Physics – Uspekhi **67** (12) 1180 – 1199 (2024)

300th ANNIVERSARY OF THE RUSSIAN ACADEMY OF SCIENCES (RAS)

PACS numbers: **12.60.–i**, **26.65.+t**, **29.20.–c**, **87.56.–v**

The most important achievements in studies of fundamental problems in nuclear physics over the past 25–30 years and their prospects

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DOI: https://doi.org/10.3367/UFNe.2024.05.039792

Contents

Abstract. **This review is based on a report delivered on May 27, 2024 at the Scientific Session of the General Meeting of the Physical Sciences Division of the Russian Academy of Sciences, "Tricentennial of the Academy, Achievements of and Progress in Physical Sciences in the 21st Century." It covers the most important achievements in studying fundamental problems in nuclear physics over the past 25–30 years and prospects for further progress in this area. The report is focused on the contribution of Russian researchers to the global advancement that has occurred over recent decades in the study of fundamental problems in nuclear physics, including elementary particle physics and high-energy physics, relativistic nuclear physics and heavy ion physics, neutrino physics and neutrino astrophysics, and the physics of ultra-high-energy cosmic rays. Presented are the achievements of Russian scientists in theoretical physics and cosmology, which largely determine the successes in the exploration of the basic properties of matter. The contribution of Russian researchers to the implementation of major international projects, which has largely been a driver of their progress in recent decades, in particular, the discovery of the Higgs boson, is outlined. The current state and projects for the development of the research infrastructure of Russian research institutions are reviewed. The important role of progress in accelerator science and technology in exploring fundamental problems in nuclear physics is highlighted. Particular attention is paid to mega-science nuclear physics projects currently being developed and implemented in Russia and to emerging update of the strategy for the development of physical research and inno-**

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Received 30 September 2024, revised 9 November 2024
Uspekhi Fizicheskikh Nauk **194** (12) 1250 – 1269 (2024)
Translated by M Zh Shmatikov

vative technologies based on their results, which benefit the economy, education, and health care.

Keywords: fundamental problems, nuclear physics, theoretical physics, particle physics, Standard Model, heavy ions, accelerators and colliders, neutrino physics, neutrino astrophysics, physics of superheavy elements, high-performance computing, cosmology, dark matter, neutron physics, neutron beam research, synchrotron radiation beam research, proton therapy

1. Introduction

Reviewing the most important achievements of research in basic nuclear physics — the cutting edge of modern natural science, which includes elementary particle and high-energy physics, neutrino physics, neutrino astrophysics and astronomy, the physics of fundamental interactions and cosmology, heavy ion physics and relativistic nuclear physics, the physics and technology of accelerators and large-scale particle and nuclear radiation detectors, high-performance computing or, as it is called now, digital physics — and in some applied innovative areas based on nuclear technologies, such as nuclear-physical biology and medicine, over the past 25–30 years is an extremely challenging task, if it is possible at all.

Nevertheless, based on information from and proposals of the Scientific Councils of the Nuclear Physics Division in the research areas they supervise, an attempt is made here to sketch a multifaceted, albeit incomplete, picture of the most important achievements of, current state of, and immediate prospects for research in basic and applied nuclear physics.

Prior to presenting the most important results in individual research areas, it would be relevant to at least outline the current state of, problems in, and prospects for research in basic nuclear physics in Russia, relying on those main, fundamental results that largely determined the areas of further development.

2. Problems and challenges

The immense contribution to the study of the fundamental properties of matter made by the USSR's and specifically Russia's researchers, which largely determined the state of and strategy for the development of basic and applied research in nuclear physics in the world, is well known.

However, over the past 30 years, there has been a tendency toward a reduction in the share of studies carried out at Russia's research centers. First and foremost, this is because of the cessation of the development of a modern experimental base in the country due to the aging and decommissioning of installations built in Soviet times. The overall state of basic research in the country being depressed, the creation of major accelerator installations has slowed down.

This situation has led to a significant lag in the development of domestic experimental and primarily accelerator technologies in some important areas and, as a result, to significant personnel losses in leading research centers. Many promising, talented, young physicists have left Russia to work in major scientific institutions abroad.

3. Results of international cooperation

Despite this situation, during this period, Russian researchers actively participated in experiments conducted at the world's largest accelerators, including CERN (CMS, ATLAS, LHC-b, ALICE at LHC), BNL, JNL (SEBAF), and GANIL, in the laboratories RIKEN, JPARC, KEK, FNAL, GSI (FAIR), XFEL, etc., and in neutrino physics experiments at major neutrino installations abroad, in particular, LCNG, Daya Bay, T2K, and NOvA.

As a result, Russian scientists have made a significant contribution to the most outstanding Nobel-level achievements of basic nuclear physics of the last few decades: the discovery of the Higgs boson at the Large Hadron Collider (LHC), which heralded the triumph of the Standard Model (SM) of elementary particles, gravitational waves (LIGO experiment), violation of fundamental *CP* parity in nuclear interactions, searches for dark matter and New Physics beyond the Standard Model, and precision determination of the fundamental properties of neutrinos.

Owing to this collaboration, Russian researchers implemented the knowledge they had accumulated and gained invaluable experience in creating a state-of-the-art research infrastructure and experimental setups, developing theory, and collecting and processing data based on modern information-computer methods and unique innovative technologies.

Outlined below are the most important achievements attained by Russian researchers in studying fundamental properties as part of international scientific and technical cooperation.

Examples of the most significant and spectacular results are:

— discovery of the Higgs boson;

— synthesis of new superheavy elements of the periodic table;

— confirmation of the existence of neutrino oscillations predicted by Bruno Pontecorvo in Dubna more than 50 years ago;

— detection of a solar neutrino deficit and precision measurement of the neutrino flux on Earth;

— discovery of the top quark and determination of its properties;

— detection of the formation of quark-gluon plasma in heavy ion collisions;

— detection of direct violation of *CP* symmetry in nuclear interactions and neutrino oscillations.

Undoubtedly, the discovery in 2012 at CERN of the theoretically predicated Higgs boson by international collaborations on experiments at the Large Hadron Collider (LHC) [1, 2] was a triumph of the Standard Model of elementary particles, This theory itself is considered by the world scientific community to be the highest intellectual achievement of modern science [3, 4].

Russian scientists have made a fundamental contribution to the development and triumph of the Standard Model, including:

• development of the foundations of the theory:

— quantization of non-Abelian gauge fields;

— proof of the renormalizability of the theory;

— introduction of the hypothesis of colored quarks;

• creation of the scientific complex of the Large Hadron Collider:

— development of a scientific program for research into the high-energy interaction of hadrons;

— participation in the creation of experimental setups for the ATLAS, CMS, ALICE, and LHCb detectors;

— development, production, delivery, deployment, and adjustment of unique equipment for LHC accelerator systems;

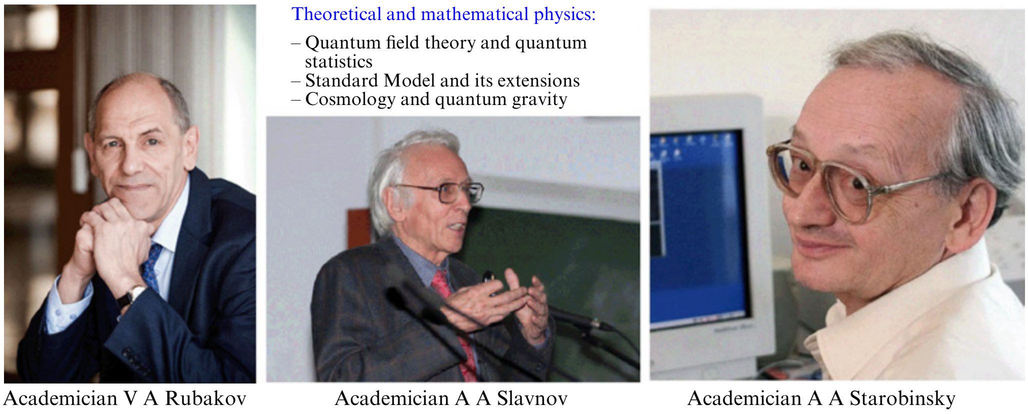

Figure 1. Outstanding representatives of scientific schools of N N Bogoliubov and L D Landau, who, together with their students, made a fundamental contribution to the development of theoretical and mathematical physics, quantum field theory, cosmology, and quantum gravity.

— scientific and engineering maintenance of equipment at the installations and conducting research;

— participation in the collection and processing of experimental data, preparation of scientific results;

— creation of TIER-1, a unique information and computing facility based on GRID technology, and its operation for event modeling and collection and processing of data from the ATLAS and CMS detectors.

4. Most important achievements of Russian researchers over 25–30 years in studying fundamental properties of matter

4.1 Elementary particle and high energy physics

We list below the most significant results obtained by Russian scientists in high energy and elementary particle physics; highlighted in bold are the achievements attained and discoveries made exclusively in Russia:

— precision verification of the electroweak interaction model in LEP experiments, determination of the number of neutrino generations (1989–2000) at the CERN-based facilities DELPHI (IHEP + JINR) and L3 (ITEP + PNPI);

— discovery and study of the t-quark (1995–2005) at the Fermi National Laboratory (USA): CDF + D0 (four Russian institutes);

— discovery and study of quark-gluon plasma (2005–2023) in the STAR + PHENIX (Brookhaven National Laboratory (USA)) and ALICE (CERN) experiments with the participation of seven Russian institutes;

— **observation of the solar neutrino deficit (1991–2009) in the Russian–American SAGE experiment at the Baksan Neutrino Observatory (BNO) of the Institute for Nuclear Research (INR) of the Russian Academy of Sciences in the North Caucasus**;

— discovery and study of the Higgs boson (2012–2024) at the ATLAS and CMS facilities at the Large Hadron Collider (CERN) with the participation of researchers from 11 Russian institutes and universities;

— detection of direct CP symmetry violation in nuclear physics in the NA48 experiment at SPS (1999) (Joint Institute for Nuclear Research (JINR)); precision measurement of the parameters of *CP* violation in heavy quark decays (2000–2023) in the BELLE + LHCb experiments (six Russian institutes);

— **precision measurement of the neutron lifetime (2005) (PNPI)**;

— **synthesis of superheavy elements (1994–2010) at the cyclotrons of the Flerov Laboratory of Nuclear Reactors (FLNR) of JINR**;

— detection and study of exotic hadrons in reactions with heavy quarks (2000–2023) in the BELLE + LHCb experiments (six Russian institutes);

— **precision measurement of characteristics of hadron formation reactions in e^+e^- interactions (2010–2023) (Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences)**;

— precision measurement of solar neutrino fluxes, study of geoneutrinos (2003–2024) in the Borexino experiment (Gran Sasso, Italy) with the participation of JINR and National Research Center Kurchatov Institute (NRC KI);

— **detection and study of exotic hadrons in reactions with light quarks (1985–2024) in the GAMS + VES experiments using U-70 accelerator of IHEP**;

— **search for New Physics in kaon decays (1995–2024) at the OKA facility at IHEP with the participation of three Russian institutes**;

— **detection of a neutrino signal from the birth of the 1987a supernova and monitoring of supernova births at the LSD facility (BNO, INR RAS)** and the Russian–Italian LSD (Mont Blanc) and LVD (Gran Sasso, Italy) facilities.

4.2 Theoretical and mathematical physics

In presenting the outstanding results in experimental physics, which, as we can see, are numerous, it would be relevant to continue with the contribution of Russian researchers to progress in theoretical and mathematical physics, in particular, in the physics of elementary particles and quantum field theory, and the advancements based on them in studying the laws of astrophysical phenomena and, ultimately, in understanding the nature of the early Universe [5–10].

It is virtually impossible to fully cover this contribution within this report.

It is worth mentioning at least the contribution of Russian scientists to the development and success of the Standard Model of elementary particles, particularly the contribution of L D Faddeev and A A Slavnov to the quantization of non-Abelian gauge fields [11] and the contribution of V A Rubakov and A A Starobinsky to modern cosmology [12] (Fig. 1).

Today, we genuinely miss these truly outstanding scientists, the most worthy successors of the scientific schools of N N Bogoliubov and L D Landau, who trained many talented students.

I remember well the day that V A Rubakov, delivering a report, said that from that day on (unfortunately, I do not remember the exact date) cosmology could be considered an accurate and experimentally verifiable theory, like the Standard Model in particle physics. While the current state of cosmology owes much to the work of A A Starobinsky, V A Rubakov made an immense contribution to combining concepts and achievements of cosmology and the Standard Model.

We now cite some important results in cosmology as an example of achievements in theoretical and mathematical physics.

4.2.1 Baryon acoustic (Sakharov) oscillations. It is well known that the correlation distribution function of galaxies exhibits oscillation peaks similar to the peaks in the expansion of the anisotropy of the relic radiation in multipoles of spherical harmonics. These peaks have the same source: sound waves (Sakharov acoustic oscillations) in the primordial plasma of the recombination era. However, the description of the peaks in the spectrum of galaxies is highly complicated: due to the inhomogeneities of matter, this problem is nonlinear [13] (Fig. 2).

The source of primordial inhomogeneities is unknown. The dominant idea is that they arose in the earliest Universe at the inflationary stage from quantum fluctuations. The first realistic inflationary model was proposed by A A Starobinsky [14], who also calculated the spectrum of the primary gravitational waves formed at this stage. V A Rubakov, A V Veryaskin, and M V Sazhin [15] noted that these waves can affect the anisotropy of the relic radiation. Since this phenomenon has not been observed, we now have the strongest upper limit on the rate of the Universe's expansion in that era, and therefore on the scale of inflation.

4.2.2 Baryogenesis and dark matter. Generalization of the SM by adding three heavy Majorana fermions, singlets over the SM gauge group, leads to the appearance of the masses of active neutrinos and explains neutrino oscillations. This extension also provides an explanation of the appearance of baryon asymmetry through leptogenesis in the early Universe [16].

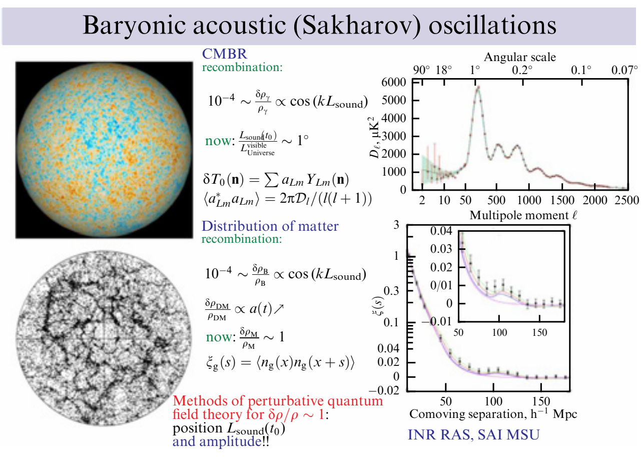

Figure 2. Baryonic (acoustic) oscillations.

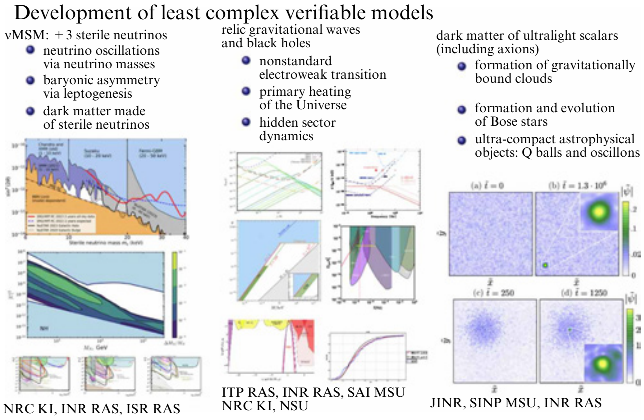

Figure 3. Baryogenesis and dark matter.

E Akhmedov, D Gorbunov, V Rubakov, and A Smirnov [17] indicated that lepton asymmetry in the oscillations of sterile and active neutrinos in the primordial plasma could emerge before the epoch of the electroweak phase transition, and the first numerical estimate of the expected effect was made (Fig. 3).

Generalizations of the SM at high energies have been proposed where relic black holes or gravitational waves are formed during the evolution of the Universe. Both are remarkable in that they have survived to this day without changes in characteristics, the measurement of which makes it possible to accurately determine the dynamics of the high-energy theory [18, 19].

One of the most straightforward candidates for the role of dark matter is a scalar field, or a condensate of very light particles, such as an axion. It turns out that such dark matter can feature inhomogeneities on small scales and form clouds, gravitationally bound clumps, and even very compact objects, so-called Bose stars [20].

V Rubakov and A Khmelnitsky pointed out the influence of the scalar field of dark matter on the time evolution of the pulsar signal, which was one of the physical grounds for monitoring pulsars [21].

It should be noted that the nature of dark matter and the possibility of observing it in laboratory conditions on Earth remain some of the most important unsolved problems of modern particle physics, astrophysics, and cosmology [22–24].

4.2.3 Inflation, dark matter, and 'another' gravity. Everything is simple in this area: the first inflationary model of the early Universe, which is still consistent with all observations, is Starobinsky's $R + R^2$ model (Fig. 4) [25].

He also proposed one of the two most popular models of inflation in the late Universe based on the $F(R)$ model (also named after him), which focuses on the role of dark energy rather than on the cosmological constant [26].

Rubakov, in collaboration with Shaposhnikov, proposed the concept of the "world on a brane in a space of higher dimension" and a method for localizing fields in a subspace of lower (3D) dimension [27]. Rubakov showed how the disappearance of electric charge and mass would be seen by a 3D observer [28, 29]. He also proposed alternatives to inflation in this paradigm (see Fig. 4).

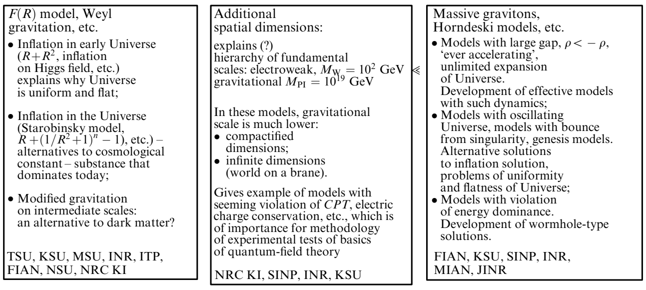

Figure 4. Progress in development of cosmological models (inflation, dark energy, and other gravitation).

4.2.4 Study of properties of quark-gluon plasma and quantum chromodynamics. Now, at least briefly, we present some important results obtained in quantum chromodynamics (QCD) in describing the properties of quark–gluon plasma and its high-energy behavior, together with examples of record-breaking multi-loop calculations in particle physics problems [30, 31].

Figure 5a displays the results of describing the phase states of quark-gluon plasma in a strong magnetic field (Mathematical Institute of the Academy of Sciences (MIAN), JINR).

The first-order phase transition in QGP was studied in holographic QCD. Its stability area in shown to decrease with magnetic field growing.

In studying rotating quark–gluon plasma in lattice QCD, the moment of inertia of the plasma was calculated, which takes negative values under certain conditions (JINR) (Fig. 5b).

The first observation of the asymptotic high-energy behavior of QCD according to the Lipatov–Fadin–Kuraev–Balitsky evolution equation in CMS data on LHC (PNPI, INR) is displayed in Fig. 5c.

Figure 5d presents the record-setting results of perturbative QCD calculations in Standard Model problems; in particular, 5-loop corrections to the anomalous magnetic moment of the muon were found, which are of importance for precision testing of SM predictions (MSU SINP, NPI SB RAS, INR RAS, JINR).

5. State of existing research infrastructure in Russian Federation

At present, outstanding schools of nuclear physics and technology have been preserved in research centers of the Russian Federation, and large physical complexes operate, maintaining a high level of basic and applied research in the country. As examples of operating facilities and major experiments conducted in the Russian Federation with significant results and prospects for further development, we note:

— Nuclotron — LHEP JINR;

— Factory of superheavy elements — FLNR JINR;

— Electron–positron collider complex of INP SB RAS;

— Experimental complex of Moscow Meson Factory of INR RAS;

— Accelerator complex U-70 of NRC KI-IHEP;

— Baikal Deep-Underwater Neutrino Telescope of INR RAS, JINR;

— Baksan Neutrino Observatory of INR RAS;

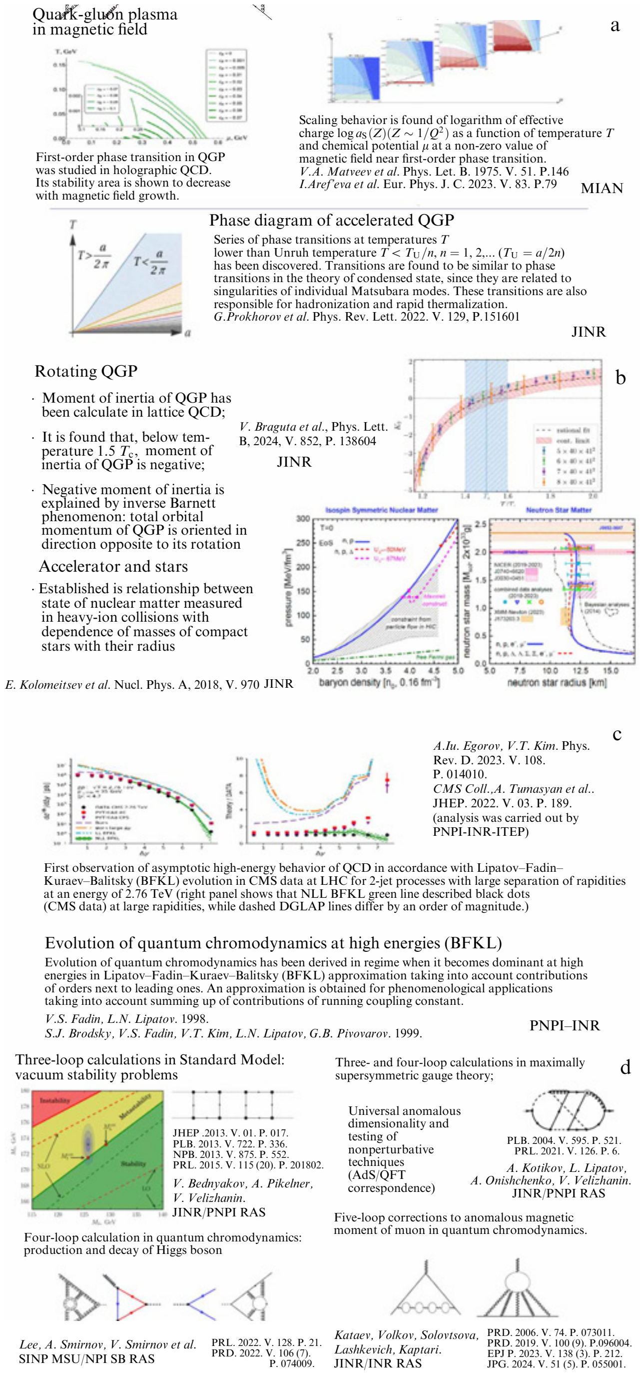

Figure 5. (a) Hadronic matter under extreme conditions. (b) Observation of the asymptotic high-energy behavior of QCD (BFLK) at LHC. (c) Record-setting calculations in quantum-field theory.

— Astrophysical facilities of SINP MSU, MEPhI, FIAN, INR RAS, ISU, JINR.

An important achievement of the accelerator community is the preservation of national facilities of various types and purposes in operable condition. Figure 6 presents a list of accelerators and accelerator complexes currently operating in Russia.

The existing accelerator complexes maintain a high level of basic and applied research in Russia, the preservation and confirmation of core competencies, and the development of new technologies and methods that enable the implementation of new accelerator projects (NICA, SKIF, SILA, etc.)

Institute	Name	Type	Types of particles	Energy, dimensions
INR RAS	High-current LA	Linear resonance accelerator	p, H^-	600 MeV (design) 300 MeV (operating) $L = 450$ m
INR SB RAS	VEPP-4M	electron–positron collider	e^-, e^+	1.5 5–5.5 GeV $\Pi = 366.1$ m
INR SB RAS	VEPP-2000	electron–positron collider	e^-, e^+	0.2–1 GeV $\Pi = 24.4$ m
NRC KI – IHEP	U-70	Synchrophasotron	p, C^{6+}	50–60 GeV (p), 25–30 GeV/u $\Pi = 1483.7$ m
NRC KI – PNPI	STs-1000	Synchrocyclotron	p	1000 MeV (1 GeV) ø6.85 m (pole)
Institute	**Name**	**Type**	**Type of particles**	**Energy, dimensions**
JINR	NUKLOTRON	Superconducting synchrophasotron	P, d, Mass-charge range ($A/Z < 2.5$)	12 GeV (p), 5.6 GeV/u (d) 4.5 GeV/u $\Pi = 251.5$ m
JINR	U-400M/U-400	Tandem of isochronous cyclotrons	Mass-charge range ($A/Z = 2$–10)	50 GeV/u ø400 cm (pole)
JINR	DTs-280	Isochronous cyclotron	Mass-charge range ($A < 50$)	5–7 GeV/u ø280 cm (pole)
NRC KI	Ring source of synchrotron radiation-Kurchatov	Synchrotron: source of synchrotron radiation	e^-	2.5 GeV $\Pi = 124.1$ m

Fig. 6. List of accelerators and accelerator complexes currently operating in Russia.

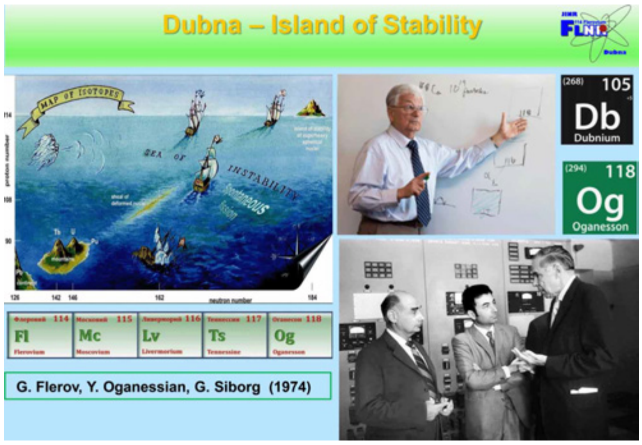

Figure 7. Search for large area around island of stability of heaviest elements, called 'Dubna stability island,' and the very existence of superheavy elements.

6. Achievements in research based on accelerator complexes

6.1. Research in basic nuclear physics. Factory of superheavy elements

In 2000–2015, at JINR, an original technique of fusing nuclei of transuranium elements with nuclei of the rare calcium-48 isotope was used to synthesize for the first time the heaviest chemical elements with atomic numbers 113 through 118. They have already been recognized and included in the Periodic Table. The list of the new elements contains many Russian names: flerovium, moscovium, and the heaviest of the new elements, oganesson, named in honor of a member of our department who supervises the research on the physics of superheavy elements conducted at JINR's Laboratory of Nuclear Reactions [32, 33].

Almost all isotopes of superheavy elements undergo alpha decay. Together with the decay products, new isotopes of elements 104–113 (a total of 52 new nuclides were discovered), they exhibit amazing vitality near the boundary of nuclear masses. Their energies and decay probabilities are a direct experimental confirmation of the fundamental predictions of the microscopic theory of the structure of nuclear matter and the role of new nuclear shells in the formation of a large island of stability of the heaviest nuclei, called the Dubna Island of Stability, and the very existence of superheavy elements (Fig. 7).

To study physical and chemical properties of new elements, a new accelerator complex was built at JINR at end of the last decade. Named the 'Superheavy Element Factory' (Fig. 8a), it includes a powerful heavy ion accelerator (Fig. 8b) and new-generation experimental setups (Fig. 8c, d) [34, 35].

For three years now, the factory has been working around the clock on experiments, significantly exceeding the level achieved in the world's leading laboratories (Fig. 9) [36].

In less than three years, elements 112, 114, and 115 were newly synthesized in reactions with Ca-48; decays of more than 40 isotopes of superheavy nuclei were observed, and their new isotopes were discovered. Preparations are underway for the synthesis of the 120th element.

In the Periodic Table, new elements occupy the 7th row. For the first time, it is now possible to test the Periodic Law under the increasing influence of the 'relativistic effect' on the chemical properties of superheavy elements in the homologues of rows 6 and 7 [37].

It is my pleasure to show the world's largest periodic table in Dubna, which is clearly visible from ships sailing along the Volga (Fig. 10).

It should be noted that the Laboratory of Nuclear Reactions in Dubna has been a world leader in the synthesis and research of the properties of superheavy nuclei and elements for 25 years.

6.2 Relativistic nuclear physics. Development of experimental base of JINR LHEP

Research in relativistic nuclear physics using accelerated beams of hadrons and heavy nuclei was initiated more than 30 years ago in Dubna on the basis of the 10-GeV synchrophasotron built at JINR under the supervision of V I Veksler. It continued with the creation of a new accelerator facility based on the advanced technology of superconducting magnetic elements developed in Dubna.

The main milestones of the development of the accelerator complex of the JINR LHEP are listed below.

1993: Nuclotron–the world's first superconducting synchrotron of heavy ions (4.5 AGeV)–is created under the supervision of Academician A M Baldin; advanced technology of the so-called Dubna superconducting magnets is developed;

2009: JINR Committee of Plenipotentiaries decrees NICA (Nuclotron-based Ion Collider fAcility) project be launched [38–40];

2016: Government of the Russian Federation and JINR sign an agreement on the creation and operation of the NICA complex;

2020: superconducting synchrotron-Booster (578 MeV/u) is commissioned; the creation of an experimental zone on a fixed target is completed; a new facility, BM@N (Baryonic Matter at Nuclotron), is commissioned; an international collaboration including 19 institutes from 10 countries totaling more than 250 participants (Fig. 11) is formed [40–42];

2018: NICA complex, a mega-science project, is included in SCIENCE, the Russian Federation's National Project;

2022: injection complex consisting of 5 structural elements: Cryon, heavy ion injector — HiLac, Booster, Nuclotron, and channels — is commissioned;

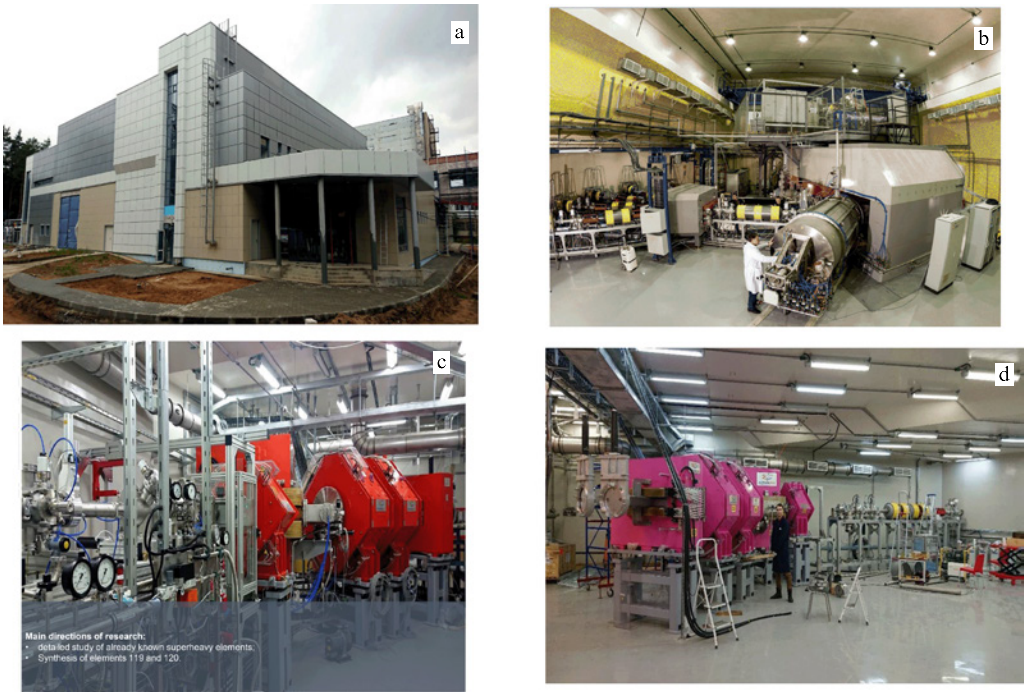

Figure 8. (a) Superheavy Element Factory of JINR FLNR in Dubna was commissioned in 2018. (b) New DC-280 cyclotron of JINR FLNR. (c) Gas-filled recoil separator — DGFRS-2. Research areas: detailed study of already known elements and synthesis of new superheavy elements 119 and 120. (d) Gas-filled recoil separator — GRAND (DGFRS-3). Research areas: nuclear and mass spectroscopy of superheavy elements and study of their chemical properties.

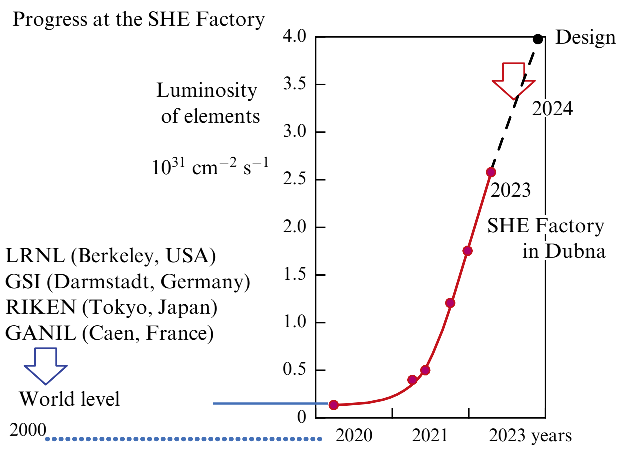

Figure 9. For three years now, Factory of Superheavy Elements has been working around the clock on the experiment, significantly ahead of world level achieved in world's leading laboratories.

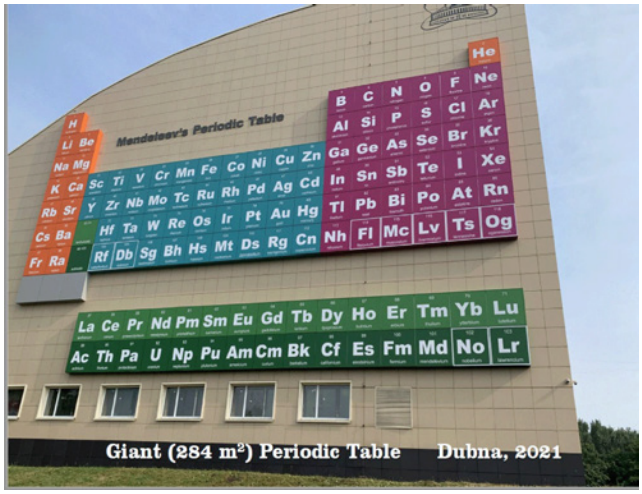

Figure 10. World's largest Periodic Table on wall of Archimedes swimming pool on right bank of Volga River.

2022: first run of SRC (Short Range Correlations) experiment with a 3-AGeV ^{12}C ion beam is conducted;

2024: stage 1 of construction of NICA complex is completed, including installation of NICA collider equipment; fixed-target experiment program is launched (Fig. 12);

The NICA scientific program has been developed, which aims at research in the following areas: QCD diagrams in the poorly studied region of high baryon density, where the use of lattice QCD is ineffective; the spin structure of nucleons; and a wide range of applied studies. Projects have been developed and work is actively underway to build unique installations at two points of intersection of colliding ion beams: MPD (Multi-Purpose Detector) and SPD (Spin Physics Detector); the corresponding international collaborations have been established and are actively working. A program of related applied research areas has been developed (Fig. 13).

At the JINR LHEP, in collaboration with specialists from the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences, electron cooling of a heavy ion beam (NICA) was implemented for the first time (Fig. 14). V V Parkhomchuk, V B Reva (INP SB RAS), and I N Meshkov (LHEP, JINR) made a pivotal innovative contribution to the creation of the Electron Cooling System for the NICA collider [43, 44].

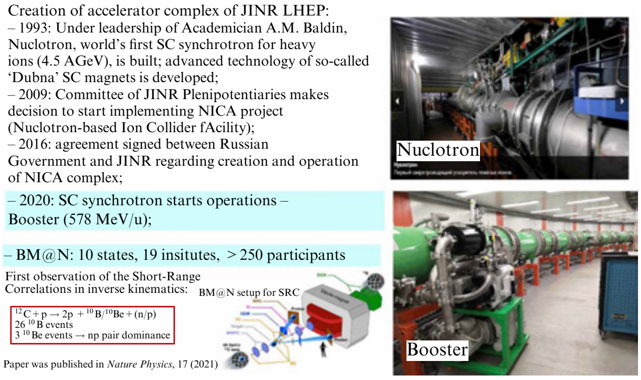

Figure 11. State of work on construction of NICA complex in 2020; commissioning of Booster and start of operations of area of fixed-target experiments.

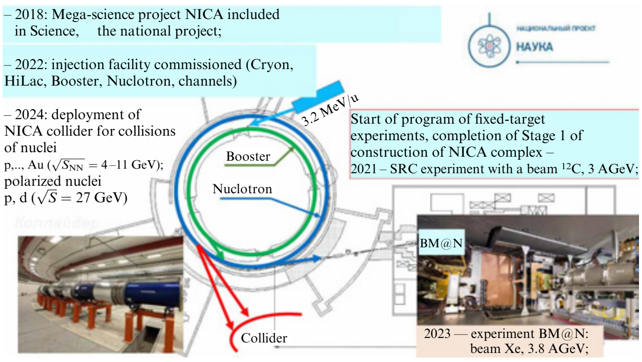

Figure 12. Completion of Stage 1 of construction of NICA complex, including installation of NICA collider equipment; start of program of fixed-target experiments.

6.3 Physics at electron–positron colliders. Development of INP SB RAS collider complex

Large-scale experiments in elementary particle physics are conducted by the Budker Institute of Nuclear Physics at VEPP-4M and VEPP-2000, the only two electron–positron colliders operating in Russia. The main area of research is precision verification of the SM and the search for New Physics.

The pioneering work in this area, which began exactly 60 years ago under the leadership of G I Budker and his student A N Skrinsky, opened a new era in particle physics: the era of colliders (Fig. 15).

Among electron–positron colliders operating in the world, VEPP-2000 'handles' the niche of the lowest energies — from the threshold of hadron production, approximately 300 MeV in the center-of-mass system, to 2007 MeV — slightly above the threshold of proton–antiproton and neutron–antineutron pair production (Fig. 16).

The **VEPP-2000 collider** is a facility which is extremely interesting as an accelerator per se. It implements a unique optical scheme of 'round' beams, proposed in Novosibirsk. This solution enables achieving record parameters of the beam meeting and record luminosity in the single-bunch mode. Another feature of VEPP-2000 is a system of continuous measurement and control of beam energy, based on precision measurement of the energy of Compton gamma quanta produced by scattering of laser radiation on an electron beam. These features enabled carrying out precise measurements of the cross sections of e^+e^- annihilation into

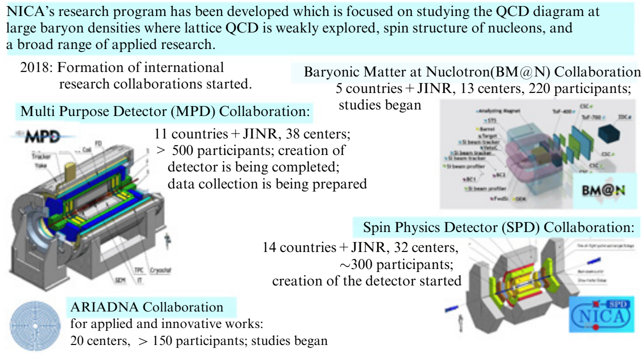

Figure 13. State of work on preparation of research program for basic and applied studies at NICA complex.

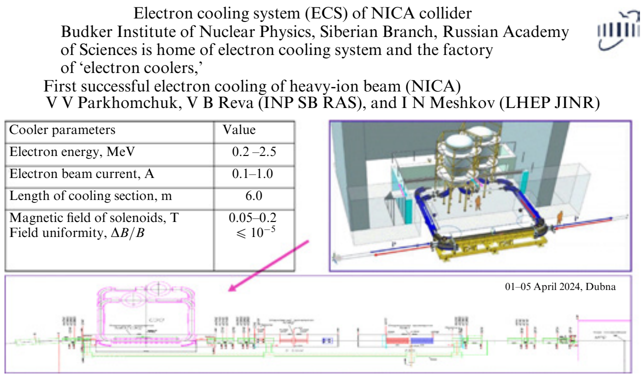

Figure 14. Development of electron cooling system for NICA collider.

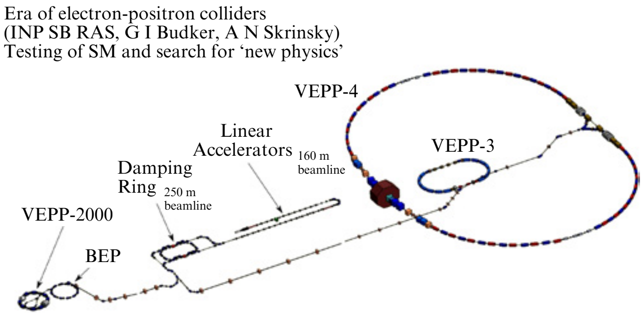

Figure 15. Colliders operated by INP SB RAS.

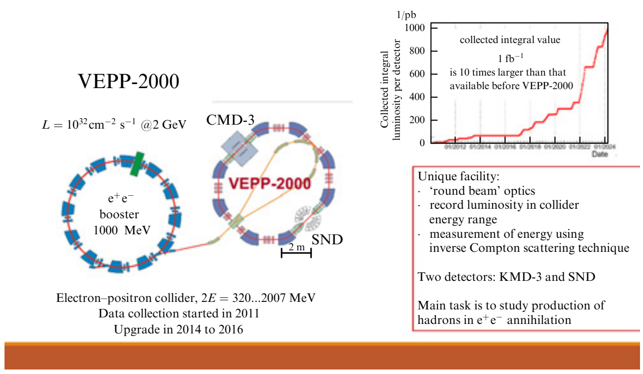

Figure 16. VEPP-2000 collider.

hadrons, especially at the threshold of $p\bar{p}$- and $n\bar{n}$-pair production (Fig. 17).

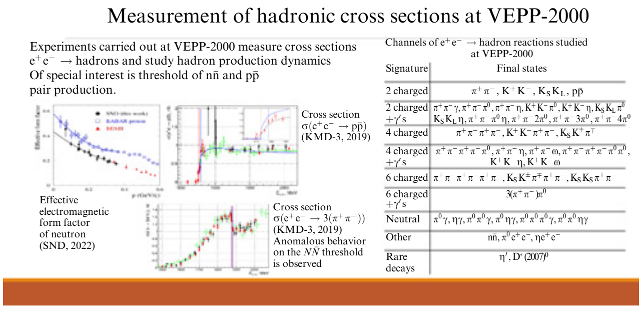

Figure 17. Measurement of hadronic cross sections at VEPP-2000.

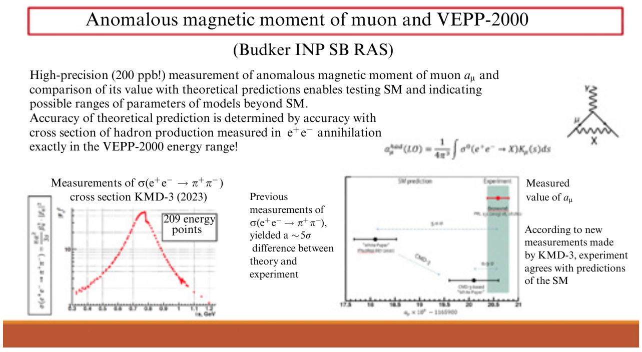

Figure 18. Measurements of anomalous magnetic moment of muon at INP SB RAS.

Figure 19. Work of INP SB RAS on electron cooling technique.

One of the most prominent tasks of the VEPP-2000 physics program is the measurement of the hadron contribution to the anomalous magnetic moment of the muon.

The results of measuring the cross section of the production of two pions, published by the CMD-3 team in 2023, cast doubt on the disagreement between the calculated and measured values of the anomalous magnetic moment of the muon that has been observed over the past two decades. The CMD-3 measurement, based on record statistics and meticulous data analysis, agrees with the prediction of the Standard Model, a result of extreme significance (Fig. 18).

We should at least briefly note the outstanding achievements of the INP SB RAS in the technology of electron cooling of accelerated beams of hadrons and heavy ions. The 50th anniversary of this outstanding world-level accomplishment of Russian science, which is related to V V Parkhomchuk and his colleagues, will be celebrated in 2024 in Novosibirsk (Fig. 19).

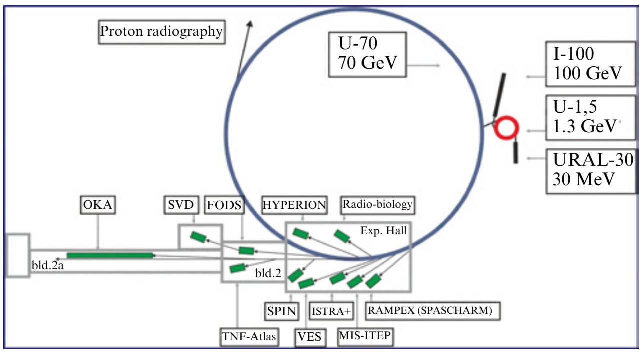

Figure 20. Complex of hadron accelerators operated by NRC KI-IHEP.

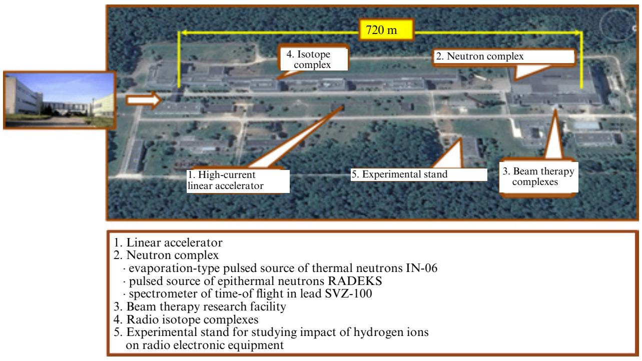

Figure 21. Complex of high-current linear accelerator of ions operated by INR RAS.

6.4 Investigations of exotic hadron states. Search for New Physics in rare decays of K-mesons. Hadron accelerator complex of NRC KI-IHEP

Experiments conducted in 1984–1997 at the U-70 accelerator complex on the GAMS setup yielded the first indications of the existence of an exotic hadron state: the so-called glueball, a bound spinless system of gluons.

In a joint experiment of IHEP, INR RAS, and JINR on the OKA setup, operating on the secondary separated beam of the U-70 synchrotron, the search for New Physics in decays of charged K-mesons was conducted in 2014–2024 (Fig. 20).

6.5 Research in intermediate-energy high-intensity nuclear physics. Multipurpose complex of high-current linear accelerator of hydrogen ions of INR RAS

Over the past 25 years, 139 sessions of accelerator operation with a total duration of more than 40,000 hours have been carried out at the installations of this multipurpose scientific complex, which yielded results pertaining to nuclear physics, medical physics, and the development of radioisotope production technology (Fig. 21). A schematic diagram of the complex of the high-current linear accelerator of hydrogen ions operated by the INR RAS with a list of its main objects is presented [45, 46].

6.6 Basic nuclear physics with neutrons

Precision measurements of the neutron lifetime at PNPI using a gravitational trap of ultracold neutrons radically altered the value of this fundamental quantity in 2005 and eliminated the disagreement with the Standard Model. This result was later confirmed by measurements conducted at PNPI with a

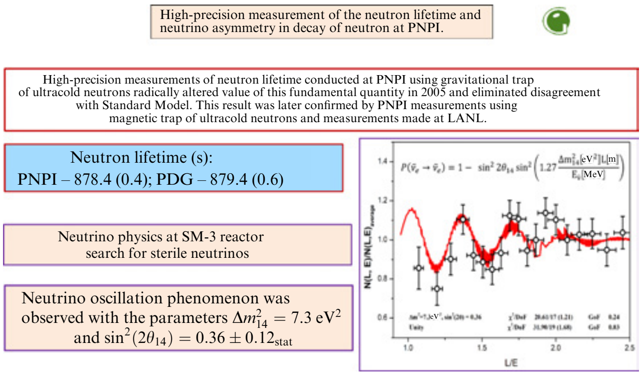

Figure 22. Studies in basic nuclear physics using neutron conducted at NRC KI-PNPI.

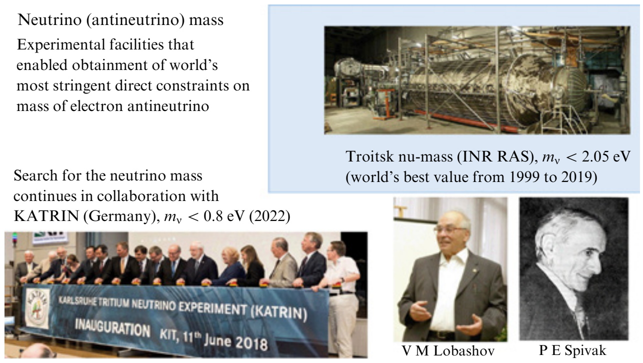

Figure 23. Experimental facilities that enabled obtainment of most stringent constraints on antineutrino mass.

magnetic UCN trap and by measurements carried out at LANL (USA).

A neutrino laboratory was created at the SM-3 reactor in Dimitrovgrad, in which antineutrino oscillations into a sterile state were searched for.

Neutrino oscillations with the parameters $\Delta m^2_{14} = 7.3$ eV^2 and $\sin^2(2\theta_{14}) = 0.36 \pm 0.12_{stat}$ were observed. Should this phenomenon be confirmed at a new level of accuracy, this will imply the discovery of a sterile neutrino — a new elementary particle not contained in the Standard Model.

To test the oscillation effect at a new precision level (higher than five standard deviations), a new facility and a second neutrino laboratory were created at SM-3.

Figure 22 presents the research conducted at the NRC KI-PNPI on the precision measurement of neutron lifetime and the search for antineutrino oscillations into a sterile state [47, 48].

7. Neutrino physics and neutrino astrophysics

In addition to research into nuclear physics based on accelerator technology, Russia is actively developing research in neutrino physics and neutrino astrophysics using unique Russia-based large-scale neutrino detectors: Baksan Neutrino Observatory of the INR RAS (PST, GGNT, Kover), Baikal Deep-Underwater Neutrino Observatory of the INR RAS and JINR (Baikal-GVD), and research into natural fluxes of high-energy cosmic rays and extensive air showers (YAKUSHAL, Kover, Telescope Array) at unique large-area and high-sensitivity ground-based installations, and cosmic ray monitoring stations and orbital detectors aboard a spacecraft (NUKLON, TUS, Pamela), etc.

In addition, scientists from the Russian Federation and JINR have made a significant contribution to global international projects BOREXINO (Italy), Daya Bay (China), T2K (Japan), NOvA (USA), and Telescope Array (USA) [49, 50].

7.1 Neutrino (antineutrino) mass

Reliably registered transitions between neutrinos of different types are only possible in the case of non-zero neutrino mass; however, despite all efforts, the mass itself has not yet been measured in laboratory conditions.

In 1999–2019, the world's most stringent direct constraints on the electron-antineutrino mass were obtained in studies conducted at the TROITSK-nu-mass facility (INR RAS) ($m_\nu < 2.05$ eV), created under the leadership of V M Lobashev (INR RAS) and P E Spivak (NRC KI) [51]. The measurements were continued as part of international cooperation at the KATRIN facility (Germany), yielding $m_\nu < 0.8$ eV (2022) [52] (Fig. 23).

7.2 Physics of solar neutrinos

Solar neutrinos, which are produced in thermonuclear reactions in the depths of stars, are directly related to the release of solar energy. Fusion reactions can occur through various channels.

The first experiments detecting solar neutrinos, due to the high energy threshold, could only study $\sim 10^{-5}$ of their total flux.

At the **Gallium-Germanium Neutrino Telescope in the Baksan Neutrino Observatory of the INR RAS** located in the North Caucasus, the integral flux of solar neutrinos, including the main pp-channel, was measured for the first time (Fig. 24) with an accuracy of $\sim 5\%$ [53]. It has been experimentally confirmed that the source of the Sun's energy is fusion reactions, and their rate has been measured. The existence of a deficit in the total flux of solar electron neutrinos has been reliably demonstrated (INR RAS) and explained by mutual transformations of neutrinos of different types.

Russian scientists have made an important contribution to the study of solar neutrinos in the Borexino experiment (JINR, NRC KI, PNPI, SINP MSU).

Borexino is a unique 100-ton liquid scintillation detector installed in the underground low-background laboratory in Gran Sasso (Italy), specially designed to detect low-energy solar neutrinos in real time using a

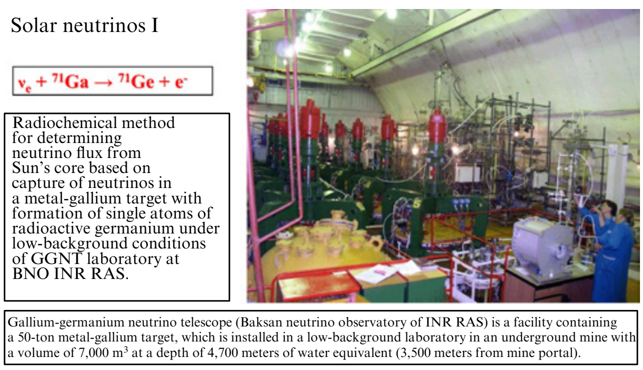

Figure 24. Experimental room and reactors of gallium-germanium neutrino telescope in underground laboratory of BNO INR RAS.

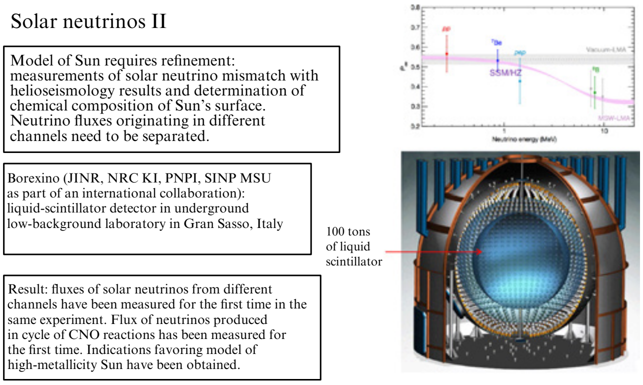

Figure 25. Borexino facility: 100-ton liquid-scintillator neutrino detector installed in underground low-background laboratory in Gran Sasso.

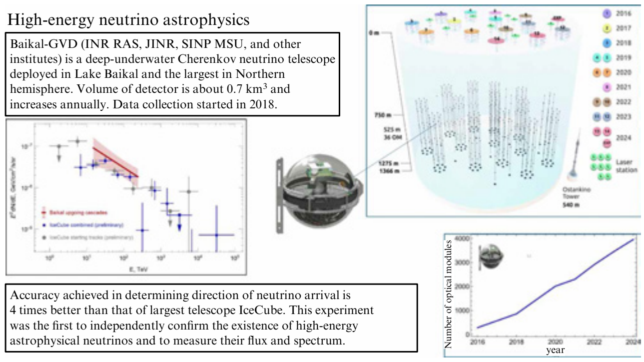

Figure 26. Growth of the number of optical modules of deep-underwater telescope Baikal-GVD.

scintillating liquid with a record low level of radioactive impurities (Fig. 25).

Russian institutes and JINR made a significant technological contribution to the creation and testing of the facility and an important intellectual contribution to the project through data analysis, including the analysis of rare processes and modeling of physical phenomena.

The main results of the experiment are:

• Borexino was the first experiment to accurately measure the energy spectra of neutrinos in the pp-chain of thermonuclear fusion reactions [54], thereby making a decisive contribution to solving the mystery of solar neutrinos.

• Of particular importance are the discovery and confirmation of the theory of neutrino oscillations and the Mikheev–Smirnov–Wolfenstein effect [55, 56], which provided a clue to understanding the processes occurring in the Sun.

• The experiments performed by the collaboration made it possible for the first time to observe neutrinos from the CNO cycle [57], clarifying the mechanisms of energy generation in the Sun. Indications in favor of the high-metallicity Sun model were obtained.

• Borexino was the first experiment in which geoneutrinos were reliably observed.

7.3 High-energy neutrino astrophysics

Astrophysical neutrinos with energies above 10 TeV were detected by IceCube (South Pole) in 2014. It is difficult to determine their sources due to the high background of atmospheric events and low accuracy of determining the directions of neutrino arrival in ice.

Russian scientists (INR RAS, JINR, ISU, SINP MSU, MEPhI) have deployed the largest neutrino telescope in the Northern hemisphere, Baikal-GVD, with a cubic-kilometer volume (Fig. 26).

Baikal-GVD (INR RAS, JINR, ISU, SINP MSU, etc.) is a deep-underwater Cherenkov neutrino telescope located in Lake Baikal. The detector's volume is currently about 0.7 km^3 and increases annually. Data collection has been ongoing since 2018.

The facility achieved a fourfold increase in the accuracy of determining the direction of neutrino arrival compared to that of the largest IceCube telescope in Antarctica [76, 77]. The existence of high-energy astrophysical neutrinos has been confirmed for the first time in an independent experiment, and their flux and energy spectrum have been measured.

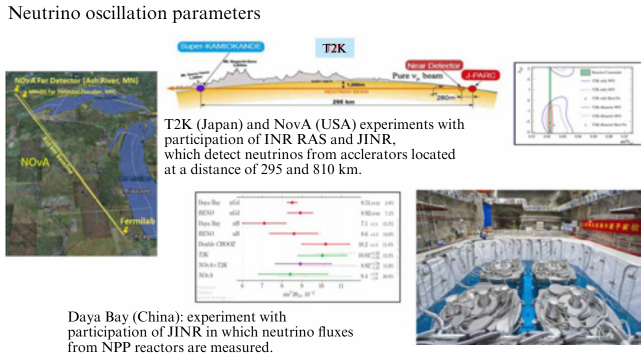

Figure 27. Experiments studying neutrino oscillation on a large flight base, in which researchers from Russia and JINR take part.

A program for further development of this unique neutrino detector is currently under implementation.

7.4 Neutrino oscillation parameters

Transitions among three types of neutrinos (oscillations) are described by six parameters, some of which are not yet measured with sufficient accuracy.

The participation of Russian scientists (INR RAS, JINR, etc.) in international teams that create and operate the best world installations, Daya Bay (China), T2K (Japan), NOvA (USA), etc., made it possible to carry out the most accurate measurements of the oscillation parameters. An indication of *CP* symmetry violation in processes involving neutrinos was discovered, which is the basis for the leptogenesis model explaining the baryon asymmetry of the Universe.

Figure 27 presents experiments to study neutrino oscillations on a large flight base conducted with the participation of scientists from Russia and JINR.

8. Physics of cosmic rays and problems of high-energy astrophysics

8.1 Structure of galactic cosmic ray spectra

A detailed study of cosmic radiation spectra in the range of $10^{12}-10^{17}$ eV, which has become possible due to the use of state-of-the-art instruments created by Russian researchers, is necessary to understand nonthermal processes occurring in our Galaxy.

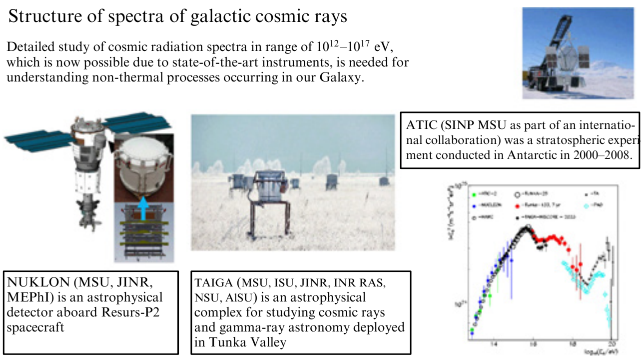

Figure 28. Facilities and astrophysical complexes for studying cosmic radiation spectra operating in Russia.

The following installations were involved in measurements (Fig. 28):

ATIC (SINP MSU as part of an international team): a stratospheric experiment in Antarctica (2000–2008) [74];

NUKLON (MSU, JINR, MEPhI): an astrophysical detector aboard the Resurs-P2 spacecraft [66, 75];

TAIGA (MSU, ISU, JINR, INR RAS, MEPhI, NSU, AlSU, MEPhI, etc.): an astrophysical complex for studying cosmic rays and gamma-astronomy in the Tunka Valley [76].

The primary energy spectrum of cosmic rays was measured using the **Tunka-133** facility [76].

Experiments showed that the spectra of galactic cosmic rays significantly differ from power-law descriptions, which requires a new astrophysical interpretation. Orbital measurements of the spectrum were carried out for the first time in the energy range that allows direct calibration of ground-based experiments.

8.2 Positrons in galactic cosmic rays

The presence of antimatter, in particular, positrons, in high-energy cosmic rays is an important signature of non-standard astrophysical processes or new particle physics.

Physicists from MEPhI, FIAN, and the Ioffe Institute of the Russian Academy of Sciences, as part of an international team, contributed to the PAMELA experiment — measurements made by an orbital detector aboard the Resurs-DK1 spacecraft (2006–2016) [77] (Fig. 29).

Significant disagreement between the spectrum of cosmic positrons with energies of 10–100 GeV and the predictions of astrophysical models was discovered, evidencing the contribution of unknown processes in the Galaxy or the manifestation of dark matter particles.

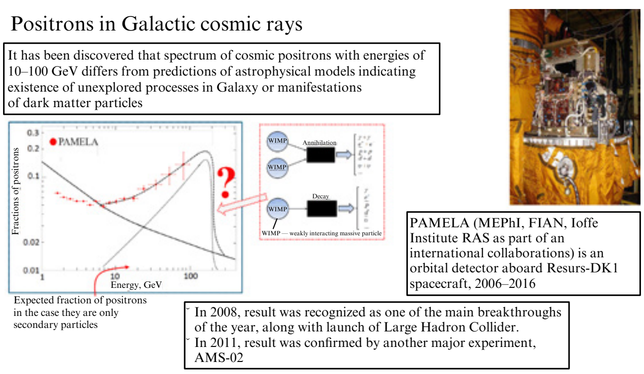

Figure 29. Results of participation of Russian physicists in PAMELA astrophysical experiment.

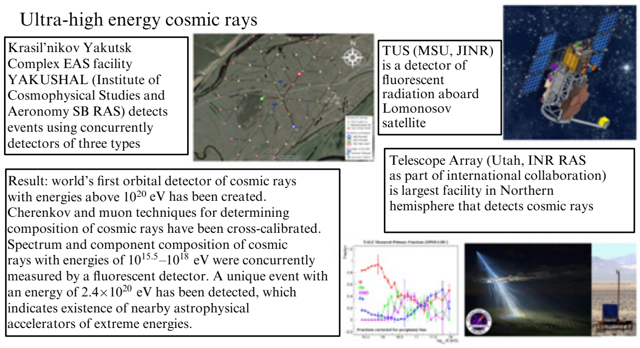

Figure 30. Facilities for studying ultra-high energy cosmic rays.

In 2008, the result was recognized as one of the main breakthroughs of the year, along with the launch of the Large Hadron Collider.

8.3 Ultrahigh-energy cosmic rays

Cosmic particles with energies above 10^{18} eV are detected through their interaction with the atmosphere. Their fluxes rapidly decrease with energy, and their origin has not yet been established.

A major contribution to the study of this range of cosmic ray energy was made by research with detectors and installations (Fig. 30):

TUS (MSU, JINR) — a detector of cosmic rays with energies above 10^{20} eV aboard the Lomonosov satellite, which records fluorescent radiation from extensive air showers;

Telescope Array (Utah (USA), INR RAS as part of an international team) — the largest installation in the Northern hemisphere recording cosmic rays.

Ground-based installations for studying extensive air showers:

YAKUSHAL (Institute for Cosmophysical Research and Aeronomy (IKFIA) SB RAS) [78];

KOVER (BNO INR RAS).

The world's first orbital detector of cosmic rays with energies above 10^{20} eV has been created. Cross-calibration of the Cherenkov and muon methods for determining the composition of cosmic particles was carried out.

Scientists from the INP RS, as part of an international team, concurrently measured the spectrum and component composition of cosmic particles with energies of $10^{15.5}$–10^{18} eV at the Telescope Array facility (Utah, USA) using a fluorescence detector. A unique event with an energy of 2.4×10^{20} eV was detected, indicating the existence of astrophysical accelerators of extreme energies close to Earth [49].

9. Activities related to high-performance computing (digital physics)

9.1 Russian GRID for intensive operations with data (RDIG)

At the international celebration of the discovery of the Higgs boson at CERN in 2012, Director General Rolf-Dieter Heuer said: "The success of this discovery is due to

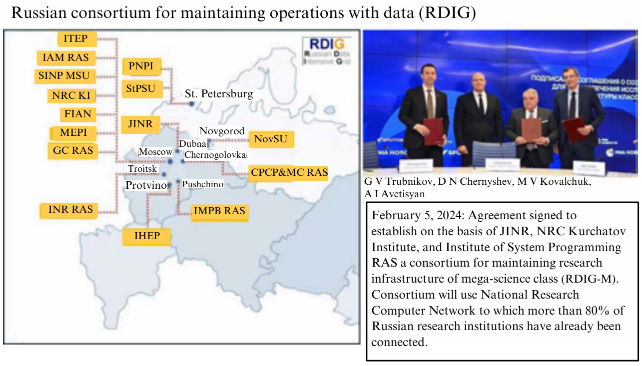

Figure 31. RDIG, a Russian consortium for maintaining operations with data and full-scale participation of JINR and Russia in experimental program implement at Large Hadron Collider.

three factors: the accelerator, the detectors, and distributed computing!''

In 2003, the Russian Consortium RDIG (Russian Grid for Intensive Operations with Data) was established to provide full-scale participation of JINR and Russia in the implementation of the LCG (LHC Computing Grid) project, the main objective of which is to create a global infrastructure of regional centers for storing, processing, and analyzing data from physical experiments conducted at the Large Hadron Collider.

9.2 Grid complexes in Russia

In 2014, two grid centers were created in Russia: Tier1–JINR to store and process data from the CMS LHC experiment and Tier1–NRC KI to support the ALICE, ATLAS, and LHCb experiments.

In Russia, a program of large-scale scientific projects is being implemented, the most important part of which is the development of distributed heterogeneous computer systems (including systems with extramassive parallelism) for processing, storing, and analyzing experimental data; developing and implementing effective methods, algorithms, and software for modeling physical systems, mathematical processing, and analysis of experimental data; and developing methods of machine learning, artificial intelligence, and quantum computing. To implement this ambitious project, it is necessary to develop RDIG-M, a distributed computer infrastructure that would unite key scientific and educational institutions participating in mega-science projects.

The consortium created in February 2024 on the basis of JINR, the NRC Kurchatov Institute, and the Institute of System Programming of RAS will become the core for IT support of the research infrastructure of the 'mega-science' class in Russia [79] (Fig. 31).

10. Required transition to a new stage in development of basic nuclear physics in Russian Federation

A new dynamic of the consolidation of experimental physicists, theoreticians, and developers of accelerators, unique detectors, and powerful information processing and computing tools has emerged in the Nuclear Physics Division of the Russian Academy of Sciences in developing responses to the challenging issues of the modern age.

This implies that nuclear physicists from the Nuclear Physics Division of the Russian Academy of Sciences are ready to offer the nation new ideas, new world-class experimental research based on a modern research infrastructure, and breakthrough technologies for detectors and digital data processing.

The Road Map for the Development of Basic Nuclear Physics has been created, the report ''Development of Accelerators for Basic Science, Medicine, and Advanced Technologies'' has been published, and a decision to develop a Road Map for High Energy Physics and Elementary Particle Physics has been made by the Council for Particle Physics.

This road map may be based on proposals from Russia-based research institutions and JINR regarding the modernization, development, and construction in the Russian Federation in 2024–2030 of accelerators and research facilities [80, 81].

The list of major accelerator projects includes:

(1) Collider accelerator complex (NICA–JINR).

(2) Complex of cyclotrons for synthesis of superheavy elements and research into exotic nuclear states (FLNR–JINR).

(3) Accelerator neutron complex (INR RAS).

(4) Development of a complex of hadron accelerators (NRC KI-IHEP).

(5) VEPP-4–VEPP-2000 Complex (INP SB RAS).

(6) Siberian Ring Source of Photons (SKIF) center for collective use.

(7) Accelerator complex with a source of Compton gamma-quanta for research in nuclear photonics at the National Center for Physics and Mathematics (Rosatom).

(8) Synchrotron complex of the Russian Federal Nuclear Center VNIIEF.

(9) Super Charm-tau Factory electron–positron collider.

(10) Synchrotron source and free-electron laser SILA (NRC KI).

(11) Electron–ion collider for nuclear physics (DERICA project).

We now present some descriptions of the projects listed above.

We start with the NICA complex, launched in 2016 at JINR, the main components of which are (Fig. 32a) a cascade of accelerators (injectors, booster, nuclotron, collider) and three research facilities (BM@Nuclotron, MPD, and SPD).

Progress on the construction of the complex can be assessed from a general bird's eye view of the complex as of the summer of 2024 (Fig. 32b).

Continuing the topic of proposed new projects and those currently being implemented for basic nuclear physics, we look at the one being implemented in Novosibirsk — the SKIF (Siberian Ring Photon Source) project, a 4+ generation synchrotron radiation source with a beam energy of 3 GeV (Fig. 33).

The next project on the list is the development of the hadron accelerator complex of the NRC KI–IHEP in Protvino (Moscow region). It is related to the implementation of the tasks set by the RF Government Decree dated March 16, 2020, No. 287, on the approval of the national scientific and technical program ''Development of synchrotron and neutron research and research infrastructure for 2019–2027'' as part of the National Project Science and Universities (Fig. 34), the upgrade of the MMF high-current linear hydrogen ion accelerator, and the development of the

Figure 32. General views of NICA research complex with its main structural sites.

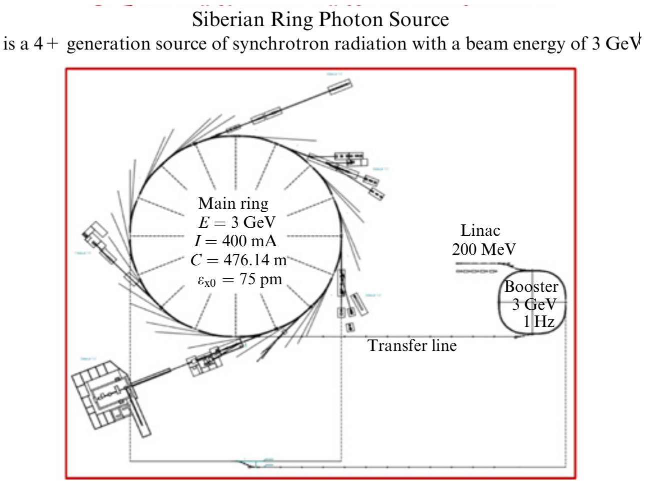

Figure 33. SKIF (Siberian Ring Photon Source) project.

Powerful Accelerator Neutron Complex of the INR RAS (MUNK) in Troitsk (Moscow) (Fig. 35).

The goal of the MUNK project is to create a superconducting (SC) linear proton accelerator (1 mA, 1 GeV) to replace the existing 'warm' (normal conductivity) MMF accelerator at INR RAS.

The purpose of the superconducting linear accelerator is to enhance the average power of the proton beam, which is necessary to create a pulsed neutron source (spallation neutron source), a subcritical nuclear reactor with an accelerator for studying ADS technology, and a neutrino factory to produce radioisotopes.

We continue with the creation of the RFNC-VNIIEF Synchrotron Complex in Sarov for testing radiation-resistant electronic components and electronic equipment with regard to operability under the ionizing radiation of outer space (Fig. 36).

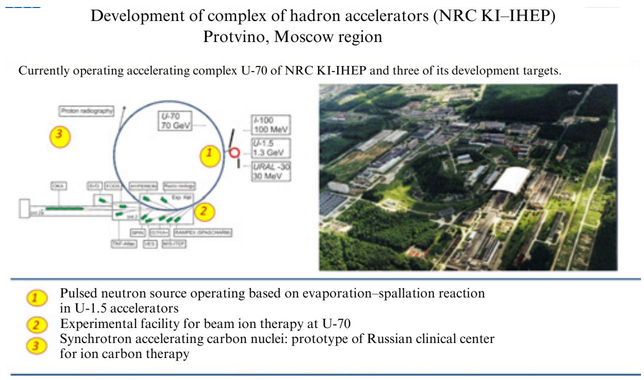

Figure 34. NRC KI–IHEP accelerating complex.

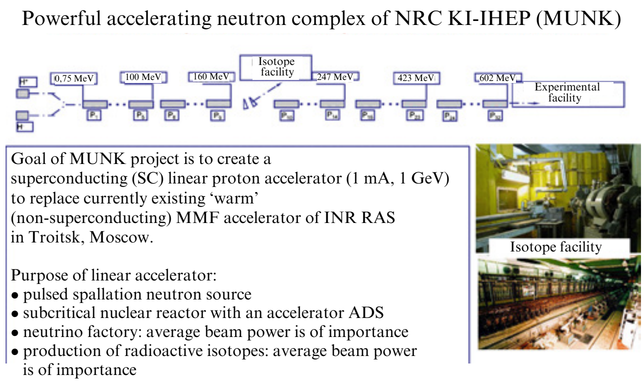

Figure 35. High-power accelerating complex with powerful neutron source of INR RAS.

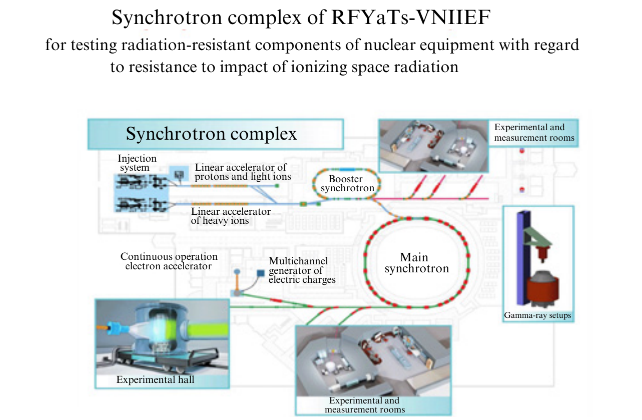

Figure 36. Project of synchrotron complex of Russian Federal Nuclear Center – Research Institute of Experimental Physics (RFYaTs-VNIIEF).

It is worth noting the project of an Accelerator Complex with a source of Compton gamma quanta for research in nuclear photonics at the IKI NCPM in Sarov. It is a source of (quasi)monochromatic X-ray and gamma quanta based on the effect of inverse Compton scattering of photons on relativistic electrons (Fig. 37).

We finish the presentation by stressing the need to realize the long-standing dream of Novosibirsk physicists regarding creation of a new Super Charm-Tau Factory electron–positron collider (INP SB RAS). The design of this complex is optimized for operations with the c.m.s. energy of colliding particles of $\sim 3-7$ GeV and a luminosity significantly exceeding that achieved at other installations operating in

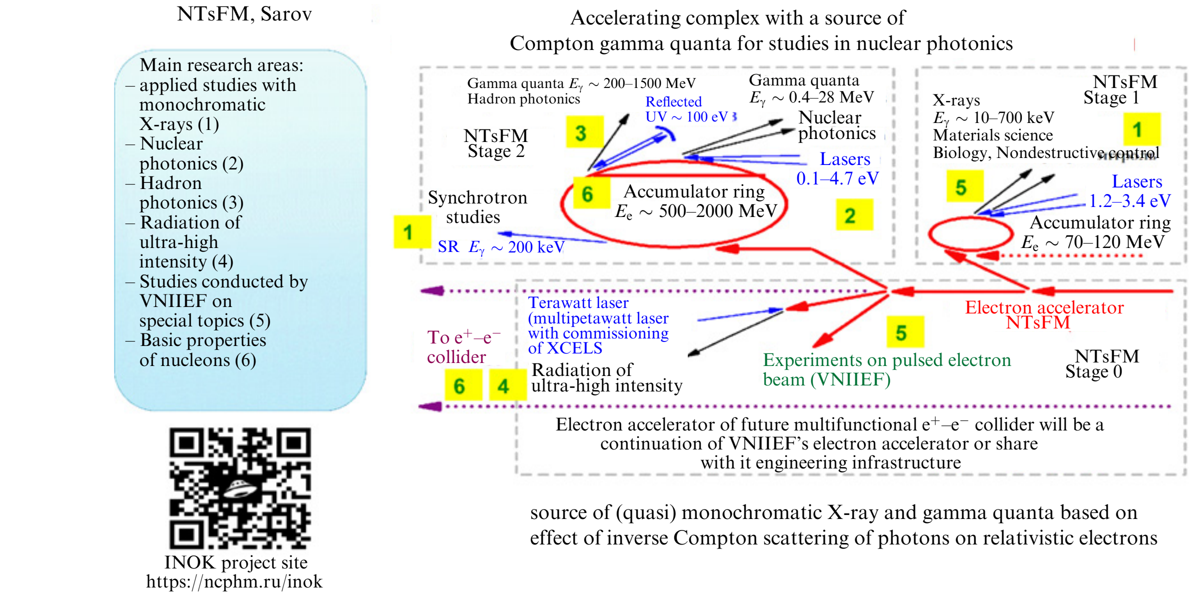

Figure 37. Structure of project of accelerating complex of National Center for Physics and Mathematics with a source of Compton gamma quanta. INOK is source of gamma-quanta based on inverse Compton effect.

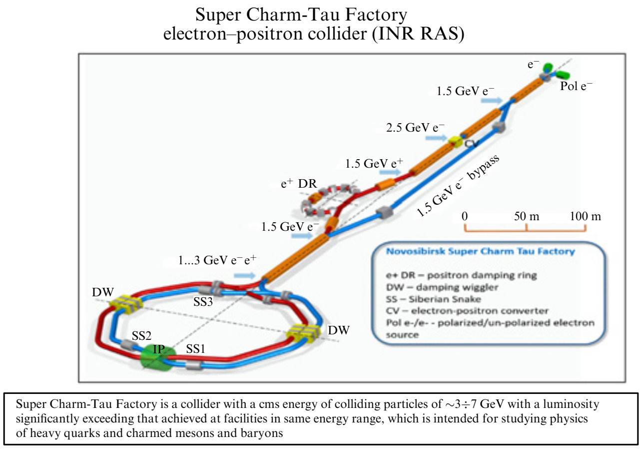

Figure 38. Projects of Super Charm-Tau Factory electron–positron collider.

this energy range (Fig. 38). Almost all states of charmonium, charmed mesons, and baryons containing one c-quark or one c-antiquark can be produced in this range.

11. Infrastructure for research in neutrino physics and neutrino astrophysics

Among the ambitious projects at the new stage of development of basic nuclear physics, one cannot but indicate the need to develop neutrino physics and neutrino astrophysics, which have already been mentioned above; in particular, the need to further increase the effective volume of BAIKAL-GVD, a deep-underwater neutrino telescope with unique capabilities, up to several cubic kilometers and to expand collaboration on work in this area of research.

The Ministry of Science and Higher Education of the Russian Federation can also be instrumental in expanding the team of scientific organizations and universities participating in these studies. On March 13, 2021, the largest deep-underwater neutrino telescope in the Northern hemisphere, Baikal-GVD, was ceremonially launched, and a memorandum of understanding between the Ministry of Education and Science of Russia and JINR on the development of the Baikal deep-underwater neutrino telescope was signed on the ice of Lake Baikal in the Irkutsk region (Fig. 39).

Figure 39. Ceremonial launch of Baikal-GVD, the deep-underwater neutrino telescope, which is the largest in Northern hemisphere.

Given that the events observed at the IceCube and Baikal-GVD facilities at ultrahigh neutrino energies require data from deep-underwater underground detectors and large-area ground-based facilities for their full interpretation, their upgrade and development are required. In this regard, it is considered to be absolutely necessary to develop the Baksan Neutrino Observatory in the North Caucasus — the only deeply located, specialized, underground research facility in Russia (Fig. 40).

12. Neutron research

Neutron research at reactors and pulsed neutron sources should be mentioned. However, in these studies, the boundary between basic and applied physics is fairly blurred, which allows, given the limited size of the review,

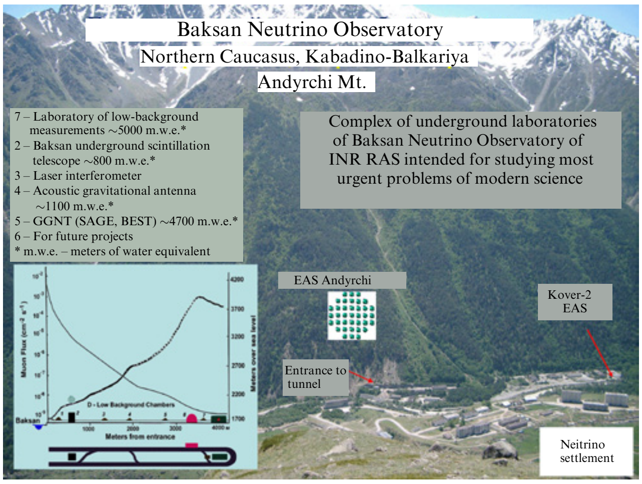

Figure 40. Complex of underground and ground facilities of the Baksan Neutrino Observatory of INR RAS in Northern Caucasus.

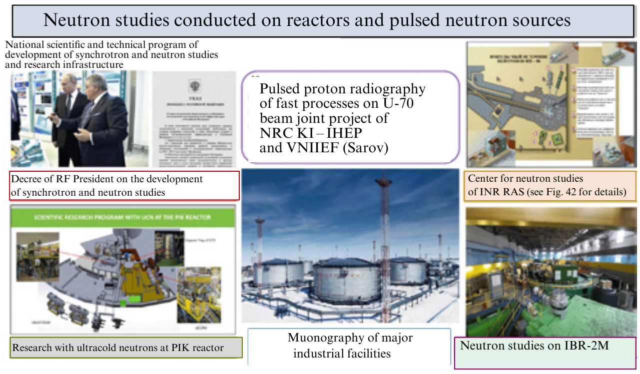

Figure 41. Examples of studies conducted by Russian research institutes on reactor-based and pulsed neutrino sources.

the analysis of their results and development trends to be maximally reduced.

I cannot but mention the joint work with Sarov on proton radiography on the beams of the U-70 accelerator in Protvino, on the preparation of a research program on the physics of ultracold neutrons in Gatchina, and on studies in muonography, which makes it possible, based on an analysis of the degree of absorption of cosmic muons in the subject under examination, to detect internal cavities in extended structures (from several meters to kilometers in size) without violating their integrity (Fig. 41).

I must mention the National Scientific and Technical Program for the development of synchrotron and neutron research for science, industry, and healthcare approved by the President of the Russian Federation.

An example of the planned activities in neutron research are the projects to establish a Neutron Research Center for Condensed Matter Physics in Troitsk (Fig. 42), to advance the studies conducted on the IBR-2 reactor, and to develop a third-generation pulsed neutron source project in Dubna (Fig. 43).

As per the priorities set by the Federal Scientific and Technical Program, important neutron studies of the atomic and magnetic structure and microscopic dynamics of new functional materials and materials in extreme states have been completed. New data on the cross sections of nuclear reactions with neutrons, which are of importance for practical use, have been obtained. The use of neutron and muon techniques for studying cultural heritage sites is expanding. Impressive advancements have been made towards the creation of new types of neutron detectors and new experimental techniques, which significantly broaden the spectrum of explorable problems.

As an example of the application of neutron methods in the study of cultural heritage sites, I briefly note only some results of applying neutrons (Fig. 44a) and cosmic muons (Fig. 44b).

13. Development of nuclear medicine

Research in nuclear biology and nuclear medicine is a separate and fairly vast area of basic research and applied studies based on the approaches and methods of nuclear physics, in particular, accelerator technology and beam dynamics, so reviewing these issues here is quite relevant.

Outlined below is the development of nuclear medicine.

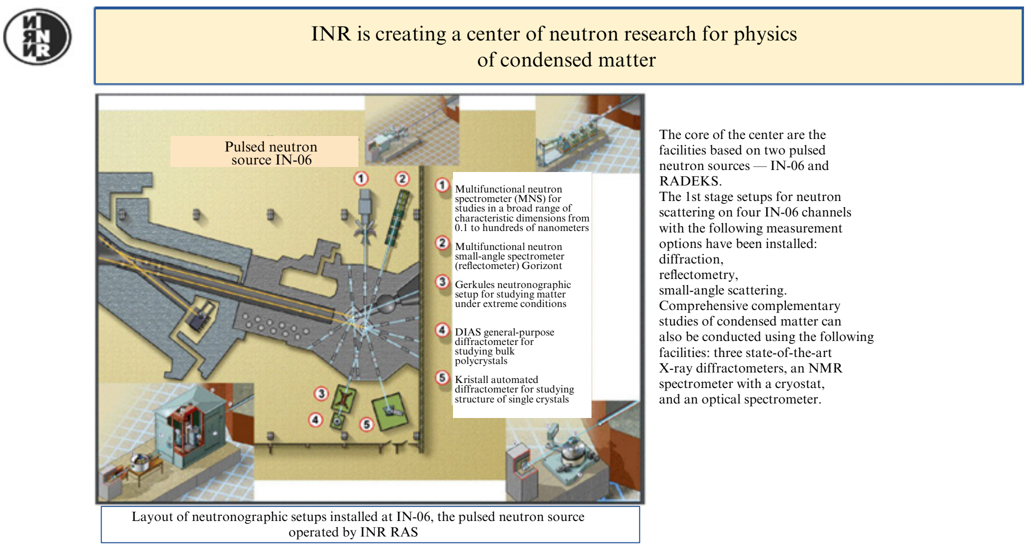

Figure 42. Creation of Center for Neutron Research of INR RAS to study the physics of condensed media.

Figure 43. Studies conducted at IBR-2M neutron facility of JINR Laboratory of Nuclear Physics in Dubna.

The USSR's first proton beam with the parameters required for the treatment of oncological diseases was obtained in 1967 at JINR (Fig. 45).

In the same year, the first radiobiological and clinical studies in the USSR began on proton beams from the phasotron of the JINR DLNP (a synchrocyclotron with a proton energy of up to 660 MeV).

At JINR, the technique of 3D conformal irradiation of deep-seated tumors was developed and successfully applied for the first time.

During the operation of the medical proton beam in Dubna, more than 1,300 patients were treated (meningiomas, chondromas, chondrosarcomas, gliomas, astrocytomas, etc.).

The development of research in nuclear medicine for healthcare was continued in several other institutes including PNPI, INR RAS, FIAN, and NRC KI (Fig. 46).

In particular, JINR developed a new project of a superconducting compact proton cyclotron MSC-230 with parameters superior to those of foreign counterparts (Fig. 47).

A prototype is now under construction with funding from JINR jointly with AO Efremov NIIEFA (Rosatom State Corporation).

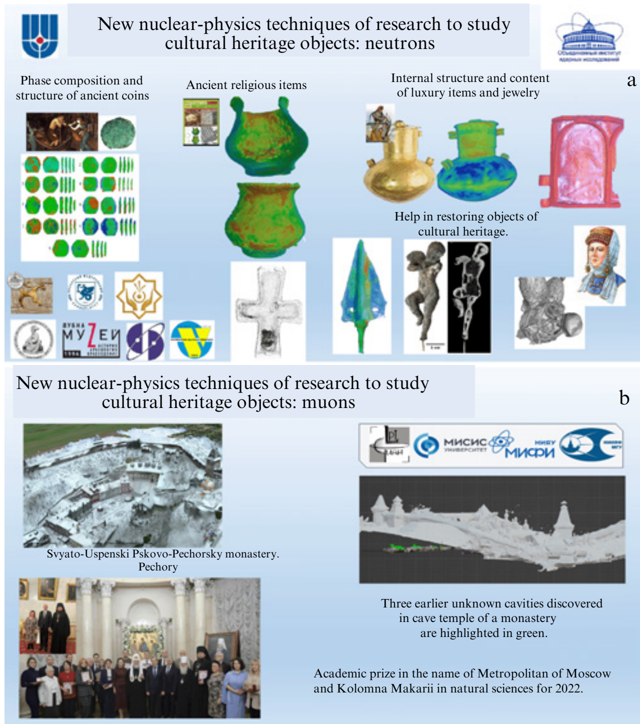

Figure 44. New nuclear-physics techniques of research to study cultural heritage objects (a) neutrons (JINR, NRC KI); (b) muons (MEPhI, MISIS, FIAN).

JINR and the Federal Medical and Biological Agency of Russia jointly developed a general concept for the creation of a pilot research and clinical center for proton therapy based on the existing Medical Sanitary Unit No. 9 of the Federal Medical and Biological Agency in Dubna.

All interested organizations are invited to participate in this project. The Divisions of Physical Sciences and Medical Sciences of the Russian Academy of Sciences supported this project.

Summarizing the observations made above about the required transition to a new stage in the development of

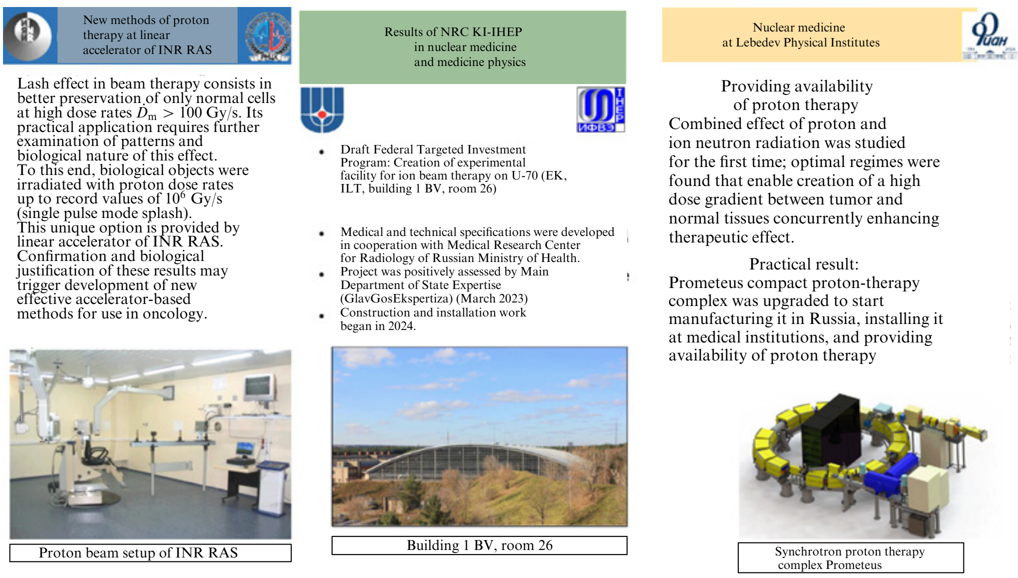

Figure 45. Dubna's experience developing proton therapy for oncology diseases.

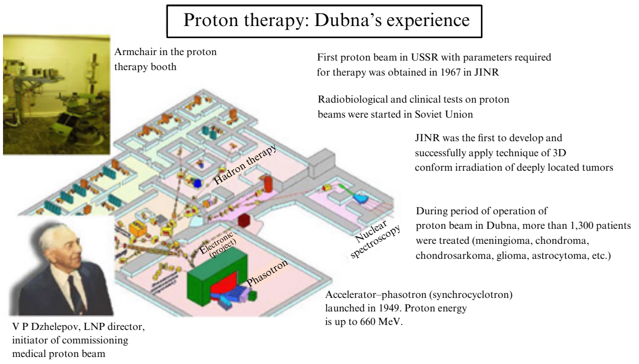

Figure 46. Examples of development of studies in nuclear medicine in Russia.

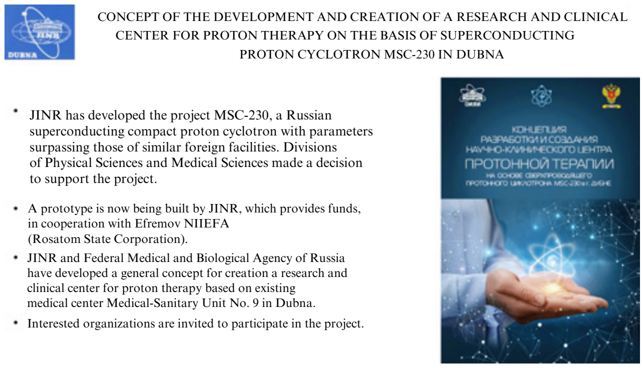

Figure 47. Project for creating a research and clinical center of proton therapy in Dubna.

basic nuclear physics in Russia, which involves the upgrade of existing and the creation of new advanced scientific complexes, primarily related to the mega-science class, presented in Fig. 48 is a diagram of the location of mega-projects in Russia.

14. Conclusions and findings

In connection with Russia's advancing to a high-tech economy and the associated increase in state support for basic and applied research, institutes of the Russian Academy of Sciences, JINR, NRC KI, and major universities are making proposals to develop some scientific research areas that use accelerators as the main tool for experiments and can become a driver of the high-tech development of the civil and defense industries, medicine, agriculture, etc.

The new ambitious projects proposed by the physics community are designed to provide scientific and technological leadership in some areas of nuclear and elementary particle physics and innovative technologies developed on their basis.

The high potential for scientific discoveries expected as a result of implementing the proposed projects will promote the participation in these projects of the international scientific community of researchers and will be a driver for the development of basic science, high technology, and human capital in Russia.

In conclusion, I would like to thank all colleagues who contributed to the preparation of the review and first and foremost the chairpersons of the Scientific Councils of the Nuclear Physics Section of the Physical Sciences Division of the Russian Academy of Sciences, and my colleagues, members of the Bureau of the Division, directors of the institutes, and heads of the most important research areas in basic and applied nuclear physics.

I received a great deal of important and interesting material, the volume of which significantly exceeds the size of this review. Many of my colleagues could apparently expect to see in the review the results obtained by their institutes and research teams presented or at least mentioned. Unfortunately, it was not always possible.

Nevertheless, I hope that this review, which is based on the material sent to me, will help to better understand the current

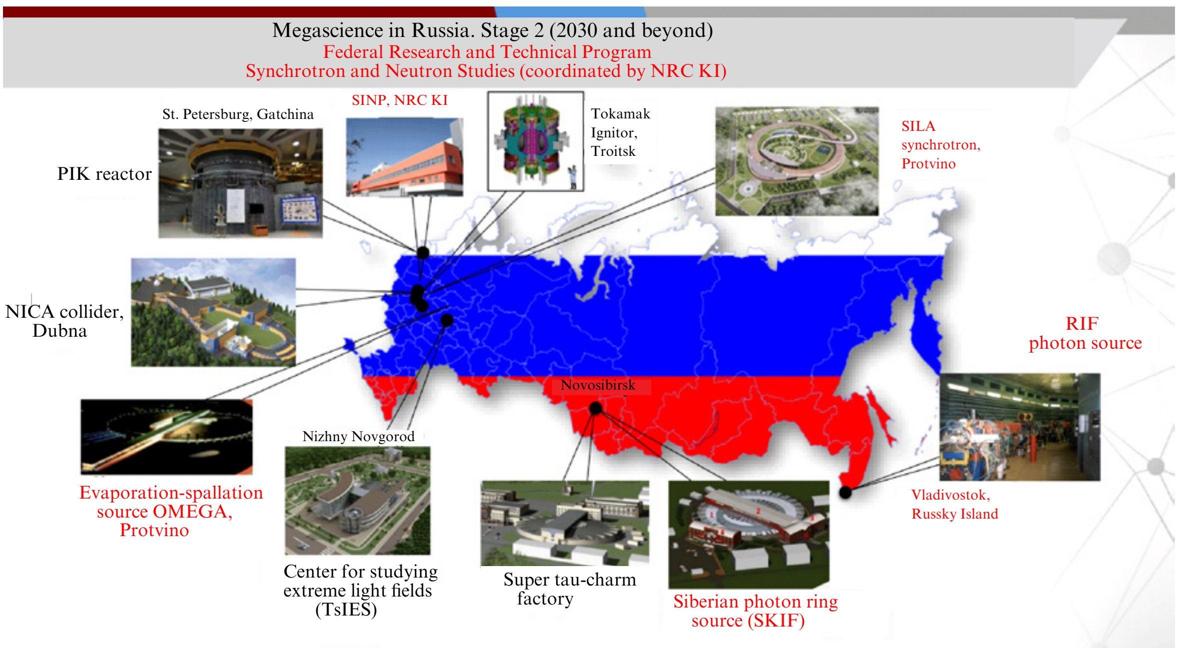

Figure 48. Location of megascience-class projects in Russia.

state of and the most important scientific achievements in basic nuclear physics over the past 25–30 years and the prospects for their development, including applied research based on them, the development of innovative technologies, and applications in medicine and in education.

I am sincerely grateful to B Yu Sharkov and my other colleagues for their help in selecting the material and determining the structure of the review.

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