in a convenient text format, ensuring flexibility and compatibility with various statistical data processing software[30]. Thanks to the service's scalable architecture, developers are able to expand its functionality based on user feedback. This iterative development approach ensures the long-term relevance and effectiveness of the service for processing data obtained at LRB JINR and the Burnasyan Federal Medical Biophysical Centre.



MOSTLIT web service developers: S. Shadmekhri, M. I. Zuev, O. I. Streltsova, and T. Bezhanyan

[30] *Shadmehri S., Bezhanyan T., Bondarev M., Streltsova O., Zuev M., Chigasova A., Osipov A., Vorobyeva N., Osipov A. N.* A Deep Learning Model for Automated Quantification of DNA Repair Foci in Somatic Mammalian Cells // Phys. Part. Nucl. 2025. V. 56. P. 1623–1627.

The name "MOSTLIT" is an acronym formed from the initials of the names of the MLIT JINR employees directly involved in the development of the service, algorithm creation, and functionality testing: M. I. Zuev, O. I. Streltsova, S. Shadmehri, and T. Zh. Bezhanyan. The development is being performed jointly with colleagues from LRB under the supervision of A. V. Boreyko, with the active participation of T. S. Hramko.

The information system continues to evolve, with algorithms being developed to analyze radiobiological experiment data using the latest neural network architectures and computer vision methods. The system's development continues with the involvement of students from Dubna State University and Tver State University.

NEUTRON METHODS FOR APPLIED PROBLEMS

The Frank Laboratory of Neutron Physics of JINR conducts numerous applied studies using neutron methods, whose results have high innovative potential in medicine, energy, ecology, and other fields of economic and social significance. Moreover, the Laboratory carries out methodological research to develop neutron methods, expanding their potential for use, including in applied research.

TAGGED NEUTRON METHOD

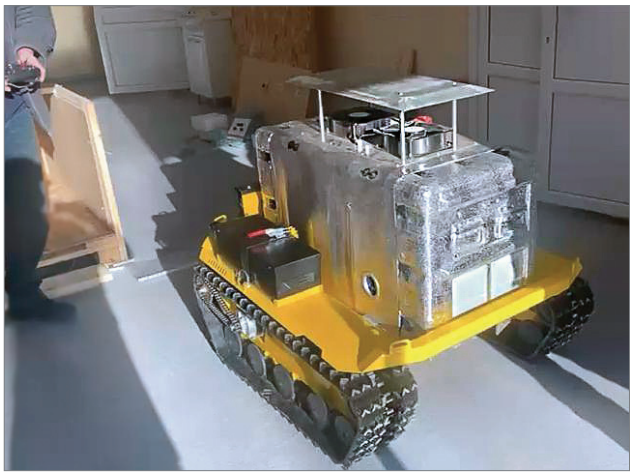
A key step in the development of the tagged neutron method (TNM) was the design of a portable neutron generator at the Dukhov Automatics Research Institute (Moscow) in 2003 under the supervision of E. P. Bogolyubov according to a technical specification from JINR. The portable neutron generator had virtually the same characteristics as the EG-5 accelerator, but instead of six storeys, it measured only 30 cm and was designed as a sealed-off device — the neutron tube was housed in a completely sealed casing.

Miniaturization of the neutron source opened the way for a variety of practical applications of TNM. One of the earliest applications was the search for diamonds within kimberlite rocks. Standard diamond mining technology involves crushing the ore and irradiating it with X-rays, which causes the diamond to glow and allows it to be sorted. However, glowing occurs only for diamonds completely freed from the rock. Therefore, the crushing and irradiation processes are repeated until the original kimberlite ore is ground to a size of 1 mm.



Diamond inclusions in a kimberlite sample

The tagged neutron method allows irradiating a piece of kimberlite



Neutron soil analyzer

rock with neutrons and identifying areas with increased carbon content – a sign of the presence of diamonds. In other words, it is possible to see the diamond at a stage when it is still hidden within the rock. The ability of TNM to determine the elemental composition in different spatial regions is very effective here. This was experimentally confirmed when an anomalously high carbon content was observed in one of 33 kimberlite rock samples, and when the sample was opened, two areas of small diamond clusters, each up to 7 mm in size, were discovered inside.

Ongoing collaboration with the Dukhov Automatics Research Institute has enabled the development of a finished commercial product — a neutron generator with a 9-pixel alpha detector with a 1,500-hour service life, which has found various practical applications. For example, it has become the basis for on-line elemental analyzers for raw materials on a conveyor belt, which operate on the TNM principle and provide information on the elemental composition of ore, coal, and cement on a conveyor belt every 40–60 s.

In 2025, a mobile neutron soil analyzer (NSA) was developed and tested in collaboration with Diamant LLC. It operates on the TNM principle and allows determining the elemental composition of soil in real time as the neutron module moves across the field, without prior sampling.

NEUTRON AND X-RAY SCATTERING METHODS

Research conducted at FLNP on the interaction of nanoparticles with amyloid fibrils, which cause Alzheimer's and Parkinson's diseases, is aimed at developing nanomedicines against amyloid aggregates. The research is carried out using small-angle neutron scattering (SANS) on the YuMO spectrometer. Neutron scattering allows monitoring the disaggregation of fibrils at the nanoscale under the influence of fullerenes and magnetic particles of magnetite in complexes with surfactants. The obtained data reveal the molecular mechanism of aggregate disassembly, paving the way for the development of nanomaterials with antifibril properties for the treatment of neurodegenerative diseases.

Biocompatible nanocomposites are a promising means of reducing the risk of antibiotic resistance. FLNP has developed biocomposites made from soy lecithin, chitin, and Ag/AgCl nanoparticles synthesized using a "green" method from plant extracts (turmeric, grape, and mint). SANS and small-angle X-ray scattering (SAXS) confirmed the nanoscale size of the components and the stability of the complexes. These materials exhibit high antimicrobial activity against *Enterococcus faecalis*, *Staphylococcus aureus*, and *Escherichia coli*, as well as cytotoxicity against HT-29 and HepG2 cancer cells without hemolytic activity, which is promising for medical applications.

The development of drugs based on water-soluble fullerenes is an important area in the search for new cancer treatments. Studies of C60 and C70 fullerene solutions in N-methyl-2-pyrrolidone (NMP) using SANS on the YuMO spectrometer and SAXS on the P12 BioSAXS instrument (PETRA III) revealed the mechanisms of cluster stabilization. Fullerene complexes with doxorubicin, cisplatin, and landomycin A demonstrate antioxidant activity and potential for cancer treatment. The results make it possible to optimize the synthesis of aqueous solutions for biotesting.

The development of new nanomaterials for lithium batteries and the optimization the properties of existing ones is a rapidly growing area of technology. Neutron studies using the YuMO spectrometer and the HRFD difractometer at FLNP JINR made it possible to investigate the structure of $Li_{1.5}Al_{0.5}Ge_{1.5}(PO_4)_3$ (LAGP) ceramic membranes for solid electrolytes. Doping with yttrium oxide homogenizes the material, increasing ionic conductivity due to the growth of grain contact areas. The deposition of lithium peroxide in carbon cathode nanopores in $Li–O_2$ batteries and the effect of additives (carbon black, graphene, CNT) on the porosity of LFP cathodes, which improves capacity and enchances electrolyte wettability, were also analyzed.

Important experimental results have been obtained for Prussian White-based sodium–ion batteries. *In situ* neutron and X-ray diffraction during cycling of an electrochemical cell revealed phase transitions in $Na_{2-x}Fe[Fe(CN)_6]_{1-y}\cdot\square\cdot yH_2O$ ($\square$ — $Fe(CN)_6$ vacancies, y — their number): the rhombohedral R-phase ($R\bar{3}$) during discharging and the cubic phase ($Fm\bar{3}m$) during charging. The identified large volume changes in the cubic phase during charging/discharging lead to structural degradation of some cathode materials for sodium–ion batteries. This opens up opportunities to reduce capacity losses, offering an effective alternative to the materials used in lithium–ion batteries.

Neutron methods are an effective tool for non-destructive testing of residual stresses in structural materials and equipment components of modern nuclear power plants. Using thermal neutron diffraction, FLNP conducts studies of residual stresses, lattice distortion, dislocation density, and sizes of coherently scattering regions (crystallites) in weld zones of reactor pressure vessel surveillance specimens reconstituted using various welding techniques (electron beam, laser, and electric arc welding). The obtained data on microstructural parameters allow predicting changes in the mechanical properties and strength of the reactor pressure vessel material. The results of these studies provide the necessary justification for ensuring safety and extending the service life of critical reactor components.

NEUTRON ACTIVATION ANALYSIS

Neutron activation analysis (NAA), a highly sensitive and accurate quantitative analysis method, was first used at FLNP in the late 1960s at the IBR-30 reactor. The commissioning of the IBR-2 reactor with its high neutron flux countibuted to the development of the method at the REGATA pneumatic transport facility. Initially, the method was used to determine the role of individual elements in the development of cancer, and since 1991, it has been widely used to assess atmospheric deposition of heavy metals based on the analysis of moss biomonitors in JINR Member States.

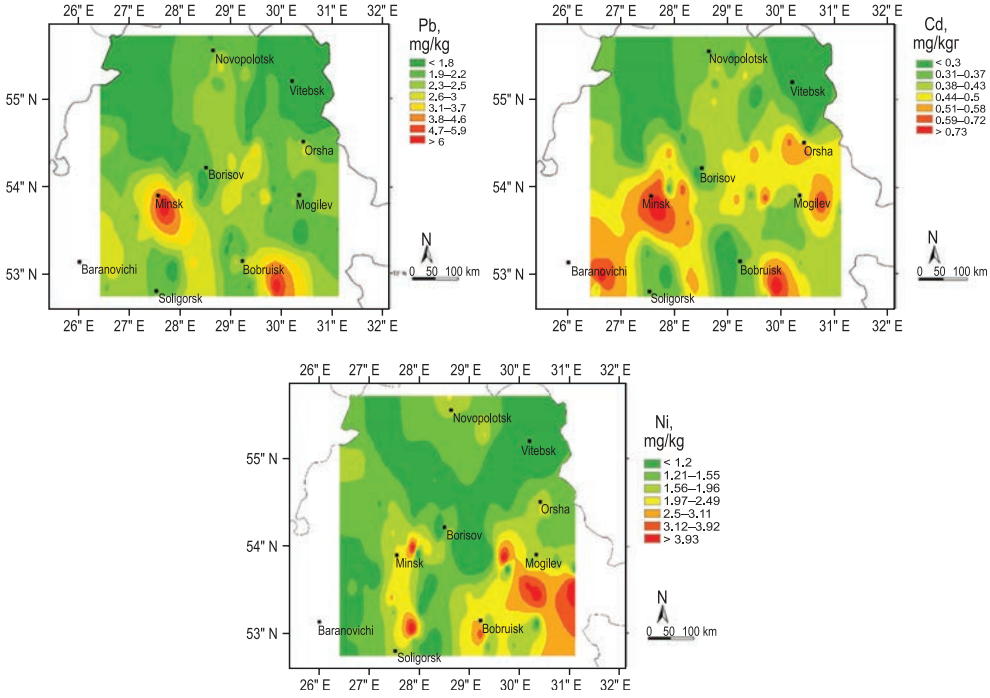
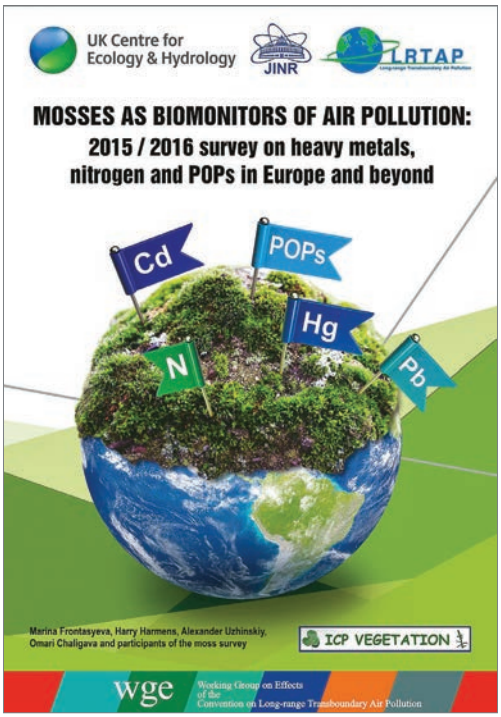


Fig. 10. Spatial distribution maps of lead (Pb), cadmium (Cd) and nickel (Ni) concentrations in moss samples collected in the Republic of Belarus

From 2014 to 2022, the UN air pollution program in Europe and partly in Asia on the basis of moss biomonitoring was coordinated by JINR (program coordinator M. V. Frontasyeva). In 2020, the JINR Publishing Department released a report from the Coordination Center of the UN international air pollution program in Europe. It contains distribution maps for 13 elements: aluminum, antimony, arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, vanadium, zinc, and nitrogen, as well as information on ozone and persistent organic pollutants.

In the early 2000s, NAA began to be widely used in biotechnology to develop pharmaceuticals based on the cyanobacterium *Spirulina platensis* and the bacterial leaching of elements from depleted ores. In 2009, the biological field was expanded to include two new areas: the use of biological objects for the development



Cover of the report on air pollution in Europe based on moss biomonitor analysis

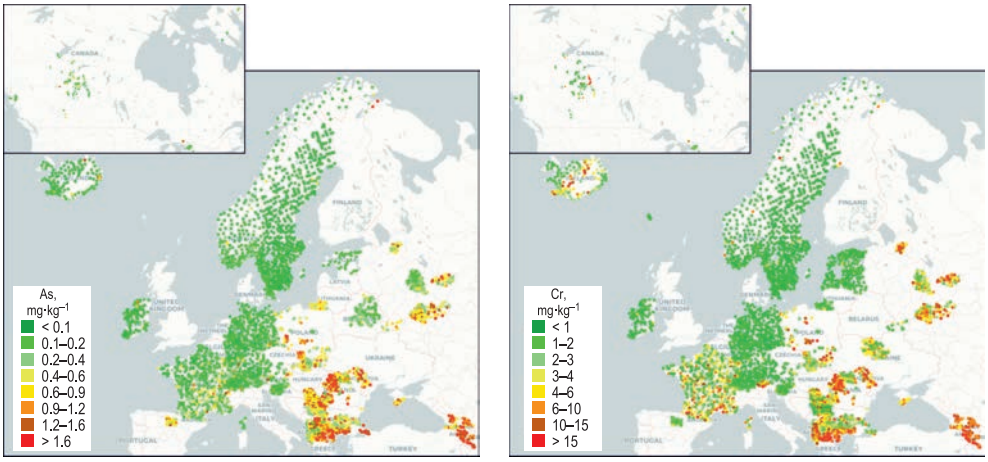


Fig. 11. Concentrations of arsenic and chromium in mosses. 2015–2016

of wastewater treatment technologies and the biosynthesis of metal nanoparticles. The work in these areas is ongoing in the Sector of Neutron Activation Analysis and Applied Research. The absorption capacities of biological, nonorganic, mineral-organic, and nanosorbents were tested to extract heavy metals and rare earth elements from industrial wastewater.

In the late 2000s and early 2010s, NAA began to be used in active biomonitoring to assess air pollution levels in urban areas. The first studies were conducted in

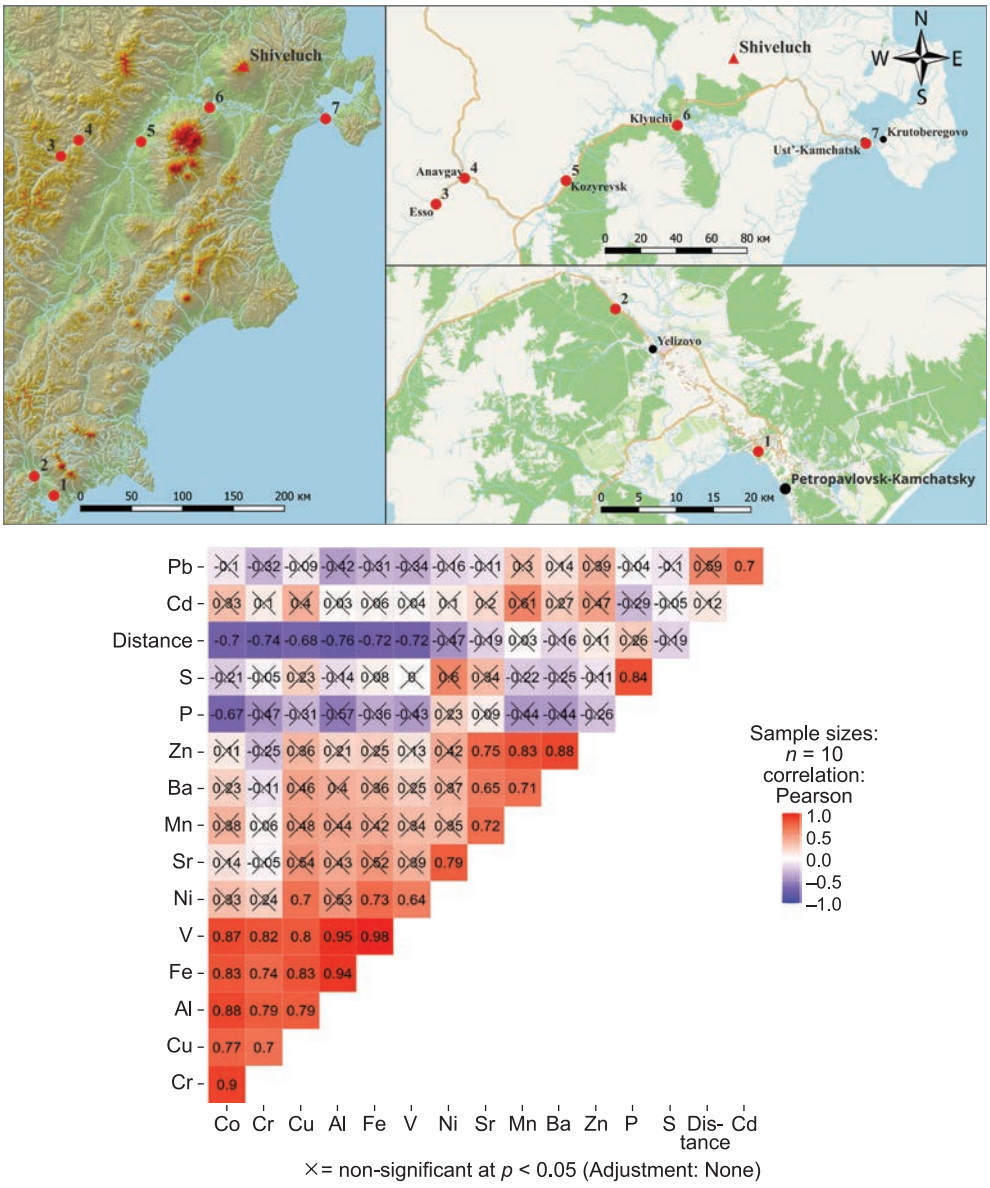
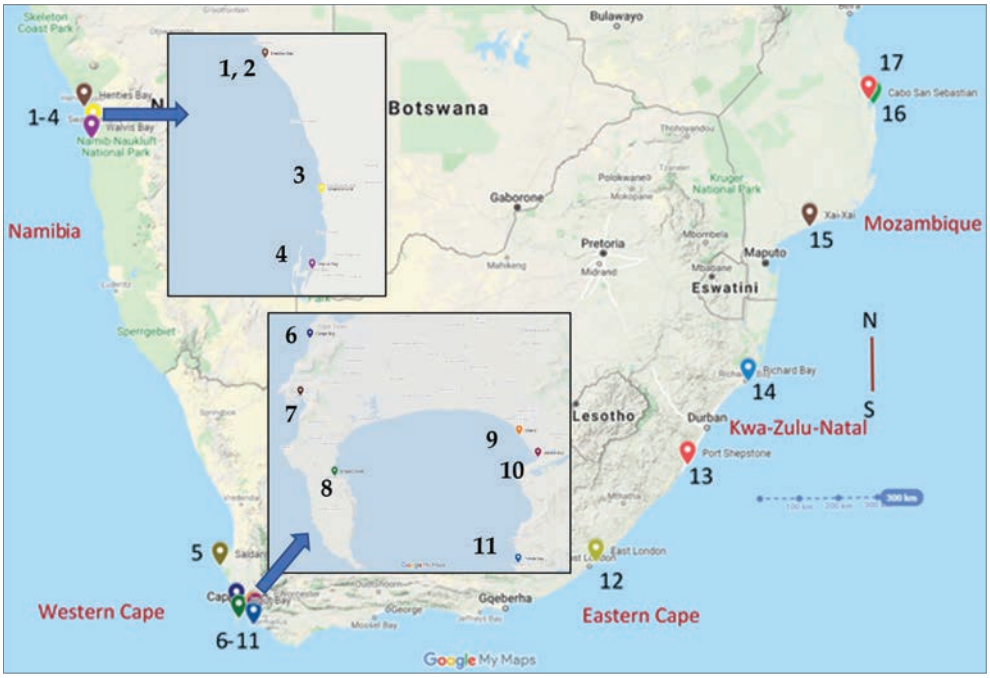


Fig. 12. Top: Map of moss bag exposure sites. Bottom: Correlation matrix for moss samples exposed in settlements located at different distances from the Shiveluch volcano (Kamchatka)

collaboration with the University of Belgrade. Over time, the geography of the research expanded significantly, and monitoring studies were carried out in a number of countries, including Azerbaijan, Vietnam, Kazakhstan, Egypt, Moldova, Mongolia, Russia, Romania, and South Africa.

At the same time, the Sector, in collaboration with Stellenbosch University, started using NAA in comprehensive marine biomonitoring studies, using bivalve



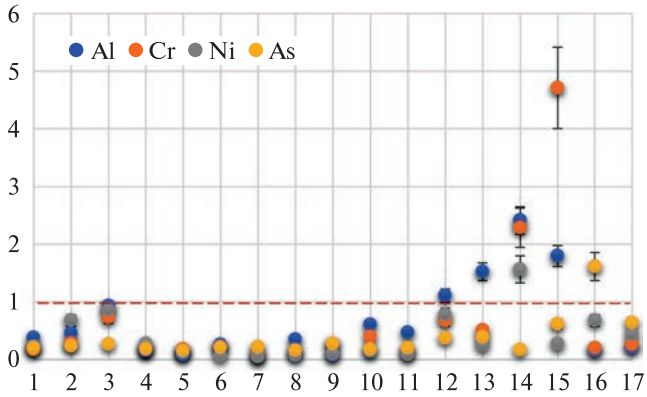


Fig. 13. Top: Map of mussel sampling in South Africa. Bottom: Risk factors for Al, Cr, Ni, and As in mussels sampled in the examined areas

mussels as biomonitors (Fig. 13). Algae, phytoplankton, corals, and sponges were also studied as biomonitors. These studies are of great interest for assessing the ecological state of coastal zones, developing mariculture, and food safety.

Alongside the development of new scientific fields, NAA automation was also underway. For example, between 2010 and 2014, as part of the IAEA program "Development of an Integrated Approach to Routine Automation of Neutron Activation Analysis", the Sector developed a database and a hardware and software system, including three automatic sample changing units for spectrometers at the REGATA facility (M. V. Frontasyeva, S. S. Pavlov, and A. Yu. Dmitriev).



The 8th International Workshop "Biomonitoring of Atmospheric Pollution" (BioMAP-8). Dubna, July 2–7, 2018



Employees of the Sector of Neutron Activation Analysis and Applied Research

In 2021, the method for determining the content of chemical elements using the neutron activation analysis at the REGATA facility of the IBR-2 reactor was certified (authors of the method: D. S. Grozdov, I. Zinicovscaia, S. S. Pavlov, K. N. Vergel). The corresponding certificate was issued by the All-Russian Scientific-Research Institute of Mineral Resources named after N. M. Fedorovsky.

In 2020, the second stage of the upgrade and automation of NAA at the REGATA facility was initiated, during which irradiation channel No. 1 and the control panel of the REGATA were replaced, a new NAA database was developed, and gamma spectrometry was automated (D. S. Grozdov, V. A. Galustov).

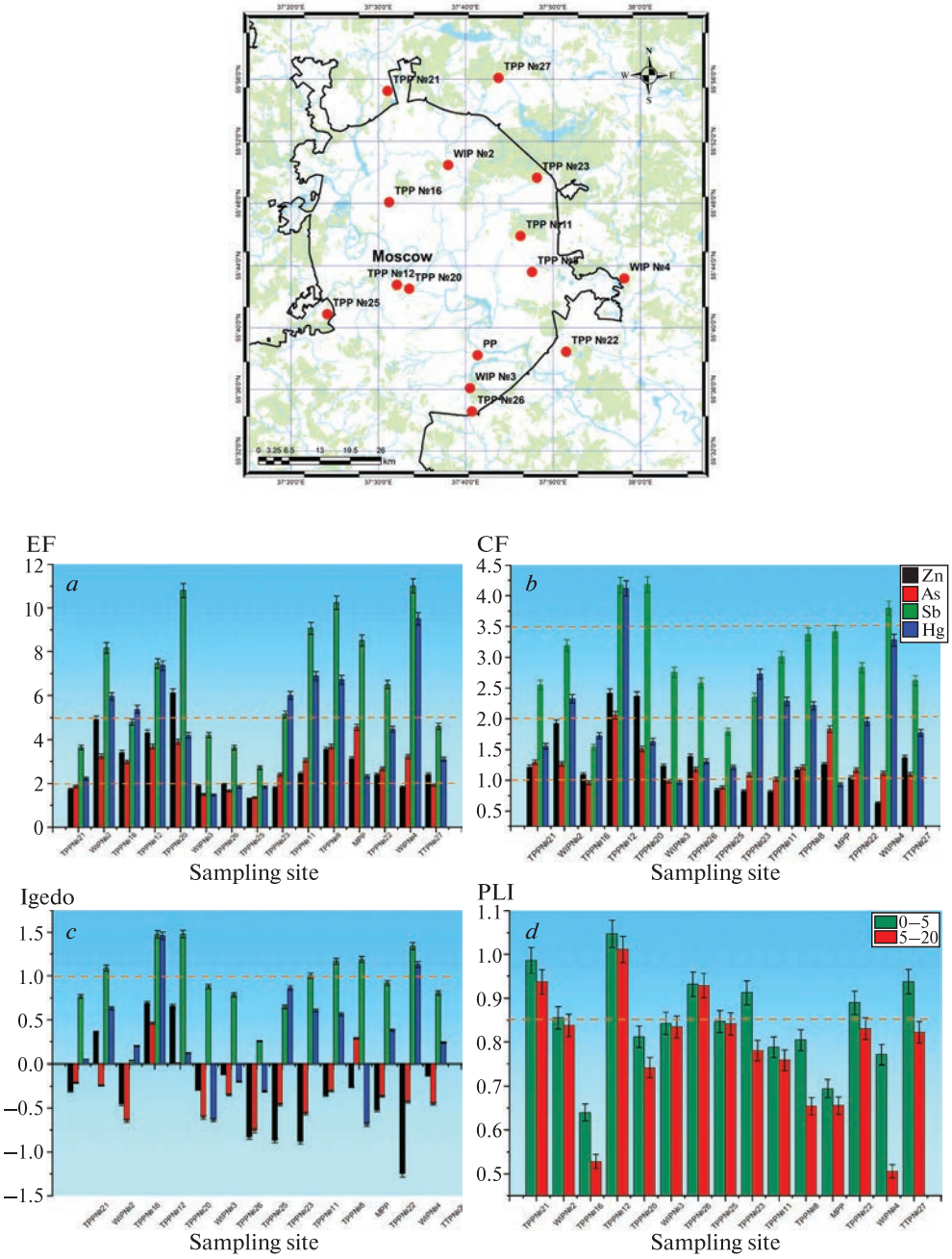


Fig. 14. Top: Map of soil sampling in Moscow. Bottom: Values of environmental indices

Over the years, NAA has remained an important tool for determining the elemental composition of soils, including agricultural soils, bottom sediments (marine and river), and rocks. Notable examples include studies of the elemental composition of bottom sediments in the Nile (Egypt), Zarafshon (Tajikistan), and Danube (Serbian sector) rivers.

In 2018, a number of new scientific areas emerged in the Sector, such as the use of microorganisms and plants for the bioremediation of contaminated soils, the assessment of the impact of metal nanoparticles on plants and animals, and the determination of the elemental composition of wines, coffee, medicinal plants, and other types of food products.

The NAA at the REGATA facility is also used to analyze unique samples. For example, fragments of a cotton cloth roll placed by cosmonaut Yu. Lonchakov and astronaut M. Fincke on the outer surface of the International Space Station were analyzed as part of the Test space experiment (Fig. 15).

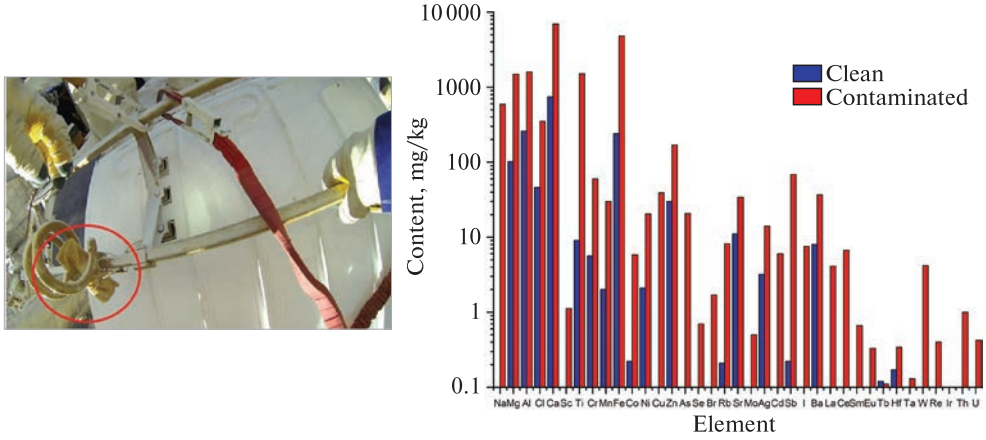


Fig. 15. Elemental composition of the cotton cloth attached to the outer surface of the International Space Station

Today, the neutron activation analysis at the REGATA facility of the IBR-2 reactor is a powerful analytical tool for solving problems in ecology, geology, nanotoxicology, archeology, medicine, and materials science.

METHOD OF NEUTRON RADIOGRAPHY AND TOMOGRAPHY

Since 2018, systematic studies of high-potential cement-based materials (S. E. Kichanov, D. P. Kozlenko, M. Balasoiu, I. Yu. Zel) for the construction of various types of radioactive waste storage facilities or for civil engineering construction have been conducted using the neutron radiography and tomography facility. The presence and nature of internal cracks or cavities are critical for such materials, as they can act as pathways for water penetration into the cement or concrete product and cause its deterioration. As part of this work, new approaches to analyzing

3D neutron tomography data (I. Yu. Zel) were developed for non-destructive microstructural testing of cement-based materials. The results obtained using neutron radiography and tomography are essential for developing new and improving existing technologies for synthesizing new compositions of promising cement-based materials, as well as for predicting the impact of external conditions (humidity, atmospheric precipitation, etc.) on their mechanical and physical properties.

The examples presented demonstrate the versatility of FLNP neutron methods for innovation, with potential application in healthcare, energy, ecology, and other fields.

PERSONNEL TRAINING

The history of personnel training began almost simultaneously with the Institute's history. As early as 1961, a branch of the Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University (SINP MSU) was established in Dubna. In order to systematically organize work, effectively plan and coordinate the efforts of all related participants in JINR's educational activities, an independent structural unit — the University Center — was established later, in 1991. In 1993, the first students from MIPT arrived in Dubna.

Svetlana Petrovna Ivanova, a theoretical physicist and talented and energetic educational organizer from the SINP MSU branch, made a significant contribution to the implementation of the idea of the University Center (UC). She became the first UC Director and led it until 2005. S. P. Ivanova was the initiator, inspirator, and driver of many important projects, including creating the UC facilities and resources, opening a graduate program at JINR, and organizing students' summer practice sessions, international schools, and visits by schoolchildren from participating countries.



JINR Vice-Director A. N. Sissakian, UC Director S. P. Ivanova, JINR Director V. G. Kadyshevsky. 1995

Along with the formation of the UC in 1994, the Dubna International University for Nature, Society and Man was opened, co-founded by JINR. Over time, it developed fields of study in support of JINR's scientific program, as well as JINR-affiliated departments, the number of which amounts to seven in 2025. Kazan Federal University, St. Petersburg State University, MEPhI, and MIPT each have one department, as well as two departments at SINP MSU. Students from these departments constitute the majority of students completing practice at the Institute, and a high percentage of them are employed in JINR laboratories.

The development of the Institute as a major educational center led to Dubna State University receiving federal status in 2022, and the SINP branch was transformed into an MSU branch.

As an international organization, JINR aims its human resources training efforts not only at the country the Institute is based in. Today, the JINR University Center offers a comprehensive set of programs and tools for training scientific and engineering personnel for interested Member States and other countries. These programs were actively developed in the early 2000s, and their development continues to this day. These include three-week international student practices at the Institute, longer practices START (in-person) and INTEREST (online), teacher training schools, and agreements with universities. JINR also hosts international trainings for directors and coordinators of science and higher education (JEMS), and is developing a network of Information Centers in various cities and countries.

JINR's programs and tools for personnel training have been developing most noticeably over the past 20 years, in line with the development of JINR and its diverse scientific program, as well as in response to demand from the Member States and partners. Over these years, the work of the UC was headed by JINR scientists: D. V. Fursaev (2006–2009), S. Z. Pakulyak (2009–2022), A. Yu. Verkheev (2022–2023), and D. V. Kamanin (since 2023).

The features of each program implemented by the UC are described below in more detail.

INTERNATIONAL STUDENT PRACTICE

The International Student Practice (ISP) program has been implemented at JINR since 2004. It was initiated by the JINR University Center and a number of universities in the Russian Federation, in particular, Moscow Engineering Physics Institute (MEPhI) and Moscow Institute of Physics and Technology (MIPT), Poland and the Czech Republic.

National groups of participants come to JINR laboratories for a three-week internship at the request of Plenipotentiaries of the Governments of interested Member States or national coordinators of Associate States. The ISP participants from among senior university students and postgraduate students are selected by the sending country, and the funding model is based on country grants from the JINR budget.



Participants of the International Summer Practice 2004 for undergraduate and postgraduate students with UC Director S. P. Ivanova and JINR Vice-Director A. N. Sissakian

The ISP program includes introductory lectures on JINR research and work on academic and research projects under the supervision of JINR specialists in international teams. This format allows students from different countries to exchange knowledge and experience, develop skills in teamwork, intercultural communication, and effective solving of sometimes challenging tasks.

A database of educational and research projects is constantly maintained and updated, accessible on the JINR website (http://uc.jinr.ru). Participants can select several projects from this database that match their research interests. Since 2023, an engineering practice has been added to this list, offering interested participants expanded opportunities for practical work.

An important component of the ISP is the cultural program, aimed at introducing the history and culture of the country JINR is based in to the participants. International days have also become a tradition, giving students the opportunity to represent their country and share cultural and folklore traditions.

As a rule, the working language of practices is English.

ISP GEOGRAPHY AND PARTICIPANTS

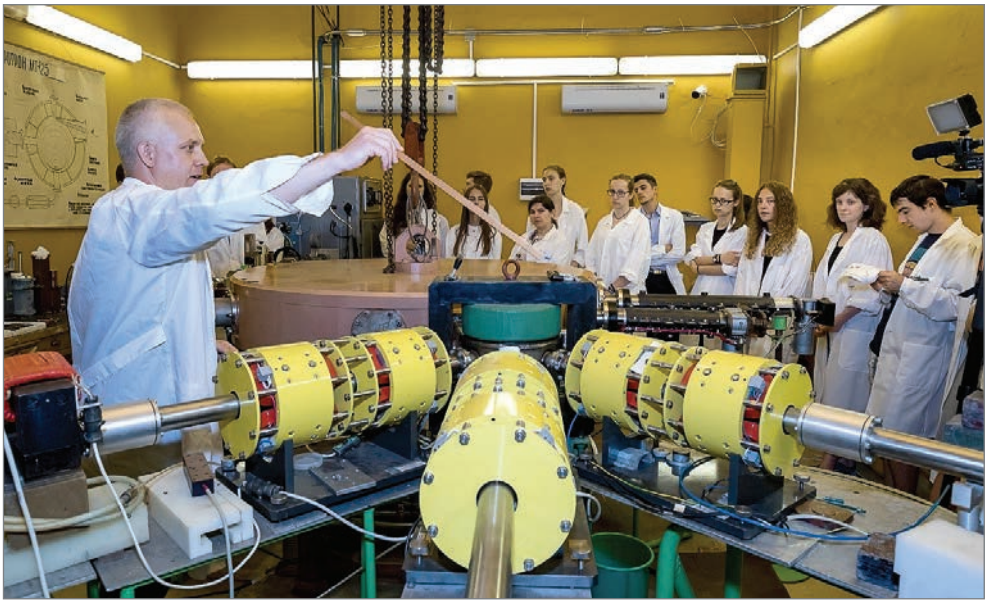
In 2004, the first year of its launch, 23 students participated in the ISP program, and in total, over the years of implementation up to and including 2025, 1946 participants from 20 countries have become alumni of the program.

Except for 2020 and 2021, when all in-person interactions were problematic due to the coronavirus pandemic, interest in the ISP has steadily increased. In 2024, Vietnam joined the program, sending its first group of six students; in 2025, their number doubled. Among the ISP participants, the largest groups came from South Africa (418 participants since 2007) and the Arab Republic of Egypt (328 since 2009). These countries view personnel training as a priority for deepening their involvement at JINR. From the very beginning, specialized ISP programs were organized for students from these countries. Serbia followed the example of South Africa and Egypt, also actively using this program to train national special-





"International Morning" in the program of the ISP 2019 autumn session. Participants from Cuba demonstrate elements of popular Cuban dances, a participant from Mexico talks about the traditions of Mexican holidays



FLNR employee G. Kaminski (Poland) conducts an excursion to the MT-25 microtron for participants of the ISP 2018 summer session from Poland, the Czech Republic, and Slovakia



A joint event for participants of the International Student Practice and the 12th JEMS Training Program at the JINR Visit Center in June 2019 held by D. V. Kamanin, Head of the JINR International Cooperation Department

ists in nuclear science and technology. During the first decade of the ISP program, students from Poland, Romania, and the Czech Republic — more than 50 students from each of these countries — also actively used it.

ISP PROSPECTS

Over time, the general concept of the International Student Practice was further developed, with South African colleagues playing a pioneering role. South African partners have always emphasized the value of using the ISP in training their national scientific and engineering personnel. Seeking to increase the impact of their participation in the program, several years ago, South Africa initiated a special Summer School (SAINTS Summer School) in South Africa in anticipation of the planned arrival of South African students in Dubna. The main goal of the Summer School is to give students an insight into the scientific research in JINR laboratories and the research facilities where they will be completing their practice, to guide them in choosing a future research project based on research already being conducted in joint teams by South African and JINR scientists, and to possibly choose a supervisor. Lectures at this school are delivered by a mixed team of lecturers from JINR laboratories and South African partner organizations.

The first SAINTS Summer School was held in South Africa in January 2023. Over the three years of its existence, it has proven its effectiveness in enhancing South Africa's ISP participation. South Africa's successful experience has not gone unnoticed and has generated strong interest from other countries. As a result, following consultations between the ISP participation national coordinators of South Africa and Egypt, preparations are underway to implement the first joint ISP program in 2026.

Starting in 2026, it is planned to synchronize in South Africa and Egypt the selection of students and the conduct of preparatory events for participation in the ISP, which is scheduled to be held at JINR for African participants in the second half of June – early July.



South African students during their practice

Rudolf Nchodu, National Coordinator for South Africa's ISP participation, shared his impressions of South Africa's participation in the ISP program and his plans for the future:



Human capacity development became a strategic priority right from the start of SA–JINR collaboration and continues its prominence to the present day. A key component of this initiative is the structured two-phase training program, comprising the Summer School at iThemba LABS and the International Student Practice at the Joint Institute for Nuclear Research in Dubna (Russia).

The first ISP for South African students was held in December 2007, with 23 students from 10 universities, and then moved to September and is now held in June/July to coincide with the South African universities' winter holidays.

Many of the participants in the first ISPs are now leaders in academia and industry in South Africa. Notably, Dr Ntombizikhona (Zina) Ndlovu Ndabeni, who in 2010 did a PhD at the Frank Laboratory of Neutron Physics (FLNP) and continues to collaborate with FLNP researchers and co-supervises South African students at the laboratory. Drs Jacques O'Connell and Jaco Olivier from Nelson Mandela University (NMU) participated in the ISP in 2008. They immediately recognised the opportunity for long-term collaboration between FLNP and NMU. Since 2009, this collaboration has grown to include groups from Belarus, Kazakhstan, and Serbia. The NMU–FLNP team has been awarded four research grants of the National Research Foundation of South Africa and JINR, they have published more than 60 peer-reviewed articles and take part in collaborative research visits at each other's institutions annually.

Gina El-Feky, President of the Academy of Scientific Research and Technology of Egypt and Plenipotentiary of the Government of Egypt in JINR, spoke about Egypt's experience in using ISP capabilities to train Egyptian specialists:



ARE students started participating in the International Student Practice program, run by the JINR University Center, and as of today, a total of 328 senior students and postgraduates from ARE have taken part in the program since 2009.

The ISP program provides motivated Egyptian students with an opportunity to stay updated on the scope of scientific research conducted at JINR; to do a research project at JINR basic experimental facilities under guidance of qualified specialists; to establish contacts with potential scientific supervisors for a future extended stay at JINR to prepare a thesis. In fact, this program could be considered as a starting point in scientific careers of many accomplished Egyptian researchers.

Today, with account of the plans of our Government to step up developments in nuclear science and industry, including nuclear power, we shall be using the ISP program among other instruments to satisfy the rising demand for highly qualified researchers and engineers. Furthermore, we see expansion and sophistication of ISP-related activities favouring development of the network of JINR Information Centers and, in a larger context, serving as a driving force strengthening the international research community of JINR Member States and partner countries.

“STUDENTS’ SUMMER”: START AND INTEREST PROGRAMS

The START (STudent Advanced Research Training) student program was launched at JINR in 2014, initially under the name Summer Student Program. The idea of the program belonged to the UC, but the need for such a tool for attracting young people to the Institute had been long-standing. The START program essentially grew out of international student practices, but unlike those, it was intended to enable Institute staff to independently participate in student selection, and the students to carry out research projects at a more advanced level. Furthermore, similar programs already existed at major international research centers such as CERN, DESY, GSI, and others.

The initiative was supported by the JINR Directorate, represented by Director V.A. Matveev, and was enthusiastically accepted by leading Institute staff who became the first to supervise the students’ research projects.

The program invites students majoring in natural sciences, engineering, and IT who have completed three or more years of undergraduate studies at universities, as well as first-year postgraduate students from around the world. Selected students have the opportunity to complete a full-time 6–8-week internship at JINR, where they work on real scientific and engineering problems under the guidance of lead-



Participants of the START 2022 summer session at the “Arrow of Time” exhibit of the “JINR Basic Facilities” multimedia exhibition at the Mir Cultural Center





Participants of the Summer Student Program 2017, together with the Director of the JINR Museum, N. S. Kavalerova, study the history of the Institute (left), and during their free time, they go to Lipnya Island together with participants of the International Student Practice (right)

ing Institute specialists. Upon completion of the program, participants prepare and publish reports on their work during their stay in Dubna on the program website; all reports are publicly available. Over the past decade, START program participants have published 907 scientific papers. The website start.jinr.ru was created to facilitate the collection of applications, their sorting, posting of program information, automation of newsletters sending, and publication of participants' reports.

Participation in START provides the opportunity to find a supervisor for a future bachelor's, master's, or candidate's dissertation, increasing the chances of becoming part of the Institute's large international team.

In addition to the program's core scientific component – project work – students are offered excursions to the Institute's operating facilities, the JINR multimedia exhibition, and cultural events.

More than 500 students from 34 countries have participated in the program over the course of its existence.

Over the past ten years, the largest groups of START program participants have come from Armenia, Belarus, Cuba, Egypt, Mexico, Russia, and Uzbekistan. Interest in the program continues to grow, as evidenced by the increasing number of applications and the expanding geography of participating countries. The program's success is further demonstrated by the fact that approximately 20% of START participants find employment at the Institute after completing the program. Among today's START project heads there are former START participants who completed the program as students.

In 2020, aiming to adapt to the challenging conditions of the COVID-19 lockdown, the University Center launched a new program for students from around the world. It was called INTEREST, an acronym for INTErnational REmote Student Training. The program was unique in its kind, and JINR became the first international scientific center to use this technology for interacting with students.

The program allows getting acquainted with the Institute's activities and conducting research projects remotely, without leaving one's own house. The program's information platform is the website interest.jinr.ru, where students and JINR staff members can register to propose research projects for remote implementation.



VBLHEP Senior Researcher A. A. Aparin conducts an excursion for START 2025 summer session participants from Belarus, Cuba, Egypt, Indonesia, Mexico, Russia, South Africa, Spain, Tunisia, Turkey, Uzbekistan, and Vietnam

The program helps establishing useful contacts, finding a supervisor for one’s thesis, and demonstrating one’s potential during the process, thus increasing chances of being selected for in-person JINR trainings, such as START. Furthermore, the work completed remotely within the program can serve as a preparatory foundation for future larger-scale projects.

Throughout its existence, the program has attracted 450 students from 39 countries. Approximately 80 JINR employees are registered as project heads on the website.

Repeated participation in the INTEREST program is quite common. The absolute record holder for this statistic is Le Binh An, a Vietnamese citizen and currently a researcher at the Flerov Laboratory of Nuclear Reactions, who participated in INTEREST five times. He shared his impressions:



My journey to become an official employee of the Joint Institute for Nuclear Research began with the participation in the INTEREST International Remote Student Training program when I was a university student.

During the waves, the supervisors guided me with great interest and dedication through tasks which were given to accomplish the goal of training. In fact, the enthusiasm, commitment and professionalism of my supervisors, as well as my passion for nuclear science, motivated me to repeat participation in INTEREST five times.

Ultimately, with the support from Professor Le Hong Khiem, at that time the Plenipotentiary of Vietnam in JINR, I applied for work at the Joint Institute and was accepted.

My participation in INTEREST proved to be very valuable and provided preliminary insights for forming physical thinking, which keep me motivated in my current work. I believe this program is useful for any student from anywhere on the globe dreaming about a future career in nuclear science.

JEMS TRAINING PROGRAM

PROGRAM STRUCTURE AND ORGANIZATION

JEMS is a five-day training program for organizers of international scientific and educational projects. It provides a comprehensive presentation of JINR as an international intergovernmental scientific organization, its research planning and organization principles, and the main areas and results of work at all of the Institute's laboratories and the UC. This program includes lectures and presentations by heads or responsible employees of JINR departments. Visits to JINR research infrastructure facilities, roundtable discussions, and direct negotiations with participants and delegations are also organized.

JEMS: FACTS AND FIGURES

A total of 365 people from 35 countries and one international organization (AAEA) participated in the 27 JEMS trainings held from 2017 to 2025.

Participants represented both JINR Member States and Associate States, as well as countries with no formal ties to the Institute at the time of their participation. The largest group — 109 participants over the entire program period — came



Participants of the first JEMS program in April 2017. In the center is Salem Hamdi, Director of the Arab Atomic Energy Agency, an international intergovernmental organization that opened the JINR Information Center at its headquarters in 2023



Closing of the 21st JEMS training with the participation of JINR Director G. V. Trubnikov. Participants included the heads of JINR Information Centers in Arkhangelsk, Vladivostok, Tomsk, and Petropavlovsk-Kamchatsky

from the country JINR is based in. Excluding it, 49% of JEMS participants came from the Member States and 37% from the Associate States, where the demand for getting acquainted with JINR was particularly high. The most active Member States, sending the largest number of participants during the period under review, were Vietnam (38), Bulgaria (29), and Egypt (18), primarily during their Associate



Signing the Cooperation Agreement between JINR and the University of Havana on the sidelines of JEMS-13 in September 2019



Among the participants of JEMS-13 are Plenipotentiary of Vietnam Le Hong Khiem, future Plenipotentiary of Egypt G. El-Feky, and Serbian Cooperation Coordinator L. Hadžievski

State status. South Africa holds the record among the Associate States using this tool (62 participants), followed by Serbia (24).

Regarding the composition of JEMS participants, they primarily represent universities, research centers, and national and international specialized agencies. However, the university community significantly predominates in this composition: from 2017 to 2025, 207 university representatives participated in JEMS, accounting for almost 60% of the total number of participants. Research centers were second in demand, with 100 participants, and scientific bureaucracy (heads and staff of national and international specialized agencies) came in third, with 58 participants.

A notable feature of JEMS programs are visits by VIP delegations and individual VIP guests, including officials from JINR Member States who wished to personally become familiar with the Institute in detail: Plenipotentiary of Vietnam Le Hong Khiem, Plenipotentiary of Mongolia S. Davaa, Plenipotentiary of the Czech Republic M. Vyšinka, Member of the Finance Committee J. Dona (Cuba), Chairman of the PAC for Condensed Matter Physics D. L. Nagy (Hungary), Member of the Finance Committee K. A. Ghinescu (Romania), Member of the Scientific Council R. Rashkov (Bulgaria).

Over the years, JEMS participants have included top-level executives from relevant national and international organizations, such as the Director General of the Arab Atomic Energy Agency (AAEA), the Deputy Director General of the National Research Foundation of South Africa (NRF), and the President of the Egyptian Atomic Energy Authority (EAEA).

"PHYSICS TEACHER INFLUENCED MY CHOICE OF PROFESSION": UC'S WORK WITH SCHOOL TEACHERS

The history of the JINR scientific schools for physics teachers began in 2009, when the European Organization for Nuclear Research (CERN) decided to open national programs for school physics teachers with the involvement of lecturers and guides speaking the native languages of the participants.

Only JINR was able to handle all the logistical, visa, and organizational issues related to implementing the program in the Russian language. The Institute's Directorate supported the idea, entrusting the work to the UC leaders. In 2009, the first All-Russian Scientific School for young Russian physics teachers was held, organized at the initiative of the Ministry of Education and Science of the Russian Federation and JINR. Lectures at the School were delivered by JINR staff members D. V. Fursaev, G. A. Chelkov, S. V. Shmatov, V. V. Korenkov, R. Lednicky, N. I. Zimin, as well as by colleagues from partner organizations. This significant event marked the beginning of a new focus for the UC and JINR: working with school teachers as a "multiplier" in attracting young people to scientific and engineering careers.

Over the years, lecturers from the Budker Institute of Nuclear Physics SB RAS, St. Petersburg Nuclear Physics Institute named by B. P. Konstantinov, and other organizations of the country the Joint Institute is based in have participated in the program. Mick Storr was one of the founders and directors of the teacher training programs for over ten years. JINR provided substantial financial support to the participants. Russian-language programs for school teachers were held at CERN until 2019. A total of 12 schools were held during this time, attended by 403 teachers from Armenia, Azerbaijan, Belarus, Kazakhstan, Moldova, Russia, Switzerland, and Ukraine.

Just one year after the launch of CERN's Russian-language scientific schools, a similar program was organized at JINR for teachers from the Institute's Member States. Fourteen such international scientific schools were held from 2010 to 2025.

"I enjoyed the opportunity to work with modern equipment and see the application of physical laws in real-life experiments. The School helped me better



The JINR–CERN videoconference for participants of the JINR Scientific School for physics teachers at the UC conducted by UC Director S. Z. Pakulyak. 2011



Participants of the School for teachers from Belarus, India, Russia, and Ukraine with their best students on an excursion in the Synchrocyclotron hall. June 2018

understand how to connect the school curriculum with real life and make lessons more interesting and understandable for pupils", said Irina Kuzminykh, a teacher from the Tyumen Region (Russia), sharing her impressions of School-2025. "For me, this wasn't just a scientific educational program, but a truly unforgettable immersion into the world of real science. I took a fresh look at physics and got a deeper understanding of its scale and significance", wrote Medina Asylbek from Almaty (Kazakhstan).



UC Leading Researcher I. A. Lomachenkov conducts a laboratory practical at the JINR Scientific School for physics teachers from the Kamchatka Region. 2023



JINR Director G. V. Trubnikov shows Russian President V. V. Putin the textbook "Engineers of the Future" in the MPD detector hall of the NICA complex. 2024



JINR Vice-Director L. Kostov (Bulgaria) welcomes the participants of the first "Teachers of the Future" School for students majoring in physics and mathematics — future school teachers — at the JINR Scientists' Club. February 2025

The UC's annual range of scientific schools for physics teachers has expanded to include three main formats: an international scientific school for teachers from JINR Member States, a scientific and methodological school for teachers, and the "Teachers of the Future" school for students majoring in natural sciences who have

decided to dedicate themselves to teaching physics in schools and are taking their first steps in this direction. In 2025, the school format was first piloted for methodologists from educational centers in South Africa.

The main goal of JINR's scientific schools is to bridge the gap between schools and fundamental science and to promote modern scientific knowledge to a wider audience. Programs for teachers include not only lectures by leading JINR scientists but also excursions to experimental facilities, laboratory work, practical training in the JINR Virtual Laboratory, and mastering of materials from the educational and methodological complex "Physics. Engineers of the Future" (edited by Yu. A. Panebrattsev (JINR)).

Throughout their existence, the physics teacher training programs have attracted over 600 teachers from Armenia, Azerbaijan, Belarus, Bulgaria, India, Kazakhstan, Moldova, Poland, Russia, South Africa, and Ukraine. JINR Information Centers now play a significant role in forming the groups of teachers who come to Dubna for teacher training.

CHILDREN ARE OUR FUTURE: JINR PROGRAMS FOR PUPILS

JINR University Center views work with children, which has been actively developing since 2009, as part of JINR's career guidance activities, carried out for the purposes of training qualified personnel for science.

During this period, significant experience has been accumulated in implementing a variety of programs for schoolchildren in the country JINR is based in and other JINR Member States. In particular, in Russia, with JINR's support, the regional robotics tournament "CyberDubna", the technical hackathon "Dubna", the JINR Days of Physics festival, and the International Computer School, first held in Dubna in 1989 for children from JINR Member States (Czechoslovakia, Germany, Bulgaria) and the Soviet Republics, are regularly held.

Since 2021, the JINR University Center has been organizing a Scientific School for students of the Children's University of the Egyptian Academy of Scientific Research and Technology. Fifteen students are selected through a competition from hundreds of applications from across Egypt. They will undergo an intensive program at JINR: an introduction to the NICA megascience project, visits to the Institute's laboratories, and laboratory work at the JINR University Center.

"The Arab Republic of Egypt places special emphasis on education and personnel training in its cooperation with JINR. It is well known that training personnel for modern science and for working with a complex scientific infrastructure requires modern approaches, including motivating talented schoolchildren so that they can make conscious scientific choices. As our Egyptian partners say, attracting schoolchildren to physics is a very important task for Egypt. And for JINR, the goal is to ensure that the Institute becomes a second home for some of them in the future", noted D.V. Kamanin, Director of the JINR University Center, emphasizing the importance of such schools.



A team of young scientists, specialists, and engineers from the Institute at the All-Russian Festival "Science 0+". Moscow, October 2022



Students of the Children's University of the Egyptian Academy of Scientific Research and Technology near D. I. Mendeleev's Periodic Table. September 2022



Pupils from grade 2 of Lyceum No. 6 named after Academician G. N. Flerov were among the first visitors to the exhibition "JINR Basic Facilities" at the Mir Cultural Center on April 15, 2021



VBLHEP Senior Researcher M. M. Shandov delivers a lecture "The NICA Accelerator Complex: The Universe in the Laboratory" at the Science Festival held at the Central Botanical Garden of the National Academy of Sciences of Belarus. Minsk, September 6, 2025

FROM STUDENT TO SCIENTIST: JINR-BASED DEPARTMENTS AND STUDENT PRACTICES

The first JINR-based departments opened back in 1961: two departments at the MSU Physics Faculty trained specialists in elementary particle physics and nuclear physics. Today, there are thirteen JINR-based departments at six Russian universities: Kazan Federal University, Lomonosov Moscow State University, National Research Nuclear University MEPhI, Moscow Institute of Physics and Technology, St. Petersburg State University, and Dubna State University.



The first joint JINR–MIPT School on the Physics of Quark-Gluon Matter was held in March 2023

The programs of the JINR-based departments cover specializations in nuclear physics, elementary particle physics, condensed matter physics, theoretical physics, technical physics, and radiobiology. The University Center develops and coordinates a unified educational process for these departments, engages leading Institute staff in teaching, and assists in organizing the research work for senior students in the Institute's research teams. The departments' curricula are supplemented with specialized courses in line with the research areas of JINR as a core research institute. Many students who have completed internships at JINR become Institute staff members and remain here after graduation.

On February 28, 2022, the Government of the Russian Federation adopted a resolution on amendments to the charter of Lomonosov Moscow State University, establishing a branch of MSU in Dubna. E. E. Boos became its head. The branch was based on the existing SINP MSU structural unit and two departments of the MSU Physics Faculty in Dubna.



On September 2, 2022, a meeting was held at the MSU branch in Dubna, which opened on the basis of the SINP branch, between students of the departments of Elementary Particle Physics and Fundamental Nuclear Interactions, their supervisors, the leadership and teachers of the departments and the branch, as well as representatives of the JINR Directorate

The branch offers master's programs entitled "Fundamental and Applied Nuclear Physics", "Particle Physics", and "Methods and Technologies for Data Processing in Heterogeneous Computing Environments" under the supervision of leading JINR scientists G. V. Trubnikov, V. A. Matveev, and V. V. Korenkov.

In the long run, the branch aims to expand its range of areas in collaboration with the Chemistry, Biology, Computational Mathematics and Cybernetics, and other faculties of Moscow State University. The MSU branch in Dubna was established at the initiative of JINR and utilizes the capabilities of the Institute as a unique international intergovernmental organization in the Russian Federation to make connections and apply scientific results and best educational practices through collaboration with international partners and participation in international projects aimed at training personnel for fundamental research in JINR Member States.

Students from any university in the relevant fields of study can participate in educational, industrial, and pre-graduation internships at JINR. Universities sign an agreement with JINR to organize the internship. Under this agreement, the JINR University Center can assist with finding a supervisor and developing an individual education plan, issue an order for the student to undertake the internship, and reserve a place in the dormitory.

The number of undergraduate and postgraduate students participating in pre-graduation and industrial internships and specialized schools of the University Center has been steadily growing year after year. In 2022–2023, the Joint Institute for Nuclear Research hosted 444 students for internships, and in 2024–2025, this number was 785 (including 67 participants in specialized schools held by the UC for MIPT, TPU, and HSE). These students are primarily from Russian universities, but also include students from Kazakhstan, Belarus, Vietnam, China, Tajikistan, and other countries (2025 data).

The Institute's laboratories host the majority of students for internships. In the summer of 2025, 62 students completed internships at MLIT, 81 at FLNP, 7 at LRB, 86 at BLTP, 188 at VBLHEP, 72 at DLNP, and 89 at FLNR. However, the infrastructure departments were also popular with students from specialized universities (12 students were accepted in the summer of 2025), meaning they too can expect to be replenished with qualified personnel in the future.

In addition to university students, college students can also undertake internships at the Joint Institute. For example, starting in 2025, JINR accepts students from the branch of the Moscow Regional Polytechnic College for internships, who can later become employees in engineering and industrial jobs at JINR's research and infrastructure facilities.

POPULARIZATION OF JINR'S RESEARCH AND CAREER GUIDANCE WORK

Popularization of JINR's scientific research and achievements, as well as career guidance for students and schoolchildren, aimed at attracting future talents to the Institute, are the key component of the JINR University Center's activities. The University Center's Group of Social Communications has been addressing these tasks since 2017. It was established to develop and implement a wide range of popular science and career guidance events as part of a comprehensive program to shape public opinion among narrow target audiences — schoolchildren and students, as well as teachers and parents.

In collaboration with JINR laboratories, JINR-based departments, and Information Centers, the Group develops various information materials, including exhibitions, printed materials, and videos, for further distribution. A mobile exhibition on scientific research conducted at JINR, developed jointly with scientists from all JINR laboratories, travels to career guidance forums, science festivals, and exhibitions at universities in Russia and abroad.

For schools and universities, the Group organizes popular science lectures by scientists of the Joint Institute for Nuclear Research, as well as excursions and scientific workshops, bringing audiences into the exciting world of research, opening doors to laboratories, and inspiring talented young people to choose a career in science, thereby building the Institute's future career pool.

JINR INFORMATION CENTERS AS A TOOL FOR PROMOTING JINR SCIENTIFIC AND EDUCATIONAL PROJECTS

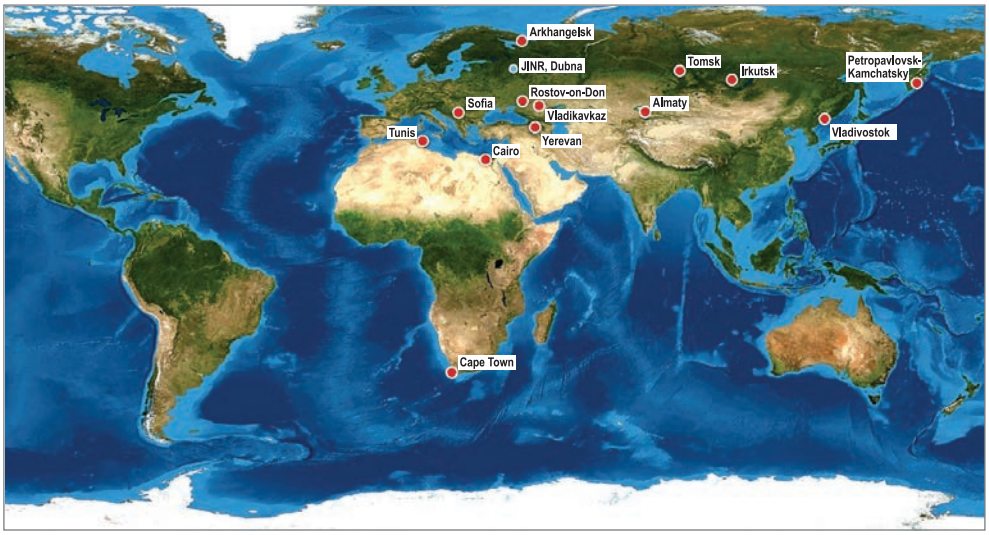
Information Centers (IC) aim to create an educational and information environment to promote JINR's activities and its diverse scientific program in countries and regions, as well as programs in the field of personnel training, to develop new scientific and educational projects, involve young personnel in research carried out at JINR laboratories, and scientific work in partner organizations.

Information Centers are created within the framework of special agreements between the JINR Director and the relevant plenipotentiary or national coordinator as structural subdivisions of the selected basic national organization (university, large scientific center or academy).

The first JINR IC was opened on October 12, 2018, in the Russian Federation, at K. L. Khetagurov North Ossetian State University (NOSU). In 2020, an Information Center opened in Cairo at the Academy of Scientific Research and Technology of Egypt, and in 2021, at Sofia University "St. Kliment Ohridski" (Bulgaria) and Vitus Bering Kamchatka State University (Russia). In 2023, the first JINR IC was opened at an international intergovernmental organization — at the headquarters of the Arab Atomic Energy Agency (AAEA) in Tunis.

By mid-2025, 13 JINR IC were opened and were successfully operating in six countries (Armenia, Bulgaria, Egypt, Kazakhstan, Russia, South Africa) and one international intergovernmental organization (AAEA).

Though the main target audience for the activities of the Information Center in a country are primarily university communities (students, postgraduate students, and teaching staff) and scientists, the IC has already accumulated interesting experience working with school audiences (schoolchildren and teachers) as well.



Officially opened JINR IC on the world map as of the beginning of 2026



University of the Western Cape (UWC), South Africa, January 29, 2016. Opening of an exhibition dedicated to JINR and its collaboration with South Africa. The ribbon was cut by D. V. Kamanin, Head of the JINR International Cooperation Department, and Professor M. Davies-Coleman, Dean of the Faculty of Natural Sciences at UWC



Higher Institute of Technologies and Applied Sciences (InSTEC), Cuba, February 1, 2016. A poster exhibition dedicated to the 60th anniversary of JINR and the 40th anniversary of Cuba's participation was opened by JINR Director Academician V. A. Matveev, InSTEC Rector B. Garea Moreda, and Plenipotentiary of the Republic of Cuba in JINR F. C. Diaz-Balart



JINR Vice-Director R. Lednicky (Czech Republic) participates in the opening ceremony of the first JINR Information Center at North Ossetian State University. October 2017



A roundtable discussion at Northern (Arctic) Federal University on the development of international cooperation in the JINR IC partner network "JINR Meridians, Arctic Latitude". Information Centers heads from Vladivostok, Irkutsk, Cairo, and Cape Town, as well as the rector of Dubna State University. Arkhangelsk, June 2021

This work is being conducted in various formats. For example, in-person schools in Dubna include visits to the Institute's basic facilities and laboratories, practical and laboratory classes at the UC educational facilities, lectures by scientists, master classes based on the "Physics. Engineers of the Future" educational and methodological complex, and the use of JINR's online educational resources.

The JINR IC network continues to develop steadily. The Information Center at the Institute of Physics of the Vietnam Academy of Science and Technology (Hanoi) is expected to officially open in 2026. The Information Center in Hanoi has already begun its operation, one of the results of which was the successful organization of the Vietnamese students' participation in the International Student Practice program in September 2025.

The entire JINR IC system is becoming a platform for mutual gain of new experience and the exchange of best practices in establishing scientific and educational processes, opening up broad opportunities for international collaboration. "Each opened IC can work with other JINR Information Centers, which already exist in Rostov-on-Don, Vladikavkaz, Sofia, Cairo, and elsewhere, and become a member of the large international JINR scientific family, distributed across the globe but working on common goals", noted JINR Director Academician G. V. Trubnikov at a meeting of IC leaders in Arkhangelsk in June 2025.

The main consequence of the implementation of all the programs described above is their direct contribution to the fulfillment of JINR's statutory goal: training personnel for the Institute's diverse multidisciplinary scientific program and meeting the needs of Member States for highly qualified personnel.

Educational programs remain a reliable source of young scientists and engineers for the Institute's diverse scientific program. For example, as mentioned earlier, 20% of START program participants find permanent employment in JINR laboratories in subsequent years.

As the example of the international student practices and INTEREST programs demonstrates, JINR's educational programs have the potential for self-development and adaptation to new conditions, opening up opportunities for innovative solutions in organizing new educational initiatives for the benefit of Member States and partners.

The importance of the alumni group, formed by students who participated in JINR's educational programs in previous periods, as well as of the international community of lecturers and project supervisors from JINR laboratories and partner organizations, cannot be understated in advancing JINR's scientific and educational agenda in other regions of the world. Horizontal connections between scientists, engineers, and specialists from different parts of the world who began their professional careers at JINR can form another integral part of JINR's network, a resource for strengthening and further developing the Institute.

CONTENTS

Compilers' note 5

HIGH ENERGY PHYSICS **7**

Construction of the Nuclotron 9
The birth of relativistic nuclear physics. Experiments at the Nuclotron 15
Project of the NICA accelerator complex 29
Cryogenics and superconductivity in the NICA megaproject 36
Experiments at the NICA accelerator complex 45
The BM@N experiment 45
The MPD experiment 47
The SPD experiment 52
Experiments at the Large Hadron Collider 54
The ATLAS experiment 54
The CMS experiment 69
The ALICE experiment 82
LHC Damper 85
Other accelerator experiments 87
The COMPASS experiment 87
The NA45/CERES experiment 89
The NA48, NA48/1, NA48/2, NA62 experiments 90
The NA64 experiment 93
The NA49 and NA61/SHINE experiments 95
The CDF project 98
The D0 project 101
The BES III experiment 101
The STAR experiment 102
The CBM experiment 105
The HADES experiment 106

PHYSICS OF NEUTRINO AND RARE PROCESSES **109**

Neutrino astrophysics 114
The BAIKAL-GVD project 114
The TAIGA experiment 121

Experiments at the Kalinin NPP 124
The νGeN experiment 124
The DANSS experiment 125
Experiments at other scientific centers 128
The Daya Bay experiment 128
The JUNO experiment 130
The EDELWEISS, Ricochet and CUPID-Mo experiments 131
The NEMO and SuperNEMO experiments 135
The GERDA, Majorana and LEGEND experiments 136
The MONUMENT experiment 139
The NOvA and T2K experiments 141
The Borexino experiment 143
The OPERA experiment 145
The Mu2e experiment 147
The PEN, MEG and MEG II experiments 150
The PIBETA experiment 151

NUCLEAR PHYSICS 153

Development of the FLNR accelerator complex 156
The DRIBs-I project 156
Ion sources 156
FLNR cyclotrons 159
FLNR electromagnetic separators: Superheavy elements 165
Reconstruction of the VASSILISSA separator 165
Gas-filled separators 166
Experimental research at the FLNR accelerator complex 169
Discovery and study of superheavy elements 169
Study of the properties of radioactive decay of heavy and superheavy nuclei produced in reactions with accelerated multi-charged ions 175
Chemistry of superheavy elements 178
Study of the dynamics and mechanisms of reactions with heavy ions at energies near the Coulomb barrier 180
Physics of exotic nuclei 184
NRV web knowledge base on low-energy nuclear physics (Nuclear Reactions Video) 191
Radiation materials science 192
Track formation and recrystallization 195
Track overlap 197
Correlation between surface and bulk radiation defects 198
Track-etched membranes, micro- and nanostructured materials produced with heavy-ion beams 200
Upgraded IC-100 cyclotron 202
Functional microstructured materials 203

Track-etched membranes as model capillary-porous media in nanofluidics and physics experiments . . . 203
Composite and hybrid track-etched membranes . . . 206
Development of the fleet of equipment and establishment of a specialized laboratory (Nanocentre) . . . 209

NEUTRON PHYSICS 213

Physics of interaction of neutrons with nuclei . . . 217
Pulsed neutron sources IBR, IBR-30, IBR-2, and IREN . . . 217
Discovery of ultracold neutrons and experimental research with them . . . 225
Search and study of the effects of violation of fundamental symmetries in neutron-nuclear interactions . . . 226
Application of the tagged neutron method for fundamental research . . . 227
Spectrometers and research at IBR-2 . . . 231
FLNP international User Program . . . 231
Fourier diffractometers and FLNP's role in developing the methodology . . . 232
Neutron studies of nanosystems at IBR-2 . . . 236
Neutron radiography and tomography at IBR-2 and other neutron sources in JINR Member States . . . 244
The development of inelastic scattering at FLNP and its place in the global research landscape . . . 247
Cold neutron moderators . . . 250
Neutron studies of condensed matter under high pressure . . . 258

THEORETICAL PHYSICS 263

Theory of fundamental interactions . . . 270
Renormalization group and its various applications . . . 270
Quantum electrodynamics . . . 272
Neutrino physics . . . 275
Quantum chromodynamics . . . 282
Quantum chromodynamics sum rules . . . 283
Anomalies in the physics of hadrons and heavy ions . . . 284
Effective theories for heavy and light quarks . . . 286
Parton distributions in exclusive and inclusive processes . . . 288
Hadronic matter under extreme conditions . . . 289
Nuclear theory . . . 295
Nuclear structure . . . 296
Nuclear astrophysics . . . 300
Nuclear reactions . . . 301
Halo nuclei . . . 305
Theory of few-body systems . . . 306
Relativistic nuclear physics . . . 309
Research in related fields . . . 316

Theory of condensed matter 317
High-temperature superconductors and cuprates 317
Bose–Einstein condensation and quantum systems 319
Fractals and small-angle scattering 320
Theory of self-organized criticality and exactly solvable models of statistical physics 321
Interacting particle models and the Kardar–Parisi–Zhang universality 322
Quantum integrable systems and superconformal indices 322
Topological defects, nanostructures and transport phenomena 324
Methods of quantum field theory in condensed matter physics 326
Modern mathematical physics 332
Geometry of Lagrangian submanifolds 333
Split Casimir operator, degrees of the adjoint representation, and Vogel parameters 335
Holographic approach 337
Strings, duality, and integrability 337
Supersymmetric Schwarzians 338
Supersymmetry 338
Models of particles and fields with higher and continuous (infinite) spins 339
Effective action in supersymmetric quantum gauge theories 341
New models of supersymmetric mechanics 343
Boson stars, black holes, and problems in two- and three-dimensional field theories 345
International workshops “Supersymmetries and Quantum Symmetries” 347
Modified gravity theories and cosmology 348
Gravitational shock waves in general relativity 350
Quantum gravity, anomalies, the relationship between gravity, thermodynamics, and quantum entanglement 354
Quantum field vacuum effects 355

INFORMATION TECHNOLOGIES 357

Telecommunication channels 361
External communication channels 362
JINR Local Area Network 366
GRID environment 369
Cloud computing 383
Heterogeneous computing 386
HybriLIT cluster 386
Govorun supercomputer 389

HybriLIT platform 394
MICC resources integration 398
Models and software packages for data processing 402
Event generators 403
Simulation of physical processes 403
Reconstruction of charged particle trajectories 404
Particle identification 406
Monte Carlo Data Base (MCDB) 407
Participation in the ATLAS TDAQ, EventIndex, and CREST projects 409
Development of computational physics methods 411
Digital ecosystem 420

RADIATION RESEARCH IN LIFE SCIENCES 425

Radiation biology 431
Research areas 431
Molecular radiobiology 431
Radiation genetics and cytogenetics 435
Radiation physiology 437
Medical radiobiology 440
Mathematical modeling 441
Radiation research at JINR's basic facilities 444
Astrobiology 447
Specialist training; collaboration and conferences 449

APPLIED RESEARCH AND DEVELOPMENT 453

Applied research at the NICA complex 460
Areas of applied research at DLNP 478
LINAC: New accelerator complex for fundamental and applied research 478
Laser metrology: From particle physics to monitoring of the seismic oscillations of the Earth's surface 481
Proton therapy 484
Radiochemical research at DLNP JINR 486
The positron annihilation spectroscopy 490
The TARDISS project 492
Artificial intelligence methods in applied problems 494
Neutron methods for applied problems 502
Tagged neutron method 502
Neutron and X-ray scattering methods 503
Neutron activation analysis 505
Method of neutron radiography and tomography 511

PERSONNEL TRAINING 513

International Student Practice 516
ISP geography and participants. 517
ISP prospects 519
"Students' summer": START and INTEREST programs 521
JEMS training program 524
Program structure and organization 524
JEMS: Facts and figures 524
"Physics teacher influenced my choice of profession":
UC's work with school teachers 527
Children are our future: JINR programs for pupils 530
From student to scientist: JINR-based departments
and student practices 533
Popularization of JINR's research and
career guidance work. 535
JINR Information Centers as a tool for promoting JINR scientific and
educational projects 536

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