Physics – Uspekhi **64** (12) 1186 – 1197 (2021)

Institute for Nuclear Research, Russian Academy of Sciences: years, people, achievements*

1. Mission and people

The Institute for Nuclear Research of the Russian Academy of Sciences was established on December 24, 1970 by Decree No. 1051 of the Presidium of the USSR Academy of Sciences based on a decision by the Council of Ministers of the USSR. The establishment of the institute was suggested by the Department of Nuclear Physics of the USSR Academy of Sciences to create a state-of-the-art experimental base and develop research on the physics of elementary particles, atomic nuclei, cosmic rays, and neutrino astrophysics.

It would not be an exaggeration to call Moisei Aleksandrovich Markov, academician-secretary of the Department of Nuclear Physics of the Academy of Sciences of the USSR, the founding father of the Institute. This outstanding scientist's ideas regarding a comprehensive approach to the exploration of the physics of the micro- and macrocosm (elementary particle physics, fundamental interactions, cosmology) underlay the program of fundamental research of the newly created Institute. His ideas on elementary particle physics and methods of detection in underground, deep-water, and other unconventional detectors were the basis for the development of the Institute's unique experimental facilities and installations.

M A Markov repeatedly stressed in his academic and pop science articles the need to create experimental installations for research on neutrino physics, astrophysics, and high-intensity physics. In particular, he wrote in the article "The future of physics (future generations of particle accelerators)": "Astrophysics has become, to a greater extent than ever before, an experimental science. This is related to the fact that, as [academician] Ginzburg correctly asserts, astrophysics now spans all wavelength ranges. ... Awaiting us ahead are the exciting neutrino astronomy and astrophysics of gravitational waves... Further, it is of interest to note that astrophysics, in a sense, is getting closer to microphysics. Ultimately, neutron stars are, in essence, grandiose atomic nuclei." He continued: "The specific features of the effects that are characteristic of high-energy physics are weakly manifested at low energies. However, feeble manifestations of these phenomena (small cross sections) can be detected using high-intensity particle beams... Typical representatives of high-intensity physics are so-called meson factories... which also offer virtually unlimited options for practical applications in technology, medicine, and the national economy" (see *Physics–Uspekhi* **16** 913–925 (1974) [*Usp. Fiz. Nauk* **111** 719–742 (1973)]).

Nikolai Nikolaevich Bogoliubov, an outstanding physicist and director of the Laboratory of Theoretical Physics of the Joint Institute for Nuclear Research (JINR, Dubna), actively supported and promoted these ideas and the efforts to establish a new research Institute. The first director of the Institute from its foundation to 1987 was Albert Nikiforovich Tavkhelidze, at that time a relatively young (he turned 40 in December 1970) theorist from JINR, Doctor of Science in Physics and Mathematics and, later, an academician of the Russian Academy of Sciences (photo 1).

Photo 1. Albert Nikoforovich Tavkhelidze, Nikolai Nikolaevich Bogoliubov, and Moisei Aleksandrovich Markov (left to right).

Two main tasks were set for the newly established Institute: to create the world's first specialized underground laboratory — the Baksan Neutrino Observatory (BNO) in Kabardino-Balkariya (currently the Neutrino Residential Settlement of the Elbrus district of the Kabardino-Balkariya Autonomous Republic) and construct the Moscow meson factory based on a high-current linear proton accelerator located at the Research Center of the USSR Academy of Sciences in Krasnaya Pakhra, now the Troitsk city district, Moscow.

* December 2020 marks the 50th anniversary of the Institute for Nuclear Research (INR) of the Russian Academy of Sciences. This article was written on the basis of a report made by L V Kravchuk at a conference held on December 3, 2020, which was dedicated to INR's 50th anniversary. It briefly describes the history of the Institute and the people who made the main contribution to its establishment and development. The Institute's unique experimental installations and facilities, its participation in international scientific projects and experiments, and some results obtained by the Institute in recent years are outlined. (*Editor's note*.)

Photo 2. Participants in the construction of the INR neutrino laboratory (1972). First row (left to right): *1*, *2* — representatives of the management of the BNO construction, *3* — M V Keldysh, president of the USSR Academy of Sciences, *4* — A N Tavkhelidze, *5* — A E Chudakov. Second row: *6* — A A Pomanskii, first director of BNO and BNO researchers: V V Alekseenko (*7*), V A Kuznetsov (*8*), G T Zatzsepin (*9*), and E N Alekseev (*10*).

Photo 3. First session of the Neutrino Council of the USSR Academy of Sciences (1974). INR director A N Tavkhelidze (left) and president of the USSR Academy of Sciences Anatolii Petrovich Aleksandrov (right).

The establishment and development of the Institute were actively supported by the then Presidents of the USSR Academy of Sciences, academicians M V Keldysh (photo 2) and later A P Aleksandrov (photo 3).

First, the Institute obtained three laboratories from the Lebedev Physical Institute of the Russian Academy of Sciences (FIAN): the Laboratory of the Atomic Nucleus headed by I M Frank; the Laboratory of Photonuclear Reactions headed by L E Lazareva, and the Neutrino Laboratory headed by G T Zatsepin and A E Chudakov.

An important role in the creation of the Institute was also played by the following prominent scientists:

I M Frank, the winner of the Nobel Prize awarded for the explanation of Cherenkov radiation, headed the Laboratory of the Atomic Nucleus. He was the author of many theoretical and experimental studies in various fields of atomic physics, including the method of spectrometry based on the time of slowing down neutrons in lead, which was implemented at the Institute;

V I Veksler, who discovered the principle of autophasing, was a founder of the Laboratory of Photonuclear Reactions, which operated the electron and proton accelerators created under his scientific guidance and the prototype of Russia's first proton synchrotron;

G T Zatsepin, a discoverer of electron-nuclear showers and other processes in cosmic rays, was scientific director of the construction and research program of the BNO;

A E Chudakov, a discoverer of Earth's radiation belt, was head of experimental research on cosmic rays in the atmosphere and space;

Photo 4. V A Rubakov, V A Matveev, and L V Kravchuk. Viktor Anatol'evich Matveev with the M A Markov award (2017).

V M Lobashev, who directed experiments on studies of violation of spatial parity, polarization phenomena in particle physics, emission of ultracold neutrons, and direct measurement of neutrino mass was scientific supervisor of the experimental program of the Moscow meson factory;

S K Esin, a prominent specialist in charged particle accelerators, who participated in the construction and launch of the JINR phasotron and headed the construction of an electron synchrotron at the Yerevan Institute of Physics, was scientific supervisor of the construction of a high-current linear accelerator of protons and negative hydrogen ions at the Moscow meson factory.

As already mentioned, the director of the Institute until 1987 was academician A N Tavkhelidze, then for more than a quarter of a century, until 2012, the Institute for Nuclear Research was headed by academician V A Matveev (from 2012 to 2020, director of JINR) and later, to 2020, RAS corresponding member L V Kravchuk (photo 4). At present, the INR director is Prof. M V Libanov, Dr. Sci. (Phys.-Math).

Deputy directors for science at different times were V D Burlakov, V A Rubakov, L V Kravchuk, L B Bezrukov, E A Koptelov; at present, A G Panin, G I Rubtsov, and A V Feshchenko.

Many famous scientists worked at the Institute, including academicians G T Zatsepin, V M Lobashev, A E Chudakov, and RAS corresponding members V A Kuzmin and O G Ryazhskaya; currently, academicians V A Matveev, V A Rubakov, I I Tkachev and RAS corresponding members V N Gavrin, D S Gorbunov, G V Domogatskii, L V Kravchuk, and S V Troitsky. Four professors from the Russian Academy of Sciences, about 50 doctors of science, and about 120 candidates of science are employed by the Institute.

About a thousand employees work at four sites of the Institute in Moscow; in the city district of Troitsk, Moscow; in Kabardino-Balkariya, the Neutrino Residential Settlement (BNO); and at the Baikal Neutrino Observatory. The Institute's research and educational center (REC) employs about a hundred undergraduate and graduate students, mainly from three departments and postgraduate studies at INR, the Moscow Institute of Physics and Technology (MIPT), Lomonosov Moscow State University, the Moscow Engineering Physics Institute (MEPhI), etc.

The Institute's main research areas are:

— elementary particle physics, high energy physics, theory of gauge fields and fundamental interactions, cosmology;

— physics of neutrinos and astrophysics of particles; neutrino, gamma, and gravitational-wave astronomy, physics of cosmic rays, physics and technology of neutrino telescopes in low-background underground and underwater laboratories;

— physics of the atomic nucleus, relativistic nuclear physics;

— physics and technology of accelerators, physics of charged particle beams;

— physics of condensed matter, radiation materials science, neutron physics, physics and technology of neutron sources;

— interdisciplinary research, applied nuclear physics, radioisotope research, nuclear medicine, electronuclear transmutation of fissile materials, information technologies in experimental and theoretical physics, etc.

2. Unique scientific facilities and installations

Baksan neutrino observatory

On June 19, 1963, the Presidium of the Academy of Sciences decreed that an underground station be constructed and a neutrino laboratory be created at the Physical Institute of the USSR Academy of Sciences (laboratory head, G T Zatsepin, sector head, A E Chudakov). The site for the future observatory was chosen not far from Mount Elbrus, in the Baksan Gorge, located in the Kabardino-Balkarian Autonomous Republic of the USSR. The scientific feasibility survey was completed in 1967, and the project of the neutrino station was then developed; in the same year, its construction began. According to the plan, two parallel horizontal tunnels had to be dug in Mount Andyrchi (the height of the mountain is more than 4000 m), along which physical facilities had to be deployed. Required engineering and support structures and a residential settlement for employees had to be constructed concurrently with the tunnels. In 1971, the BNO construction project was turned over to INR, which implemented the project. Since 1973, BNO has carried out scientific research, the framework of which expands as new facilities are commissioned. A schematic rendering of the underground part of the observatory is shown in Fig. 5, and an external view of BNO, in photo 6.

The main areas of scientific research are:

— elementary particles physics, high energy physics, cosmology;

— neutrino astrophysics, neutrino and γ-astronomy, physics of cosmic rays, solar neutrinos;

— development and creation of neutrino telescopes in low-background underground laboratories for the study of natural fluxes of neutrinos and other elementary particles;

— double beta decay;

— search for dark matter.

BNO includes the following research facilities.

The *Baksan Underground Scintillation Telescope* (BUST), a multipurpose underground detector intended to explore various problems in astrophysics, elementary particle physics, and cosmic rays, was commissioned in 1978. BUST is located at an altitude of 1700 m above sea level in an underground mine under the slopes of Mount Andyrchi, at a distance of 550 m from the entrance to the tunnel shaft. The effective soil thickness above the telescope corresponds to the effective threshold muon energy of 220 GeV. The detector consists of 3200 scintillation counters arranged in four horizontal and four vertical planar arrays. The telescope has yielded many important results: the flux of muons produced by atmospheric cosmic ray neutrinos has been measured; restrictions on the parameters of neutrino oscillations have been obtained; a limitation on the flux of high-energy neutrinos from local sources in the Galaxy plane was obtained; the energy spectrum of cosmic ray muons in the energy range of 1–30 TeV was measured; the photonuclear interaction cross section at photon energies in a range from 0.9 to 10 TeV was measured; etc.

Photo 6. Baksan Neutrino Observatory.

The *Andyrchi facility* designed to detect air showers with an energy of more than 1 MeV was commissioned in 1996.

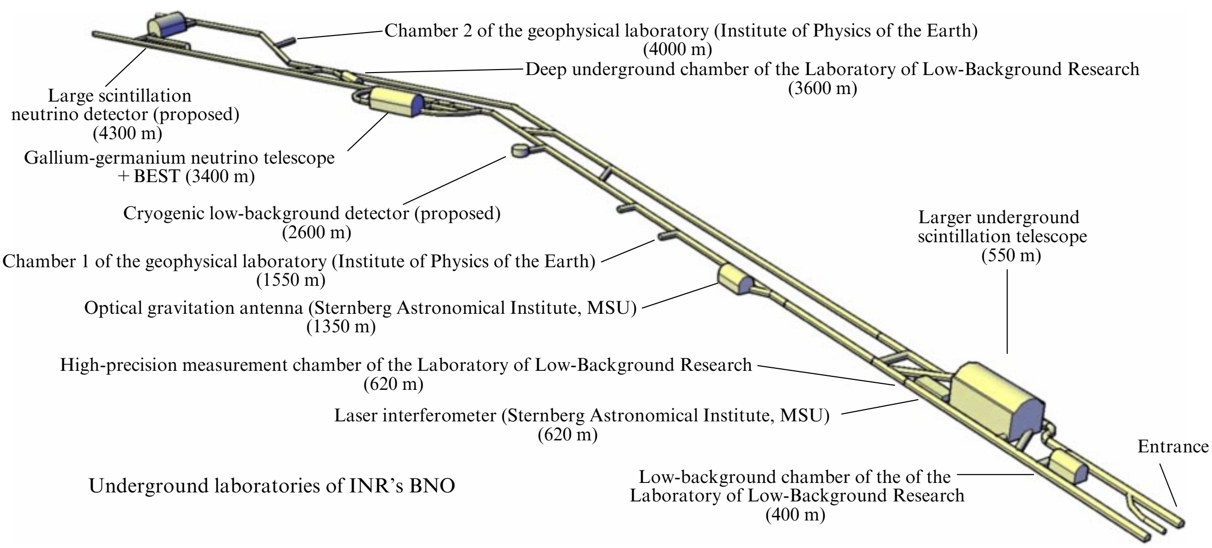

Photo 5. Layout of the underground part of the Baksan Neutrino Observatory.

Located on a gentle slope of Mount Andyrchi, it consists of 37 standard scintillation counters based on plastic scintillators with a total area of 1 m^2. The central counter of the facility is located above BUST at a vertical distance of 350 m. This setup makes it possible to study the high-energy muon component of extensive air showers (EASs) in showers generated by primary particles. The combined data from BUST and Andyrchi enable research in various fields of particle astrophysics.

The *Kover* (Carpet) *facility* was upgraded in 1998, when the first stage of the large muon detector (MD) was commissioned. Underground tunnels are covered by a 2-m-thick layer of rocky soil (5 m of water equivalent), which absorbs the soft component of radiation. The information obtained from the Kover-2 MD made it possible to significantly enhance the sensitivity of the search for local sources of ultrahigh-energy γ-quanta, to begin studies of the chemical composition of primary cosmic rays with $E > 1014$ eV, and to examine variations in muons with energies above 1 GeV. The facility is currently being upgraded to the Kover-3 version. To this end, the MD area has been increased to 410 m^2, and the number of ground-based shower stations will be increased to 39. The facility in the new configuration will be most sensitive to the flux of primary gamma quanta with energies in a range of 100 TeV–1 PeV. The experiment has now been completed, and data processing and analysis are in progress.

The *Gallium-Germanium Neutrino Telescope* (GGNT) is designed to measure the flux of solar neutrinos. The flux data contain unique information about thermonuclear reactions in the Sun's core and properties of neutrinos. Research has been carried out since 1986 at the GGNT (under the guidance of V N Gavrin) as part of the US–Russian SAGE experiment. The telescope operates based on the reaction of capture of neutrinos (ν_e) by a ^{71}Ga nucleus with the production of a ^{71}Ge nucleus and an electron. The advantage of this detection method proposed in 1965 by V A Kuzmin is the low energy threshold of the reaction, equal to 0.233 MeV. Due to this, the gallium neutrino telescope can detect pp-neutrinos, which are the largest component in the total solar neutrino flux. Based on the SAGE results, an estimate was obtained of the flux of pp-neutrinos reaching Earth in their original electronic flavor, and the total flux of neutrinos from pp-reactions in the Sun that reach Earth in the form of various flavor states emerging as a result of oscillations.

The *Laboratory of Low-Background Research* carries out searches for various modes of double beta decay of some isotopes, particle-candidates for dark matter in the Universe, violations of the law of conservation of electric charge, etc. These studies are carried out in the observatory in three specially created underground low-background laboratory rooms (chambers): a low-background chamber (NIKA) located at a distance of 385 m from the entrance; a precision measurement chamber (KAPRIZ) at a distance of 620 m from the entrance; and a low-background deep underground laboratory located at a distance of 3670 m from the entrance.

The *Baksan Experiment on Sterile Transitions* (BEST) is a search for transitions of electron neutrinos to a sterile state. For this experiment, a facility was created with a two-zone gallium target GGNT in which two gallium targets located at different distances from the source are irradiated by a powerful neutrino source. Calorimetric and spectrometric systems for measuring the source intensity have also been developed and created. For the first time in the world, an artificial neutrino source with an intensity of 3.41 ± 0.02 MCi was produced, and an accuracy of measuring this activity of less than one percent was achieved. A 50-ton metal gallium target divided into two zones, internal and external, was subject to ten nine-day exposure sessions from July 5 to October 13, 2019. At present, the final stage of the experiment, gauging of counters and processing the data obtained, is being carried out.

The Institute staff was awarded in 1998 the State Prize of the Russian Federation "for the creation of the Baksan neutrino observatory and research in the field of neutrino astrophysics, elementary particle physics, and cosmic rays." The results obtained at the GGNT in the research on the solar neutrino flux won the Pontecorvo International Prize and, for outstanding contribution to the exploration of solar neutrinos and the discovery of neutrino oscillations, the Skobeltsyn golden medal.

The project to create a large-volume underground detector (NBNT) (10,000 tons of ultrapure liquid scintillator) at the Baksan Neutrino Observatory of INR RAS, which is part of the megaproject called the Multipurpose Neutrino Observatory, is a natural and extremely important step in BNO's development.

The high-current linear proton accelerator (Moscow meson factory) located in Moscow, in the Troitsk city district, includes:

- a high-current linear accelerator of protons and negative hydrogen ions with a design energy of up to 600 MeV and an average beam current of up to 0.5 mA;
- an experimental hall with channels of primary and secondary particles of various energies, experimental setups, and a beam diagnostics system;
- a neutron facility, which includes pulsed neutron sources IN-06, RADEKS, and SVZ-100, a set of neutron diffraction and X-ray installations, and a Mössbauer spectrometer for materials science research;
- a facility for the production of radioactive isotopes for medicine and industry in the segment of intermediate extraction of the proton beam with an energy of 160 MeV;
- a facility for radiation therapy that includes an X-ray tomographic device, an X-ray irradiation device, an electron accelerator for gamma radiation, and a proton beam channel.

Installed at the accelerator exit is an irradiation stand designed to study the effect of accelerated protons on radio electronic equipment and other products and materials.

The *high-current linear accelerator of hydrogen ions* is a unique scientific facility of national and international significance. It is the only accelerator of this class in Russia and, to date, the largest linear accelerator of hydrogen ions in the Eurasian region. Based on high-current linear accelerators of hydrogen ions of this class, the Los Alamos Center for Neutron Research, LANSCE, and ORNL SNS, currently the most powerful evaporation neutron source, are operating in the USA. A high-current linear accelerator of H^- ions launched in Japan is the basis of the J-PARC research accelerator complex. The construction of the Sweden-based accelerator of the European Neutron Complex ESS will be completed shortly.

INR's accelerator consists of H^+ and H^- ion injectors with corresponding beam transport channels, the initial part where particles are accelerated up to an energy of 100 MeV (photo 7), and the main part where they are accelerated up to an energy of 600 MeV (photo 8).

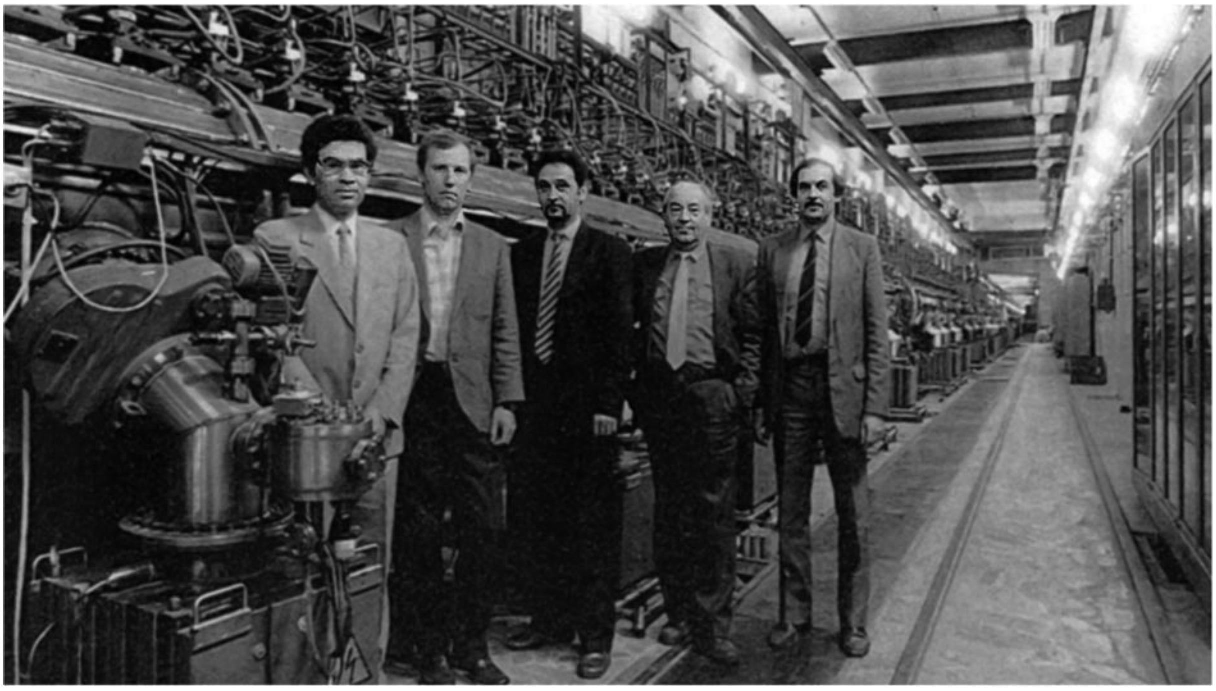

Photo 7. After the launch of the initial (100 MeV) segment of the accelerator in 1990. P N Ostroumov, A V Feshchenko, V L Serov, S K Esin, and L V Kravchuk.

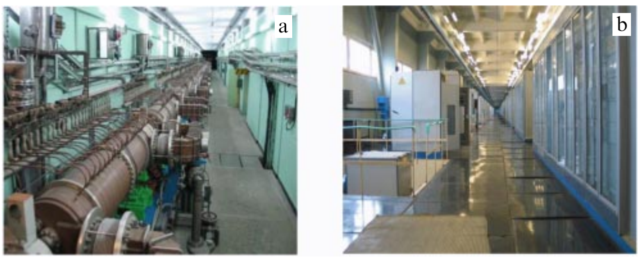

Photo 8. Accelerating cavities (a) and RF power gallery (b) of the main (600 MeV) segment of the accelerator.

Regular operation of the accelerator for physical and applied problems began in 1993. Since then, more than 140 sessions have been carried out with a total duration of over 50,000 hours. The accelerator has been fully constructed to accelerate the proton beam to an energy of 600 MeV; however, the maximum energy attained was 502 MeV, and then the accelerator operated for a considerable time at energies up to 209 MeV, since the production of high-frequency generators, klystrons, was halted. In recent years, the accelerator has been operating at energies of up to 305 MeV.

The *neutron facility*, based on INR's proton accelerator, includes:

• a pulsed source of thermal neutrons, IN-06, designed for research on condensed matter;

• a pulsed source of epithermal neutrons with time-of-flight spectrometers based on the RADEX facility (studies of neutron-nuclear interactions and the development of neutron techniques for materials science research);

• a spectrometer based on the time of slowing down neutrons in lead, SVZ-100, intended for exploring neutron-nuclear interactions.

The main advantages of neutron sources based on secondary neutron beams generated by accelerated protons in heavy metal targets in cascade-evaporation nuclear processes (spallation neutrons) are:

• nuclear safety;

• a wide range of neutron energies from cold neutrons to several hundred MeV;

• the possibility of using in experiments the time-of-flight technique to separate neutrons by energy and to vary the time and frequency characteristics of neutron beams over a wide range;

• the use of the accelerator for concurrent studies of many problems and the implementation of several diverse scientific programs (for example, research on condensed matter physics; nuclear and neutron physics; intermediate-energy physics — mesonic and neutrino processes; nuclear power energy — the development of electronuclear energy sources and transmutation of long-lived radioactive waste from nuclear power plants; medical physics and the production of neutron-deficient radioactive isotopes);

• a fairly long service life of source targets in intense fluxes of accelerated particles and their low cost in comparison with the reactor core;

• a low energy release per produced neutron in reactions of interaction between medium and high-energy protons and the target material (spallation process) in comparison with fission reactions.

Such sources are becoming increasingly popular worldwide. It should be noted that Soviet scientists made a significant contribution to the development of multipurpose research facilities based on high-current accelerators of hydrogen ions, including the US patent issued in 1975, one of the holders of which was Prof. Yu Ya Stavissky, a prominent INR researcher. The main concepts were implemented under his guidance in creating IN-06, a pulsed source of thermal neutrons at the Moscow meson factory.

Photo 9. Proton irradiation facility. S V Akulinichev, Dr. Sci. (Phys.-Math.) and head of the Laboratory of Medical Physics (center).

At present, the IN-06 neutron source incorporates various instruments, including spectrometers, reflectometers, and diffractometers such as MNS, Gorizont, Hercules, and Kristall.

The Laboratory of Neutron Research also carries out computational and theoretical studies of the interaction of medium- and high-energy particles and nuclei with complex macroscopic targets, including the generation and transport of neutrons and other particles, energy release in targets, the production and transmutation of radionuclides, and the effect of irradiation on materials, for which SHIELD, a universal hadron transport code, has been developed.

The *installation for irradiation of radioisotope targets* with a proton beam from the linear accelerator, which was created in 1993, is efficiently used to produce radioisotopes for medical and engineering purposes.

Today, this installation, which is one of the world's largest in terms of the energy accumulated for the production of isotopes, is used on a regular basis to obtain many of the most valuable radionuclides, including strontium-82, actinium-225, tin isomer-117m, palladium-103, and germanium-68.

The most important of the obtained isotopes is strontium-82 (half-life of 25.5 days) used for positron electron tomography (PET) diagnostics. INR has developed a medical generator of strontium-82/rubidium-82 of its own, the basic characteristics of which are superior to those of the US analogue. The generator has passed clinical trials in Russia for cardiology and neuro-oncology, and has been certified. One of the new promising plans is the production of actinium-225 (half-life of 10 days) from metallic thorium, irradiated with medium-energy protons. This alpha-emitting radionuclide and short-lived product of its decay, bismuth-213 (46 min), are promising agents for the treatment of various oncological diseases by means of radioimmune therapy. INR's linear accelerator can produce in a 10-day irradiation session actinium-225 in the amount of 1–2 Ci, a value which is comparable to the world's annual production. The Institute has also developed a new technology for producing tin-117m radio nuclide, a promising agent for the diagnosis and concurrently therapy (theranostics) of some oncological and vascular diseases. The prospects for producing radioisotopes in INR's linear proton accelerator are presented in more detail by B L Zhuikov, Dr. Sci. (Chem.) and head of the Laboratory of the Radioisotope Complex, in his article published by *Physics–Uspekhi* (see Vol. **64**, p. 1311).

The *radiation therapy complex* (first stage) was built in 2009 to carry out research in nuclear medicine using INR's linear proton accelerator; the research program of the meson factory initially assumed it would be employed for the development of methods for treatment of malignant neoplasms using a beam of accelerated protons. This complex includes the following generating facilities: a proton beam facility, a medical electron accelerator SL-75-5-MT, a close-focus X-ray therapy apparatus RENTGEN-TA-02, and a Toshiba Aquilion LB-16 X-ray computer tomography device. The proton beam facility is used for research, while conventional units almost immediately were used for both treatment and diagnostics (photo 9).

Research is concurrently being carried out in the following areas: brachytherapy methods using new isotopes, laser separation of ytterbium and the production of radiation sources for medicine, enhancement of the conformity of proton radiation therapy, and radiobiological experiments with cell cultures. Of most interest recently has been research on proton flash therapy, in which neoplasms are irradiated with extremely high dose rates. This technique enables the destruction of neoplasms by radiation exposure without damaging healthy tissues. INR's proton accelerator provides unique opportunities for this type of therapy due to the record setting power of its proton beams. INR's Laboratory of Medical Physics actively collaborates in these areas with Russia's major radiological centers.

Baikal deep-water neutrino telescope

Back in 1960, M A Markov in his speech at the Rochester conference said: "We propose to install detectors deep in a lake or in the ocean and to determine the direction of charged particles with the help of Cherenkov radiation" (M A Markov, "On high energy neutrino physics" in *Proc. 10th ICHEP*, Rochester, 1960, p. 578).

The implementation of this proposal in Russia began in 1980, when the Laboratory of High Energy Neutrino Astrophysics (headed by G V Domogatskii) was established at INR, and feasibility studies on the deployment in Lake Baikal (proposed by A E Chudakov) of NT-200, the first deep-water neutrino telescope, commenced. The development of the project was preceded by lengthy (more than 10 years) studies on the hydro-optical, hydro-physical, and hydrological conditions for conducting experiments in Lake Baikal. As part of the preparations, a number of design and technical solutions were found, a highly sensitive Quasar-370 hybrid photodetector with a photocathode 370 mm in diameter was designed and created in Russia, and the production of pressure-tight glass spheres started. Owing to this, the necessary conditions for the long-term operation of the measuring equipment at depths of up to 1400 m in Lake Baikal were created.

During the annual winter expeditions of 1993–1998, equipment was deployed and the collection of data began on a regular basis. The detecting equipment of the NT-200 telescope located at a depth of about 1100 m at a distance of 3.6 km off the coast is connected to the coastal control and data collection center by bottom communication lines. The telescope is a three-dimensional array of optical modules (OMs) placed on vertical strings, the lower ends of which are attached to bottom anchors, and the upper ends, to buoys. Each vertical string with optical modules is a structural unit of the telescope, OM garland. The telescope contains 192 OMs, placed on eight strings each 68 m in length. Peripheral strings are evenly arranged around the central string forming umbrella-like frames each 21.5 m in length. The optical module contains a Quasar-370 hybrid photodetector housed in a low-radioactive glass case (photo 10).

A winning combination of natural factors, good knowledge of the operation site, and experience gained in deploying and operating the first generation neutrino telescope, NT-200, made it possible to start designing and making the NT1000 deep-water neutrino telescope with an effective volume of about one cubic kilometer. This work was performed from 2008 to 2011.

The NT1000 deep-water neutrino telescope is designed to study problems in astrophysics, cosmology, and elementary particle physics, in particular, to search for local neutrino sources, examine diffuse neutrino flux, look for manifestations of dark matter, and search for magnetic monopoles and other hypothetical particles. It is an experimental facility for exploring natural neutrino fluxes in the energy range above 10 TeV by means of detecting Cherenkov radiation from secondary muons and showers generated in neutrino interactions.

The basic configuration of each of the 12 NT1000 clusters consists of eight strings, each containing 24 OMs (two sections per string) located at a distance of 60 m from each other. The distance between adjacent clusters is 300 m. The clusters are connected to the coastal center by combined electro-optical cables $\sim$ 6 km long. Each NT1000 cluster is a functionally complete facility that can operate both as part of a combined installation and in stand-alone mode. Owing to this, the telescope can easily be extended and its individual parts can be commissioned as the NT1000 is upgraded.

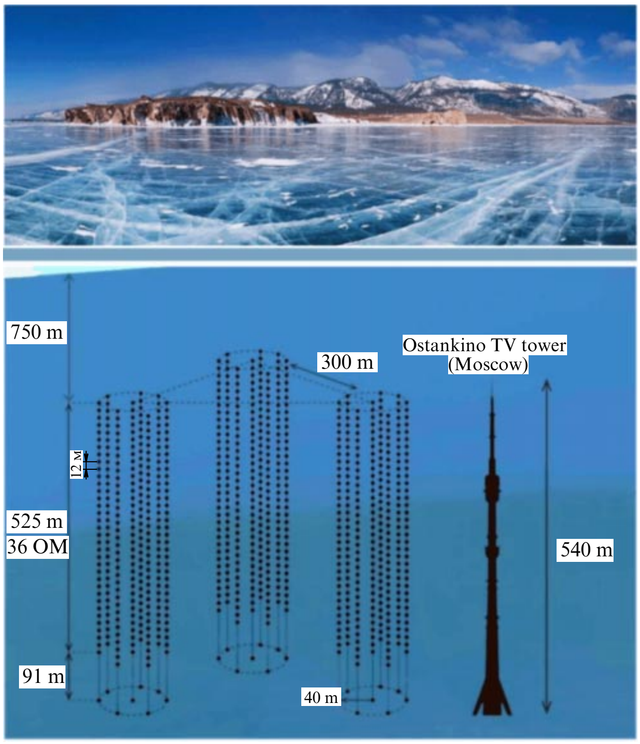

Photo 10. Deep underwater neutrino telescope Baikal-GVD.

The cluster acquired its modern configuration by 2016 after a series of field tests were carried out and adjustments made based on the results of annual winter expeditions and astrophysical events identified by the Ice Cube detector: the length of the strings increased from 24 to 36 optical modules and the distance between the strings and the cluster center increased from 40 to 60 m. The world community has come to know the NT-1000 project as the Baikal-GVD (Gigaton Volume Detector).

Activities related to the development of the Baikal-GVD were boosted when the Joint Institute for Nuclear Research (Dubna) joined the project. Since April 2020, the neutrino telescope has been operated using seven clusters (photo 10), and the total effective volume of the facility for detection of shower events from high-energy neutrinos ($E \geqslant 100$ TeV) increased to ~ 0.35 km^3, a value that will hopefully allow detection and identification of three or four such events a year.

In early March 2021, the Baikal-GVD deep-water neutrino telescope, consisting of eight clusters of underwater strings (2304 optical modules), was officially commissioned during the visit of V N Falkov, minister of Science and Higher Education of the Russian Federation. In analyzing the data obtained during the operation of the detector in its configurations of 2018, 2019, and 2020, 10 candidates for events triggered by high-energy astrophysical neutrinos were identified. This implies that, in searches for shower events associated with high-energy astrophysical neutrinos, the Baikal detector is already one or two successful upgrade stages from Ice Cube, where the average counting rate of such events (depending on the energy detection threshold) is four to six a year.

Troitsk-Nu-Mass facility

Since 1983, the Institute's Department of Experimental Physics, under the guidance of academician V M Lobashev, has carried out research to determine the effective mass of the electron antineutrino in the β-decay of tritium. The discovery of the effects of neutrino oscillations, which came early on, convincingly demonstrated that the neutrino mass is not zero, and the splitting of mass states can be measured. However, the absolute mass scale remains unknown. Knowledge of the absolute scale of neutrino mass states is of great importance both for particle physics (since the very existence of neutrino mass is an indication of a new physics beyond the Standard Model) and for cosmology, where the total mass of all types of neutrinos plays a significant role in the evolution of a large-scale structure of the Universe.

A new type of spectrometer for electrons from the β-decay of tritium — an electrostatic spectrometer with adiabatic magnetic collimation — was implemented at the Troitsk-Nu-Mass facility (photo 11), where a record-setting upper limit on the effective neutrino mass equal to 2.05 eV was obtained in 1994–2003.

To further enhance the sensitivity of the experiment, the tritium source intensity had to be increased by at least two orders of magnitude. Such a source was successfully created as part of the KATRIN international project (Karlsruhe, Germany). The general layout of the KATRIN detector reproduces that of Troitsk-Nu-Mass facility. It took 17 years to build KATRIN. In 2019, acquisition of data began at the KATRIN facility with the participation of INR researchers. After processing data, the limit on the effective mass of the electron antineutrino was diminished to 1.1 eV.

After the main program for measuring the effective mass of the electron antineutrino was completed in Troitsk, a decision was made to expand the range of measurements of the energy of electrons emitted in the β-decay of tritium. Such a setup of the experiment makes it possible to search for theoretically predicted particles — sterile neutrinos. The Standard Model of particle physics is incomplete, as evidenced by the nonzero mass of conventional neutrinos and the existence of dark matter in the Universe. Both phenomena can be explained based on a single assumption about the existence of sterile neutrinos with masses of the order of 0.1–8 keV. To solve this most challenging problem of fundamental physics and astrophysics of particles, the Troitsk-Nu-Mass facility was modernized for conducting high-precision measurements of the beta spectrum from tritium decays, which will enable searching for sterile neutrinos in a mass range up to 7 keV in the absence of additional systematic effects.

3. International cooperation

The Institute has been collaborating for a long time with many major laboratories, research centers, and universities around the world in the areas of basic and applied research described above, of which the following should be distinguished.

Institute researchers have been actively involved in experiments at the CERN-based Large Hadron Collider (LHC) virtually from its very creation. INR is a member of the CMS, LHCb, and ALICE collaborations. Researchers from the Department of High Energy Physics are co-authors of the article, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," published in *Physics Letters B*, which announced the discovery of the Higgs boson, one of the most prominent discoveries in high energy physics and awarded the Nobel Prize in physics in 2013.

The Institute participates in the LHCb experiment, which it is in charge of, in particular, the development and construction of the front part of the electromagnetic calorimeter. The list of the main results obtained in this experiment includes the discovery of CP violation in decays of charmed D0 mesons, a tetraquark, and new baryons. Since the mid-1990s, the Experimental Physics Department has taken part in the development and later carrying out of the ALICE experiment, for which INR has produced a T0 detector, a key component in the formation of a trigger and identification of particles by time of flight in luminosity monitoring. Operation of the collider, whose luminosity was increased more than ten-fold, and studies of previously inaccessible rare processes required an upgrade of the ALICE facility. An intelligent forward Fast Interaction Trigger (FIT) has been developed by INR, and a next-generation readout and trigger electronics based on FPGA processors is currently under development. The FIT, which is the main trigger detector of the ALICE experiment after its modernization in 2019–2020, is used to precisely determine the instant of collision, the multiplicity of secondary particles, the centrality, and the position of

Photo 11. General view of the Troitsk-Nu-Mass facility.

the reaction plane in nucleus–nucleus collisions and to measure the luminosity.

The Institute's researchers have participated in obtaining an estimated intensity of axion fluxes generated due the conversion of high-energy gamma quanta in extended intergalactic magnetic fields (the CERN Axion Solar Telescope, CAST); studies of neutrino oscillations on the CERN–Gran Sasso neutrino beam in the OPERA and ICARUS experiments; the search for neutrino bursts from gravitational collapses of stars (ICARUS); and measurements of the free fall acceleration of unbound antihydrogen atoms (AEgIS).

Worth special mention is the NA64 experiment at CERN (spokesman S N Gninenko, a staff member of the Institute) in which INR researchers play a decisive role. The main goal of the experiment is to search for the birth of light dark matter in the decays of 'dark' photons A'invisible.

The NA61/SHINE experiment on the SPS at CERN has recently completed measurements of the yields of charged particles in collisions of light and heavy nuclei with fixed targets at incident nucleus energies in the range from 13 to 150 GeV per nucleon. INR has developed and produced for this experiment a front hadron calorimeter, maintained its operation, and carried out calibration and data analysis. The Institute has modernized the calorimeter for the new research program of the NA61/SHINE experiment on the production of D-mesons in collisions of lead nuclei. This upgrade makes it possible to carry out research at higher intensities starting in 2022.

The Institute has been collaborating for a long time with KEK Laboratories, J-PARC, and the University of Tokyo (Japan). Joint experiments have focused on the search for neutrino oscillations in the K2K experiment and, later, T2K.

The Institute's researchers (Department of High Energy Physics (DHEP), headed by Prof. Yu G Kudenko, Dr. Sci. (Phys.-Math.)) actively participated in the development, creation, and maintenance of muon path length detectors (SMRD) of the ND280 near detector and in carrying out the T2K experiment and modeling and analyzing data.

In 2017, modernization of the ND280 near detector began and is to be completed in 2022. It is expected that the upgrade will significantly enhance the sensitivity of the T2K experiment to the oscillatory parameters of neutrinos, including CP violation. The upgraded ND280 near detector is planned to be integrated starting in 2027 into Hyper-Kamiokande, a next-generation neutrino experiment.

The Institute is actively involved in studies of kaon physics, including experiment E949 at the Brookhaven National Laboratory (BNL, USA) and NA62 (CERN) in which ultra-rare decays are searched for. The DHEP researchers also developed methods of analysis that yielded the most stringent limitations on the parameters of massive (sterile) neutrinos in the mass range up to 500 MeV in the E949, T2K, OKA, and NA62 experiments.

An integral part of high-current linear hadron accelerators is a device developed at the Accelerator Complex Department (ACD) for measuring the longitudinal charge distribution in accelerated ion bunches, which provides a phase resolution better than one degree. Such devices, developed under the guidance of A V Feshchenko, Dr. Sci. (Phys.-Math.), were produced by INR for accelerators operated at CERN; DESY, GSI (Germany); ESS (Sweden); KEK and J-PARC (Japan); SSC, SNS, LANSCE, and FRIB (USA); MIRRA (Belgium), and other research centers. The team that developed the device was awarded the V I Veksler prize of the Russian Academy of Sciences.

The ACD has also developed an accelerating structure, a number of parameters of which are superior to those of many similar devices. Its long-term operation has been tested in collaboration with DESY (Germany) on electron beams of the PITZ facility. Based on subsequent studies, which expanded the area of applicability of the device, it was recommended for the upgrade of the first cavity of the main part of the INR accelerator.

To determine the characteristics of the longitudinal distribution of particles in short bunches of free electron lasers, deflecting structures have been developed, which are used in European XFEL, the free electron laser accelerator. A special ACD team focuses on the development of specialized deflecting structures for diagnostics of longitudinal distributions of particles in bunches of ultra-high brightness.

Lately, interest has sharply increased in collisions of nuclei with energies lower than those of the LHC. This is due to the fact that, at lower energies, the nuclear matter can be explored that is less heated but features a density of baryons (nucleons) which is 5–10 times higher than that in normal-state nuclei. It is hypothesized that such a relatively cold form of matter exists in the interior of neutron stars. These studies aim at finding the onset of deconfinement, the critical point of the phase transition from ordinary nuclear matter to quark-gluon plasma. At present, the detectors BM@N at JINR, NA61/SHINE at CERN, and HADES at GSI are in operation, where the interaction of light and heavy nuclei with fixed targets is studied at energies from 1 to 158 GeV per nucleon. Two new accelerator facilities are being constructed to continue this research: NICA at JINR (Dubna) and FAIR at GSI (Darmstadt, Germany). The Experimental Physics Department of (EPD) of INR participates in all these experiments.

EPD researchers are actively involved in GERDA-II, the international experiment to search for double neutrinoless beta-decay of germanium-76. The facility at which this experiment is conducted is located in the Italy-based underground Gran Sasso National Laboratory (LNGS INFN). Such a decay is predicted by theoretical models that include new properties of matter, which can manifest themselves at small distances. The LEGEND experiment is now under development, which will be a continuation of the GERDA experiment. The Institute is a member of the international teams that measure the oscillation parameter of reactor antineutrinos: Double Chooz θ13 (France) and JUNO (China), which is a multitask neutrino experiment in non-accelerator particle physics. The experiment will be carried out at a distance of 53 km from two reactor facilities in an underground laboratory at a depth of $\sim$ 700 m.

The International Scientific Committee adopted in 1984 a plan for the LVD (Large Volume Detector) facility to be deployed in the underground laboratory under construction in Gran Sasso (Italy). The LVD project was developed jointly by INR (Laboratory of Electronic Methods for Neutrino Detection headed by O G Ryazhskaya) and the Italian Institute of Cosmo-Geophysics. The deployment of scintillation counters in Gran Sasso began in 1990, and the third tower was completed in 2000. In total, about 700 scintillation counters were produced by INR. The LVD setup, which is currently the largest scintillation detector with unique capabilities for research in underground physics, yielded a number of fundamental results. The Institute also participates, as part of the international project CERN Neutrinos to Gran Sasso (CNGS), in which the properties of neutrinos are explored, in the OPERA experiment, where neutrinos can be distinguished from antineutrinos by the charge of muons in tau-muon decays. The muon data provided by the LVD detector were used as part of the OPERA experiment to monitor the characteristics of the muon neutrino beam from CERN.

The Institute's Laboratory of Photonuclear Reactions participates in several international collaborations, including A2 at the microtron in Mainz, BGOOD at the ELSA accelerator in Bonn, and NUSTAR at GSI (Darmstadt, Germany). In collaboration with JINR, the Institute has developed and produced for polarization experiments in Mainz and Bonn a unique polarized target with world-record setting characteristics. A number of pioneering results have been obtained in these experiments, in particular, proton spin polarizabilities have been measured for the first time. A series of experiments on the photoproduction of strange mesons in the range of photon energies up to 4 GeV has been carried out at BGOOD with the participation of the Laboratory of Photonuclear Reactions. The first experiments on the study of exclusive reactions of photoproduction of mesons and multifragmentation of nuclei have started.

The list and description of several dozen international projects and experiments in which INR is involved can go on, but they go beyond the scope of this article.

4. Present state and outlook

Institute researchers have recently obtained a number of important results highly estimated by the scientific community. They publish annually about 450 articles in major scientific journals in Russia and worldwide; about 60 reports are delivered at major conferences held in Russia and abroad.

The Institute organizes and conducts conferences that enjoy popularity in Russia and abroad, including QUARKS, international seminars on high-energy physics; Particles and Cosmology international schools; Electromagnetic Interactions of Nuclei at Low and Medium Energies international workshops; Markov readings; and a number of other national and international workshops and symposia.

Well known and highly acclaimed worldwide are the theoretical studies of the Institute's scientists in high-energy physics, perturbation theory methods in quantum field theory, ground state (vacuum) in gauge theories, methods for studying the dynamics of strong interactions of hadrons beyond perturbation theory, processes beyond the Standard Model of elementary particles, the formation of the baryon asymmetry of the Universe, the relationship between particle physics and cosmology, and the construction of dark matter and dark energy models. These studies have won numerous awards. In 2020, academician V A Rubakov was awarded the prestigious Hamburg Prize in Theoretical Physics for his significant contribution to solving the question of the Universe's origin.

New experimental data have been obtained on nuclear reactions involving protons and neutrons of medium energies and photonuclear reactions, including the study of the proton spin structure using an active polarized target, new effects have been observed in collisions of relativistic nuclei, and a new research area called 'nuclear photonics' has been formed.

The Institute is proud of its well-developed system for training scientific personnel. The Scientific and Educational Center has been operating for many years, providing training and work for more than a hundred undergraduate and postgraduate students, including those trained at the Institute's departments at the Moscow Institute of Physics and Technology (Fundamental Interactions and Cosmology) and Moscow State University (Particle physics and cosmology). Institute employees teach students from several other departments at Moscow State University and the Moscow Engineering Physics Institute and collaborate with Irkutsk, Kabardino-Balkarian, and Southern Federal Universities. Two joint research laboratories have been created in the North Caucasus, where undergraduate and graduate students are trained and perform research on the basis of the Baksan Neutrino Observatory; students and postgraduates take part in annual scientific expeditions to Lake Baikal to work on the Baikal deep-water neutrino telescope. Every year, seminars on Fundamental Interactions and Cosmology are held together with the Moscow Institute of Physics and Technology for students and postgraduates. The best postgraduates and graduate students attend CERN schools for young researchers and participate in experiments conducted by international collaborations. INR offers postgraduate studies and is authorized to confer academic degrees. Degrees of doctor and candidate of science are bestowed every year to researchers for their achievements in the most important and promising areas of modern physics.

The Institute is not only active in the development of unique research facilities. It made a significant contribution to the construction and development of the city of Troitsk (now an urban district of Moscow); several employees of the Institute have been elected honorary citizens of Troitsk; the Neutrino Residential Settlement was built in the Elbrus region for the staff of the Baksan Neutrino Observatory.

The future of research at INR is associated with megascience class projects.

The construction of the Baikal-GVD Baikal neutrino telescope with an effective volume of 1 cubic kilometer will be completed. This volume of the detector will make it possible to detect astrophysical neutrinos with the same sensitivity as is provided by the Ice Cube experiment in the Southern Hemisphere and thus to determine their origin.

Creation of the New Baksan Neutrino Telescope (NBNT) has been proposed, in which 10,000 tons of an ultrapure liquid scintillator will be used as a working substance. Such a telescope will be able to detect neutrinos emitted in the CNO cycle of thermonuclear reactions in the Sun. The sensitivity of the experiment will be sufficient to confirm one of several Sun models. Fulfillment of these projects would enable the creation in Russia of a multipurpose neutrino observatory, an integral part of the Global Neutrino Network.

A project for the modernization of the Troitsk-based linear proton accelerator has been proposed, and a physical feasibility study has been completed. It consists of replacing part of the accelerating structure in the existing tunnel with superconducting cavities. After the upgrade, the accelerator will provide a beam with an energy of 1 GeV and a power of 1 MW, which will enable transforming the existing IN-06 pulsed neutron source into a world-class facility. It is also planned to create a nuclear medicine center based on the accelerator complex in Troitsk. It will include a compact linear proton accelerator for radiation therapy and a radiochemical laboratory for the production of radiopharmaceuticals for the diagnostics and treatment of cardiovascular and oncological diseases.

Owing to the availability of highly qualified researchers and unique scientific facilities created at the Institute, close and fruitful collaboration with major research centers in Russia and abroad, and an advanced system of training scientific personnel, the Institute can successfully solve basic and applied problems of modern physics at the level of the world's highest standards.

The history of the Institute for Nuclear Research of the Russian Academy of Sciences, the activities of its structural units, the facilities created and the results obtained with them, and the awards, prizes, etc. won by the Institute and its researchers are presented in more detail in the booklet published by the Institute for its 50th anniversary.

Leonid Vladimirovich Kravchuk
INR director, 2014–2020