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The Joint Institute for Nuclear Research in Experimental Physics of Elementary Particles

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Abstract—The year 2016 marks the 60th anniversary of the Joint Institute for Nuclear Research (JINR) in Dubna, an international intergovernmental organization for basic research in the fields of elementary particles, atomic nuclei, and condensed matter. Highly productive advances over this long road clearly show that the international basis and diversity of research guarantees successful development (and maintenance) of fundamental science. This is especially important for experimental research. In this review, the most significant achievements are briefly described with an attempt to look into the future (seven to ten years ahead) and show the role of JINR in solution of highly important problems in elementary particle physics, which is a fundamental field of modern natural sciences. This glimpse of the future is full of justified optimism.

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1. INSTEAD OF INTRODUCTION: JINR AT ITS 60th ANNIVERSARY

In the Soviet Union, nuclear research was launched on the initiative and under the supervision of Academician I.V. Kurchatov during the Great Patriotic War. In 1947, construction of the then-largest accelerator, a synchrocyclotron (Fig. 1, left), began on the banks of the Volga 120 km away from Moscow. It was successfully commissioned in December 1949, laying the groundwork for modern high-energy elementary particle physics through the researches under the supervision of M.G. Meshcheryakov and V.P. Dzhelepov [1, 2]. On its basis, the Institute of Nuclear Problems of the Academy of Sciences of the USSR was established, which is now the Dzhelepov Laboratory of Nuclear Problems [3]. In 1949, design of a large proton accelerator, a synchrophasotron (Fig. 1, right) began under the supervision of V.I. Veksler, and the Electrophysical Laboratory of the Academy of Sciences of the USSR was established [4].

These two laboratories became part of the Joint Institute for Nuclear Research (JINR), the first intergovernmental research organization of the socialist countries [5]. The agreement on establishment of the Joint Institute for Nuclear Research was signed by the representatives of the governments of eleven Member States on March 26, 1956. In 1957, the synchrophasotron was successfully commissioned and physical experiments started at the Laboratory of High Energies (Director V.I. Veksler). Three new laboratories were established: the Laboratory of Nuclear Reactions (Director G.N. Flerov), the Laboratory of Neutron

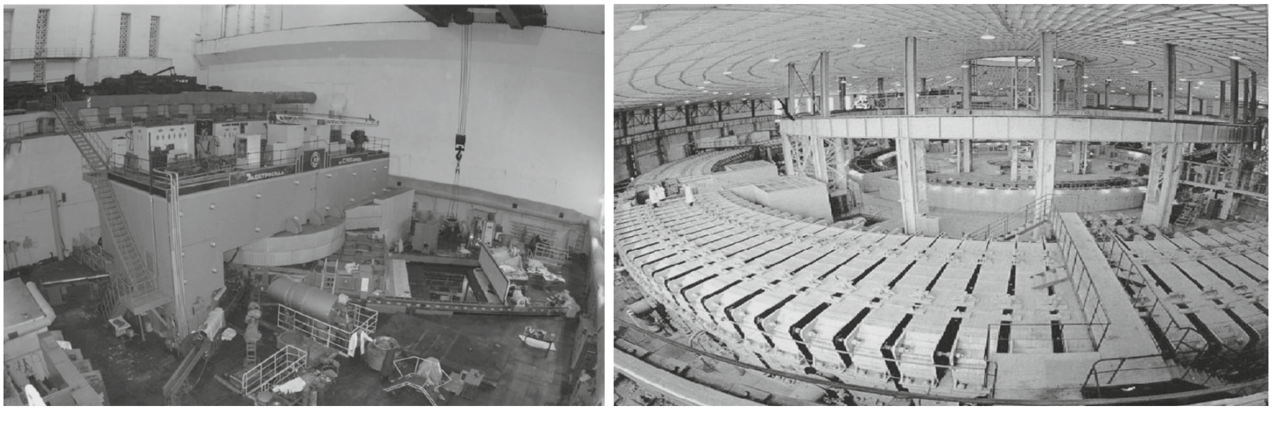
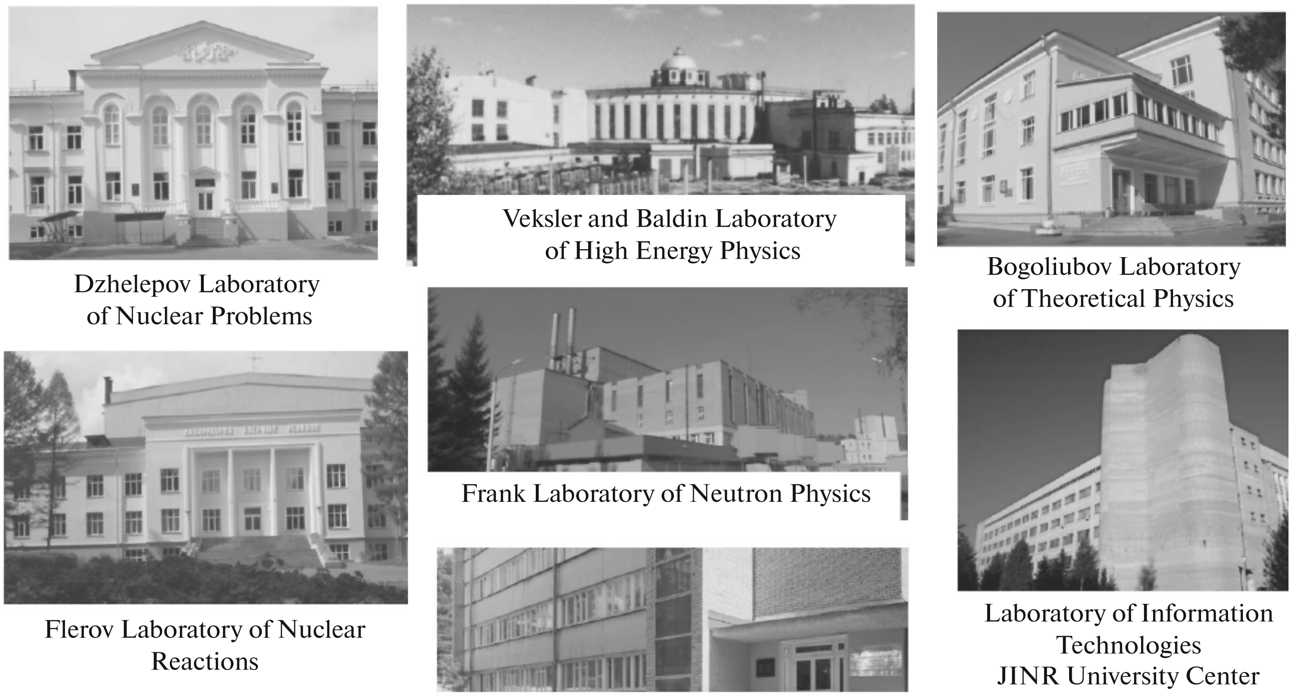


Fig. 1. Synchrocyclotron (left) and synchrophasotron (right), the first Dubna accelerators.



Dzhelepov Laboratory of Nuclear Problems

Veksler and Baldin Laboratory of High Energy Physics

Bogoliubov Laboratory of Theoretical Physics

Flerov Laboratory of Nuclear Reactions

Frank Laboratory of Neutron Physics

Laboratory of Information Technologies
JINR University Center

Laboratory of Radiation Biology

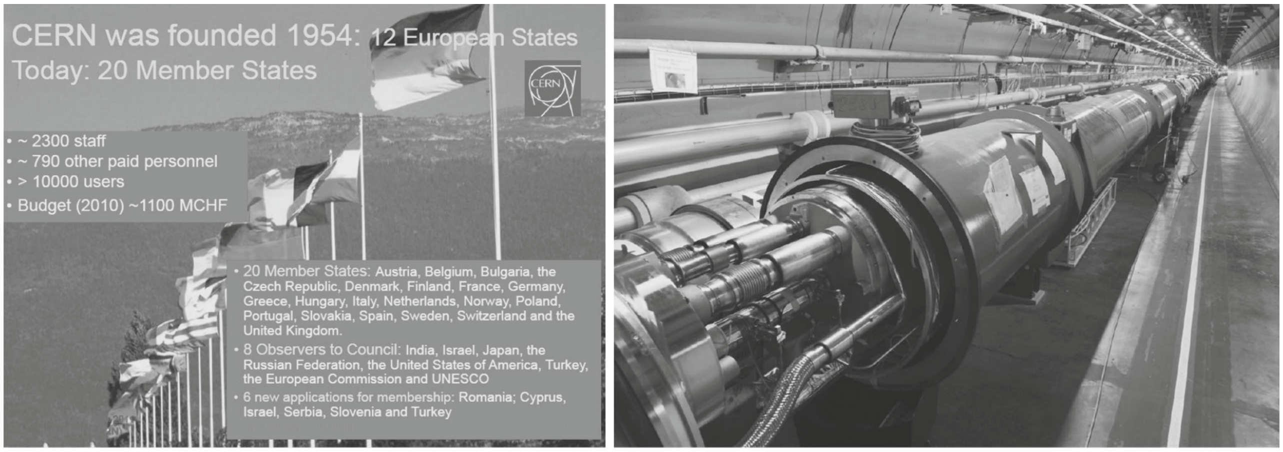
Fig. 2. JINR laboratories are full-scale research institutes.

Fig. 3. Flags of JINR Member States.

Physics (Director I.M. Frank), and the Laboratory of Theoretical Physics headed by N.N. Bogoliubov. Construction of new facilities began in the laboratories, a powerful cyclotron for acceleration of heavy ions at the Laboratory of Nuclear Reactions and a unique pulsed fast-neutron reactor at the Laboratory of Neutron Physics, which were commissioned in 1960. In 1966, the Laboratory of Computing Techniques and Automation (now Laboratory of Information Technologies) was established. In 2005, the Laboratory of Radiation Biology was set up [6–8].

Each JINR Laboratory is a full-scale scientific research institute (Fig. 2) in terms of both the Laboratory staff and the range of the scientific problems.

Today's Joint Institute for Nuclear Research is an international intergovernmental organization of 18 countries (Fig. 3) engaged in basic research on elementary particle physics, nuclear physics, and condensed matter physics [9, 10]. Agreements on cooperation are also concluded with Germany, Hungary, Italy, the Republic of South Africa, and Serbia. The supreme governing body is the Committee of Plenipo-



CERN was founded 1954: 12 European States
Today: 20 Member States

- ~ 2300 staff
- ~ 790 other paid personnel
- > 10000 users
- Budget (2010) ~1100 MCHF

- 20 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
- 8 Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO
- 6 new applications for membership: Romania; Cyprus, Israel, Serbia, Slovenia and Turkey

Fig. 4. Flags of CERN Member States (left); a fragment of the LHC, the gem of CERN.

tentiaries of the governments of the JINR Member States, which determines all the activities of JINR and elects the JINR Directorate at its session [7].

The world has greatly changed in the past 60 years. There is no longer socialist community, Warsaw Treaty Organization, Council for Mutual Economic Assistance, and a great state called the Soviet Union. This all has undoubtedly had an impact on the life of JINR. However, in the hard 1990s it survived owing to the efforts of eminent scientists and public officials. As V.G. Kadyshevsky writes, what played the decisive part was the foresight and wisdom of the founders of JINR, traditions of its scientific schools, top-level research, a unique scientific basis, and dedication and unwavering commitment to science of the highly skilled JINR personnel [7].

Now JINR is the internationally renowned research center unique in that it is probably the only organization where basic research has been carried on at the world's top level in an unprecedentedly wide range of topically important scientific fields for 60 years [11].

Indeed, JINR embraces frontier nuclear physics of superheavy elements with its world-known "island of stability" and new elements in the periodic table, precision nuclear spectroscopy and radiochemistry, physics of new materials and condensed matter, fundamental and applied neutron researches, high-energy particle physics, precision neutrino physics and astrophysics, theoretical and mathematical physics, up-to-date information, communication, and computer technologies, advanced experimental techniques and instruments, radiobiology, genetics, biophysics, scientific methodological and applied works on proton (hadron) therapy, etc.

Apart from the European JINR Member States, scientists from Africa, Asia, and Latin America are engaged in this research. Therefore, the scientific interests and policies of JINR go far beyond Europe, being actually of a global nature and thus implementing to a maximum extent the principle "science brings nations together" [12, 13].

The time-proven constructive triunity of fundamentality, internationality, and multidisciplinarity of the research carried out in Dubna is the feature essentially distinguishing JINR from the European Organization for Nuclear Research (CERN) (see for example [14, 15] and Fig. 4), which, as should be admitted, has recently also been set to attract scientists not only from European countries.

As is known, the fundamental nature of scientific research, and it alone, inevitably gives rise to the New: entirely new knowledge, technologies, materials, instrumentation, etc., eventually improving the quality and safety of life.

Long-term stability of successful scientific research allows researchers to gain extensive experience and skills, and, consequently, to effectively share their knowledge with the younger generation of scientists and engineers. Moreover, an ultimate potential is created for a wide range of activities in applied science and innovation.

All this naturally makes JINR attractive for young researchers from various countries: anyone can find a scientific activity of interest and high importance. This guarantees further successful development of JINR.

In modern research, when the way from the idea of an experiment to its results can be decades long, multidisciplinarity ensures continuous gaining of new scientific results by the JINR researchers. This continuity unites all lines of research by common values and attitude to work, unified striving for fundamental knowledge, and continuous exchange of experience, equipment, and ideas within the framework of open international cooperation defined as necessary and obligatory in the JINR founding documents [10].

The experience of the past hard years and the logic of science development show that the successful future

Fig. 5. Monument to Bruno Pontecorvo and Venedikt Dzhelepov in Dubna. B.M. Pontecorvo is an Italian and Soviet physicist, full member of the Academy of Sciences of the USSR, author of fundamental works on nuclear physics and neutrino physics, worked in Dubna since 1950, invented the neutrino logging method for oil prospecting. V.P. Dzhelepov is a Soviet physicist, corresponding member of the Academy of Sciences of the USSR, the first LNP director. Among achievements in fundamental science, he developed a method for tumor treatment with proton beams.

of JINR is inevitably based on the time-proven principles of fundamentality, internationality, and multidisciplinarity of scientific research.

In connection with the 60th anniversary of JINR it seems appropriate to discuss in this review the role and importance of JINR in modern elementary particle and nuclear physics with an emphasis on the experimental component of research.

2. MAIN DIRECTIONS IN THE DEVELOPMENT OF ELEMENTARY PARTICLE PHYSICS: THE SEARCH FOR NEW PHYSICS AND THE QCD STRUCTURE OF HADRONS AND NUCLEI

Elementary particle physics is a science studying the most fundamental laws of Nature. It is inherently fundamental, extending from the structure of the smallest particles of matter to the astrophysical scales of the Cosmos. The study of mutual transformations between interatomic particles gives a clue to the understanding of the laws that govern the Universe. For this reason, being the basis of modern astrophysics and cosmology, elementary particle physics plays a key role in searching for utterly knew knowledge without which further interplay of man and Nature is hardly possible. According to Bruno Pontecorvo (Fig. 5, left), it is this most fundamental field that holds tremendous potential for unexpected discoveries [16], capable, as experience shows, of radically improving the quality of life. Finally, both the contemporary methodology and the essentially unique instrumentation of elementary particle physics intrinsically enrich and stimulate development of modern natural science in all its aspects.

A strategic goal of elementary particle physics itself (together with astrophysics cosmology) is to formulate a new unified physical view of the world free from “disadvantages” of the modern Standard Model of weak, electromagnetic, and strong interactions (see for example [17–20]), which in turn is an outstanding achievement of the human mind [21, 22]. This is confirmed by the discovery of the Standard Model’s missing element, the Higgs boson [23, 24] (Fig. 6, right)

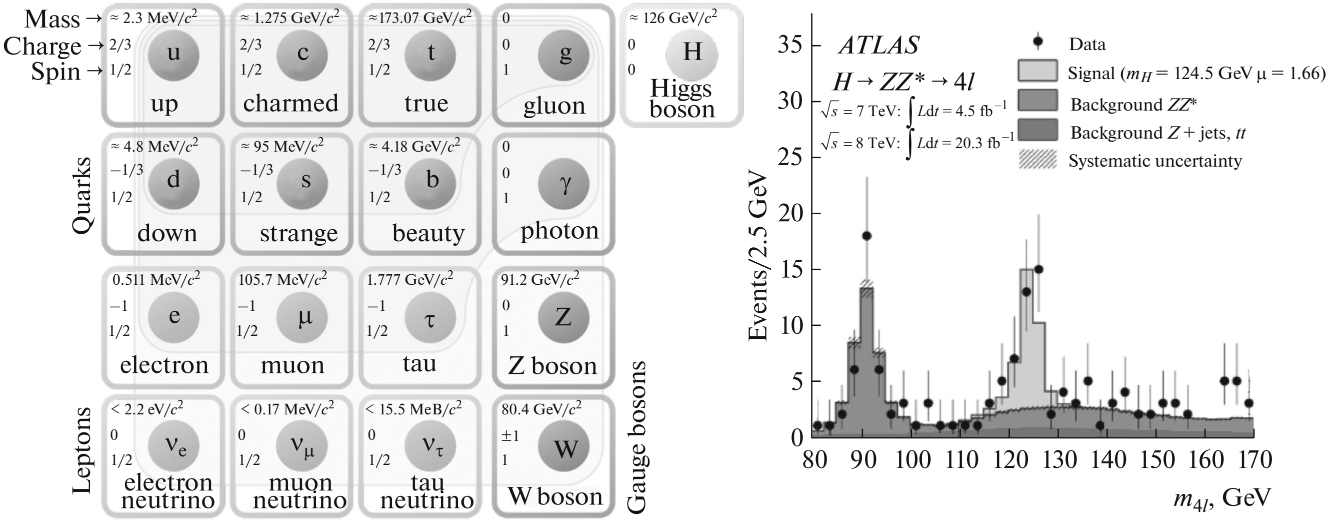


Fig. 6. Left: particles of the Standard Model; the first three columns are three generations of fermions. Right: discovery of the Higgs Boson (124.5 GeV/c^2) by its decay into four leptons.

and by the precise description of numerous data at the electroweak scale of the Large Hadron Collider (LHC, CERN) energies (see for example [25–29]).

The Standard Model constructed on the basis of quantum field theory consistently describes all particles (Fig. 6, left) as excitations of fields organized in accordance with the $SU(2)_L \times U(1) \times SU(3)$ gauge symmetry which uniquely defines the interactions between these fields (particles). The most important element of the Standard Model is the specific scalar Higgs field that causes spontaneous breaking of the $SU(2)_L \times U(1)$ symmetry (Higgs mechanism) and gives rise to masses of gauge $W^{\pm}, Z^0$ bosons, quarks, and leptons through their interaction with the Higgs field.

Nevertheless, the Standard Model cannot be thought of as the sole consistent fundamental theory, an adequate basis of the modern worldview (see for example [25, 26, 28]). It is only the "low-energy limit" of a more fundamental theory capable of embracing all energy scales, including probably the astronomic large scale of the Planck mass (10^{19} GeV). The Standard Model has too many external parameters and internal problems. In particular, there is no clear understanding of the electroweak symmetry-breaking mechanism, nor explanation for existence of exactly three fermion generations [30] and the stability of the Higgs boson mass (hierarchy problem). Moreover, gravitation does not fall into this model at all, etc. (see, for example, the unstable vacuum of the Standard Model in [25, 28, 31]).

There are also experimental data that are now considered as indications of new physics beyond the Standard Model. These are the extreme smallness of nonzero neutrino masses (consequence of neutrino oscillations), baryon asymmetry [32], accelerating expansion of the Universe (dark energy), in which a lot of matter is found to be missing (dark matter), and a few so-called flavor anomalies ($H \to \mu\tau$, $B \to K\mu^+\mu^-$, $B \to D^{(*)}\tau\nu$, $B_s \to \phi\mu^+\mu^-$, $g - 2$, etc.), which, however, have not been appropriately verified yet (see for example [25, 26, 28]).

Therefore, the main sources of decisive information on the way to creating a new theory of elementary particles—a new physical picture of the world—are considered to be [33–40]:

(i) A direct search for new physics at the LHC (manifestations of supersymmetry, extra dimensions of space, new forces, new particles, etc.).

(ii) Neutrino physics and astrophysics.

(iii) The nature of dark matter and dark energy (cosmology).

(iv) Precision studies of (extremely) rare transformations of leptons and hadrons breaking (flavor) symmetry of generations (indirect search for new physics).

Of great importance is the matter structure problem, which is now supposed to be solved within nonperturbative quantum chromodynamics. At first glance, this problem may not seem to be directly associated with new physics, but its solution is as significant as the discovery of new physics itself.

In this connection¸ the first main objective at the new stage of the collider experiments at the LHC (RUN-II etc.) is to thoroughly investigate properties of the Higgs boson (Fig. 7, left) in order to find convincing evidence of its belonging (or not belonging [41]) to the Standard Model [25, 42–44]. The decisive continuation (and completion) of this objective is now associated with future linear electron–positron collid-

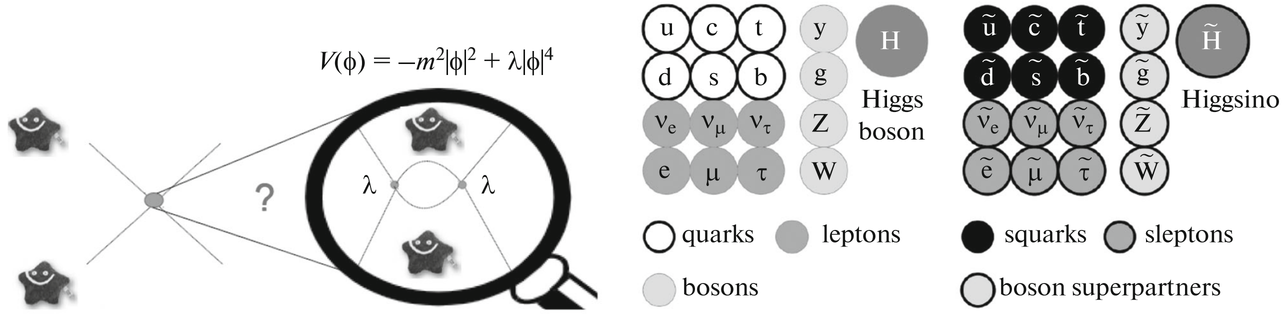


Fig. 7. Main objectives at the LHC (RUN-II). Left: investigation of properties of the Standard-Model Higgs boson. Right: particles of the Standard Model and the minimum supersymmetrically expanded model.

ers (CLIC, ILC, FCC-ee), new-generation precision machines (see for example [45–48]).

The second main objective is to find the answer to the question of whether new physics exists (or does not exist) at the TeV energy scale [49, 50], where particular interest (aroused by the RUN-I results) is focused on the experimental substantiation of the idea of supersymmetry (Fig. 7, right) [25, 26, 51–55].

Both demonstration of "standardness" of the Higgs boson and existence of new physics in the form of, say, supersymmetry will be a real triumph of modern physical thought and absolute justification of the construction of the LHC. On the other hand, the nonstandard character of the Higgs boson and especially complete absence of any new-physics TeV signals appreciably undermining the foundation of the idea of supersymmetry will be the strongest impetus to the search for entirely different concepts for constructing a new picture of the physical world.

There are also other currently important objectives for the LHC research (RUN-II), such as investigation of nucleon structure [26, 29] and the electroweak sector of the Standard Model [56, 25], study of properties of heavy quarks [25, 57], especially top quarks [58–61], the search for and investigation of new CP symmetry violation effects (see for example [25]), etc. In general, there are strong reasons to believe that the operation of the LHC (RUN-II, etc.) will give new, utterly unexpected results that will change our view of fundamental physics (see for example, [26, 28, 29]).

Apart from important LHC objectives in elementary particle physics, now the central problem is the nature of neutrinos (see for example [29, 44, 62, 63]). This is considered to mean those fundamental properties of the neutrino which dictate the specific character of their interactions, namely, particular values of extremely small neutrino masses [64], their hierarchy (order) [65] and a possibility of CP violation [63, 66–68], character of mixing (mutual conversions), number of sterile neutrinos [69], whether they are Dirac or Majorana particles [70], whether they have electromagnetic or other exotic properties [71, 72], how they interact with various forms of matter [73, 74], and what their natural (space) sources are. Table 1 illustrates "omnipresence" of neutrinos in terms of sources, fluxes, energies, and cross sections for interaction with matter. Neutrino physics is indeed a key interdisciplinary problem that permeates elementary particle physics, cosmology, and astrophysics [78].

Nonzero neutrino masses are important for constructing modern theories of elementary particles, understanding the structure of the Universe and the formation of large-scale structure in it. Here, neutrinos play the role of hot dark matter [69, 79, 80]. To study neutrino properties (including electromagnetic) is necessary for solving the solar neutrino deficit problem [81], clarifying mechanisms for supernova explosions [80] and the formation of energy in stars (Sun) [80, 81] and in the Earth's interior, and understanding the origin of ultrahigh-energy cosmic rays [80, 82]. Only cosmic neutrinos can provide information about the most distant regions of space [83]. No solution has been found so far for the problem of relic neutrinos [84, 85], which are presumed to exist according to the modern concept of the early Universe [86, 87]. Together with photons, neutrinos are the most common particles in the Universe.

It is believed that heavy Majorana sterile neutrinos decaying with CP violation [67, 79, 88] give the desired key (through asymmetry of leptons, Fig. 8) to the explanation of baryon asymmetry, i.e., the excess of baryons over antibaryons observed in the Universe [89].

Today, "many-faced" neutrinos (heavy, right-handed, sterile, etc.) are coming to the fore in high-energy and ultrahigh-energy collider physics [82, 91–93], giving hope for finding the answer to the question of the origin of the very small masses of active neutrino states.

Only all-pervasive neutrinos and antineutrinos capable of probing an unprecedented range of distances and densities due to weakness of their interaction allow us to obtain information about what goes on inside the Sun, the Earth [78, 94], the exploded supernova, the nuclear reactor core at a nuclear power plant

Table 1. Properties of the known neutrino and antineutrino sources [75, 76]. Neutrino energies and fluxes vary within 24 and 26 orders of magnitude respectively [77]

Neutrino source, historical order	Flux estimate, s^{-1} cm^{-2}	Energy estimate, eV	Cross section estimate, b
Big Bang	10^{14}	10^{-4}	$<10^{-32}$
Beyond our galaxy	10^{-12}	10^{20}	10^{-4}
Our galaxy	10^{-10}	10^{15}	10^{-8}
Supernovae	10^{12}	10^{7}	10^{-16}
Sun	10^{10}	10^{6}	10^{-17}
Earth's interior	10^{6}	10^{4}	10^{-21}
Atmosphere	10^{2}	$10^{7–13}$	$10^{-(16–11)}$
Reactor	10^{13}	10^{6}	10^{-18}
Accelerator	10^{7}	10^{11}	10^{-13}

[80, 95, 96], or in the farthest reaches of space (see for example Fig. 9).

Due to currently available detectors with unique size and sensitivity and high-intensity sources, the initial weakness and elusiveness of neutrinos turned into their exceptional strength and informativity of their interactions. As a result, in terms of the degree of fundamentality, importance for the worldview paradigm, and a potential of new unexpected discoveries in physics, the neutrino has no rivals in modern physics (from the decision of the Neutrino Council, Russian Academy of Sciences, 2012).

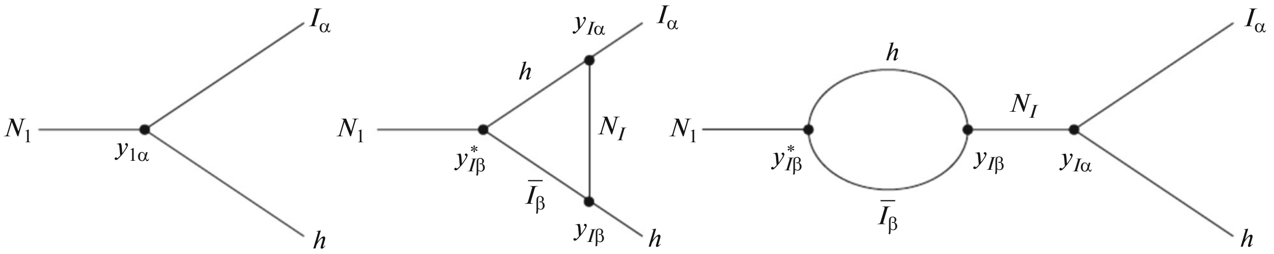


Fig. 8. Examples of diagrams contributing to the emergence of asymmetry in decays of heavy Majorana sterile neutrinos (leptons), which, according to the Standard model mechanism [90], is transferred to the baryon sector. From [88].

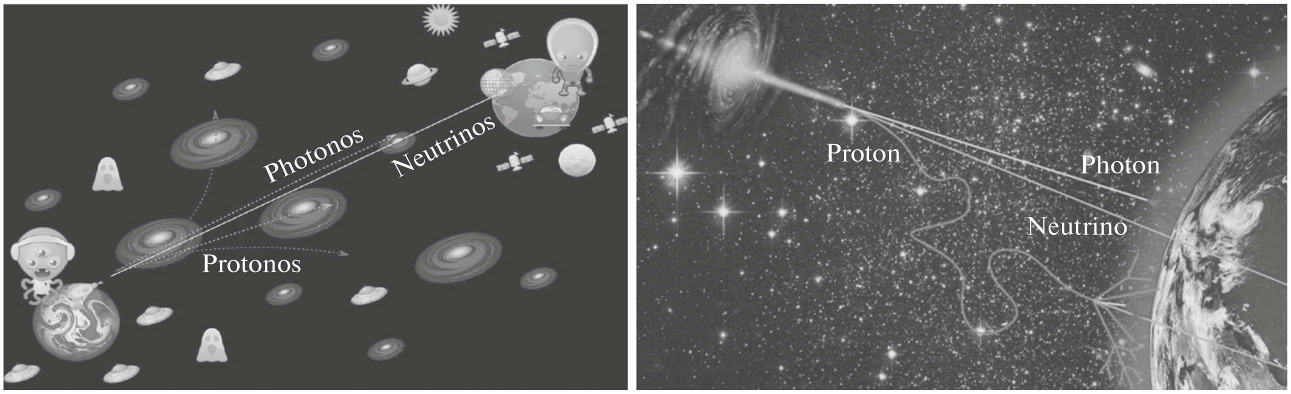


Fig. 9. It seems that farthest-living aliens will be able to transmit their signal to us only via the neutrino channel.

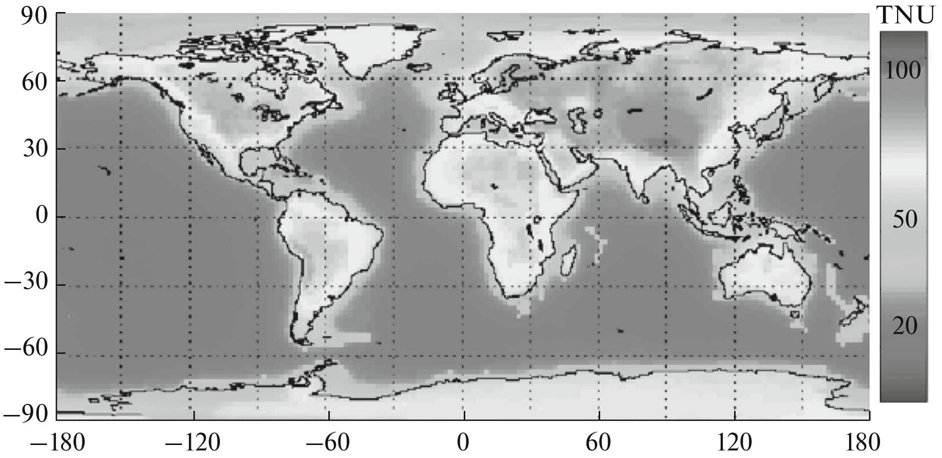


Fig. 10. View of the Earth in the "information channel" of geoneutrinos from uranium and thorium decays. 1 TNU = 1 event/10^{32} protons/year. Calculation from [100].

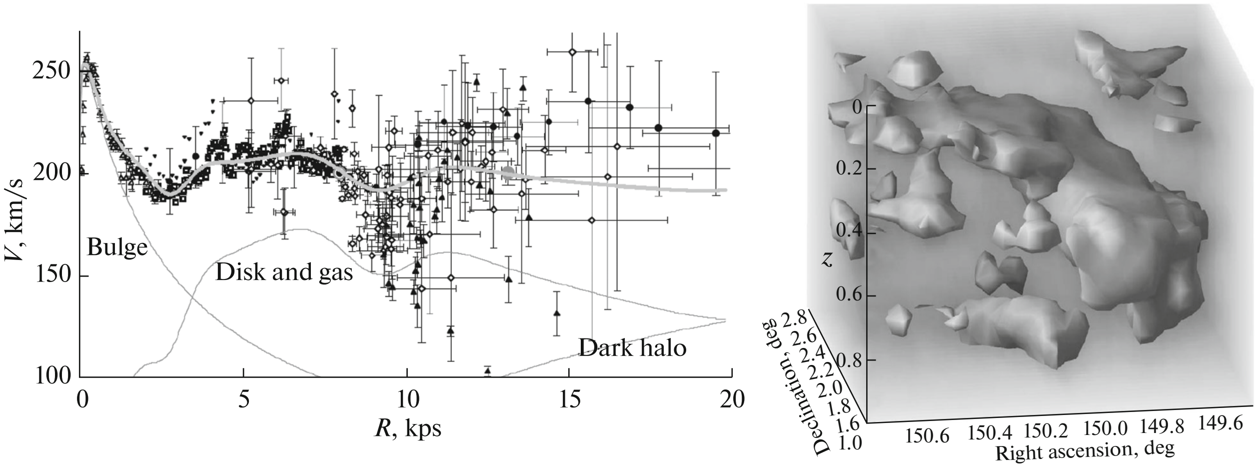


Fig. 11. Left: velocity distribution of objects in our galaxy as a function of distance—the rotation curve. Contributions from the bulge, disk and gas, and dark halo are shown [109]. Right: 3D reconstruction of dark mater distribution obtained by the gravitational lensing method [110].

Prospects for applied neutrino research can hardly be overestimated [97]. Recently, geoneutrinos from the Earth's interior have been detected [98, 99]. Their investigation is highly important for geophysics and for the understanding of the processes in our planet's interior [100] and thus of the possible causes of various natural disasters and climate changes (Fig. 10). With antineutrinos, applied research at nuclear reactors comes to a new level [96], approaching the possibility of continuously measuring the reactor power, degree of burnup, and fuel burnup tomography in real time [101]. Compact antineutrino detectors are under development [95, 102] for remote control of production and unauthorized removal of plutonium during the operation of the reactor, and so on. It is shown that the neutrino beam can in principle be used for transmission of information [103].

This is a striking example of how basic science can be of practical use. To solve its internal problems, neutrino physics requires unique instrumentation that never existed before, and its development gives rise to utterly new and equally unique technologies, materials and instruments that turn out to be in demand in other fields of science and in everyday life.

Neutrino and weak interaction physics is most intimately related to new physics [104]. An indisputable example of the latter is dark matter [105–108]. Existence of dark matter particles (Fig. 11) is currently deduced from their gravitational effect on various astronomical objects [111]. Numerous observations at astronomic and cosmological scales and very complicated numerical calculations (see for example [112]) of processes of formation of different-scale space struc-

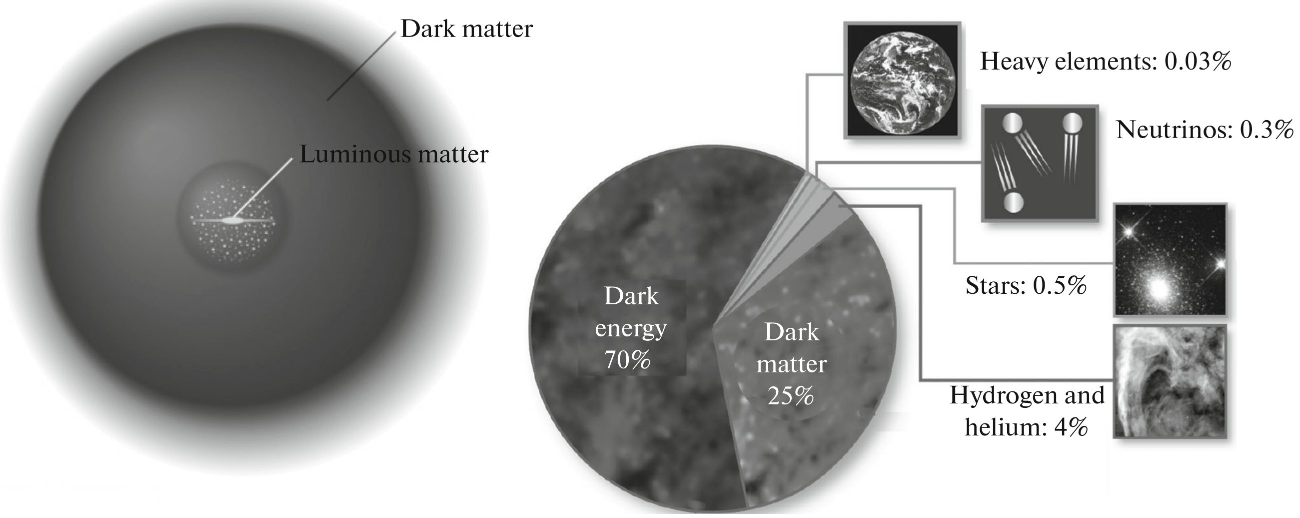


Fig. 12. Left: dark matter forms the (spherical) galaxy halo and affects the rotation velocity distribution of luminous stars in the galaxy. Right: matter–energy balance in the Universe.

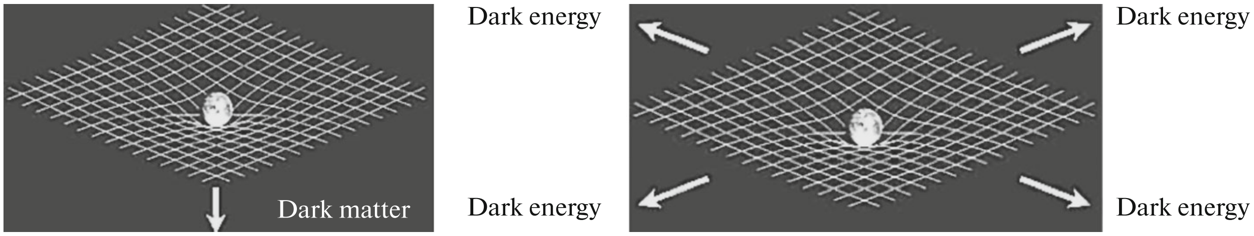


Fig. 13. Left: Dark matter manifests itself through gravitational attraction. Right: dark energy antigravitates and ensures the accelerating expansion of the Universe.

tures indicate the existence of this new, absolutely invisible form of matter in the Universe (see for example [113–117]). The shape of the rotation curve (see for example Fig. 11, left) allows the conclusion (Fig. 12, left) that stars and gas clouds in galaxies and galaxies in galaxy clusters move noticeably faster than could be expected from the gravitational attraction of visible matter alone [105]. Light from very distant objects is distorted by a considerable amount of dark matter on its way to the Earth—a gravitational lensing effect (see for example [110, 118–120] and Fig. 11, right).

Distribution of large-scale structures in the Universe is governed largely by dark matter, which accounts for about 85% of the entire mass of the Universe with the remaining 15% visible matter (Fig. 12, right).

At the same time, all matter makes up about a quarter of the total space energy budget (see for example [114, 121] and Fig. 12, right), and the rest is dark energy (Fig. 13), an antigravitating substance of unknown origin (see for example [87, 122–124] and also [125, 126]) that serves to explain accelerating expansion of the Universe within the general theory of relativity. In the simplest case, it is the Einstein cosmological constant.

From the concept of the early Universe formation after the Big Bang there follows the need for nongravitational interaction of dark and ordinary matter (see for example [86, 117]). It must exist, though it can be very weak. For this reason, the Weakly Interacting Massive Particle (WIMP) is now the main candidate for a relic dark-matter particle. Being electrically neutral and weakly interacting, these particles give the correct relic density of dark matter provided that their masses are close to the TeV scale of new physics (see for example [106, 107, 117, 127]). The latter explains the great interest in the search for these dark matter particles (more specifically, for their candidates) in the ATLAS and CMS experiments (see for example the discussion of this issue in [115]).

These weakly interacting dark-matter particles cannot be ordinary baryons (mesons, protons, neutrons, or stable nuclei). They have no place in the Standard Model because otherwise the well-working

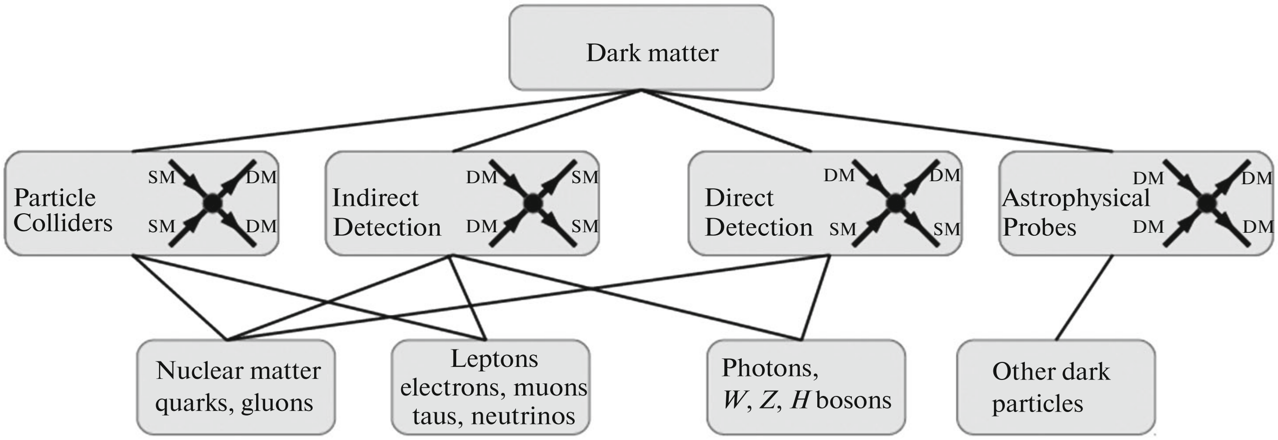


Fig. 14. The idea of detecting dark matter particles is based on the belief that they can nongravitationally interact with nuclear matter and other particles [115].

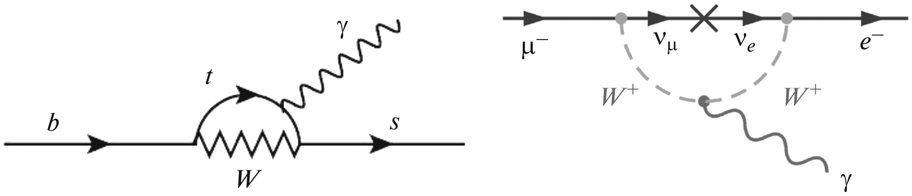


Fig. 15. Flavor(generation)-changing transitions of quarks $b \to s$ (left) and charged leptons $\mu \to e$ (right). They are only possible in the loop approximation. The cross marks the transition of the muon neutrino to the electron neutrino (neutrino oscillations).

nucleosynthesis of the early Universe (see for example the Particle Data Group Review [128]) would lead to wrong concentration predictions for light elements (deuterium, helium, lithium). Next, to explain formation of galaxies and their clusters, these massive particles should be nonrelativistic, otherwise their relativistic motion would considerably hamper the gravitational formation of galaxies. The latter would have no chance to form (see for example [129]).

Thus, dark matter and dark energy (see Fig. 13) are a serious challenge of "cold" space, the study and understanding of which are inevitably associated with the future of humanity. Therefore, the main joint objective of particle physics, astrophysics, and cosmology (here they are linked together [87]) is to find and clarify the nature of the dark matter particles that form the massive invisible halo of our galaxy. Unfortunately, it is an exceptionally difficult problem, and its solution requires the use of all available capabilities and data from astrophysics, cosmology, theoretical models, and accelerators (Fig. 14). Of decisive importance are results of direct searches [115, 130] for dark matter particles in laboratory low-background precision experiments [127, 131–135].

The second (indirect) but no less significant way to search for new physics is associated with flavor physics (see for example [29, 104, 136–139]), where the practical task is precision investigation of processes in which fermions of one generation (quarks and leptons) transform to fermions of another generation (flavor), e.g., processes like $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$ [140], where the $\bar{s}$ quark goes into the $\bar{d}$ quark (Fig. 6, left: the s quark from the second column becomes the d quark from the first column). Another example from the quark sector is the decay $B \to K\mu^+\mu^-$ [141] or $B \to X_s\gamma$ [142], where the b quark goes into s quark (as in Fig. 15, left). In the sector of charged leptons, an example of the flavor-changing transition is the neutrinoless decay of the muon to the electron $\mu^- \to e^-\gamma$ (Fig. 15, right).

In the Standard Model, the (global) symmetry between three (the first three columns in Fig. 6, left) generations of fermions (or their independence of each other) is broken [28, 137] due to their so-called Yukawa interaction with the Higgs boson field H ($\mathrm{SU(2)_L}$ doublet). This interaction is described using the Lagrangian

$$L_{\text{Yukawa}} = Y^e_{ij} H^\dagger \bar{e}_{iR} l_{jL} + Y^d_{ij} H^\dagger \bar{d}_{iR} q_{jL} + Y^u_{ij} \tilde{H}^\dagger \bar{u}_{iR} q_{jL} + \text{h.c.},$$

where Y^e_{ij}, Y^d_{ij}, and Y^u_{ij} are the Yukawa coupling constants of the charged leptons e_{iR}–e_{jL}, bottom quarks

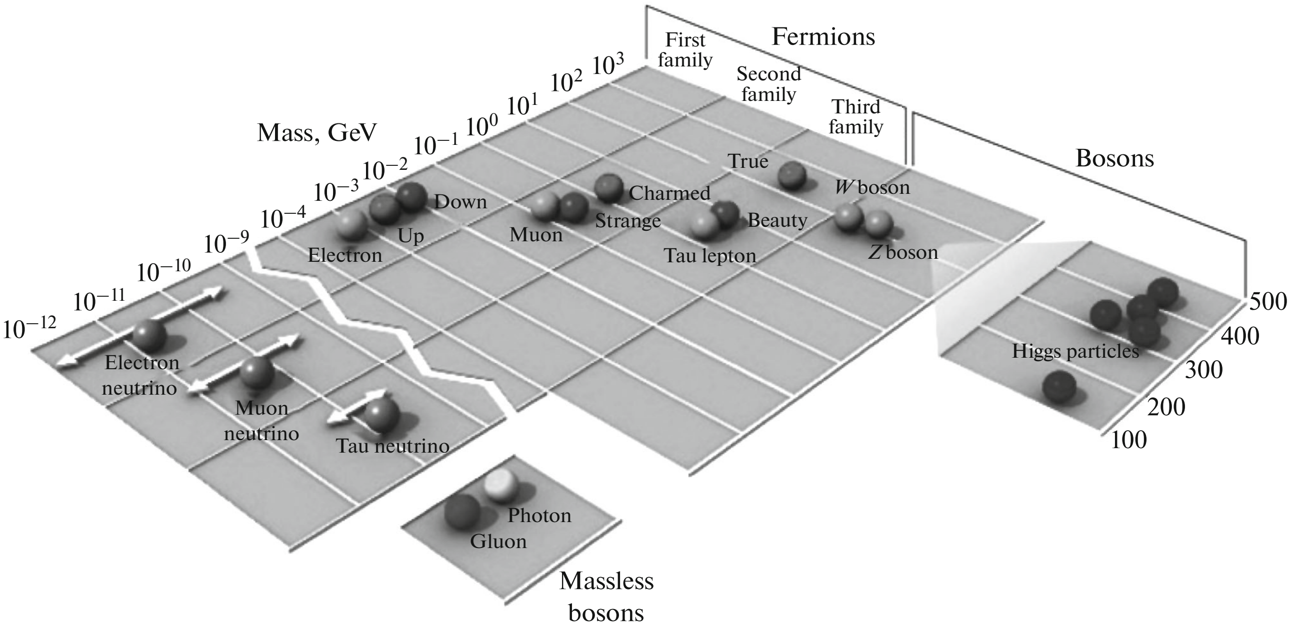


Fig. 16. Mass spectrum of fundamental particles in the Standard Model, a mystery for new physics.

d_{iR}–g_{jL}, and top quarks u_{iR}–g_{jL}, and $\tilde{H} = i\tau_2 H^*$. After spontaneous symmetry breaking, when the Higgs boson field acquires the constant component $H \to v > 0$ (Higgs mechanism), this interaction gives rise to quark and lepton masses

$$L_{\text{mass}} = -\bar{e}_{iR} M^e_{ij} e_{jL} - \bar{d}_{iR} M^d_{ij} d_{jL} - \bar{u}_{iR} M^u_{ij} u_{jL} + \text{h.c.},$$

where $M^e_{ij} \simeq vY^e_{ij}$ and $M^q_{ij} \simeq vY^q_{ij}$ are the mass matrices of (charged) leptons and quarks. As a result, fermions acquire masses in the gauge-invariant way, but the particular values of these masses and the mixing angles are dictated by the three-dimensional space of generations [28].

Diagonalization of this type of matrix, say, in the quark sector leads to the Cabibbo–Kobayashi–Maskawa mixing matrix:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix},$$

which successfully accumulates all “flavor information” in terms of three mixing angles and one CP violation phase [28, 29]. However, the physical cause for this unique (hierarchical) structure of the mixing matrix in the Standard Model is still utterly obscure. The main questions are why the observed set of fermion masses and mixing angles is as it is and why these sets are so different for quarks (V_{CKM}) and leptons (V_{PMNS}) [29, 64]

$$V_{\text{PMNS}} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \simeq \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix},$$

and whether there are mechanisms for mixing of fermions of different generations other than Yukawa mechanisms. The answers to these questions are hidden deep in new physics [28, 29]. It can be said that particular values of fermion masses ranging from fractions of eV/c^2 to 175 GeV/c^2 (Fig. 16) directly indicate the necessity of new physics.

Successful description of quark–flavor physics in the scope of the Standard Model is based on the unitarity of the mixing matrix and its hierarchic structure that substantially (GIM mechanism [143, 144]) suppresses flavor-changing neutral current processes (see for example [25, 28]). This extremely fine suppression mechanism can be easily destroyed by any new physics contributions [28]. Therefore, there are very strict limitations on any new variants of flavor symmetry breaking, which allows probing new physics scales unattainable in accelerators (10^5 TeV), and there is also a deep internal connection with the problem of the absolute neutrino mass value [28, 29, 93, 137].

Due to the Pontecorvo–Maki–Nakagawa–Sakata neutrino mixing matrix V_{PMNS}, which lacks a pronounced hierarchic structure [29, 104], neutrino oscillations “guarantee” (see Fig. 15, right) neutrinoless transitions between generations of charged leptons

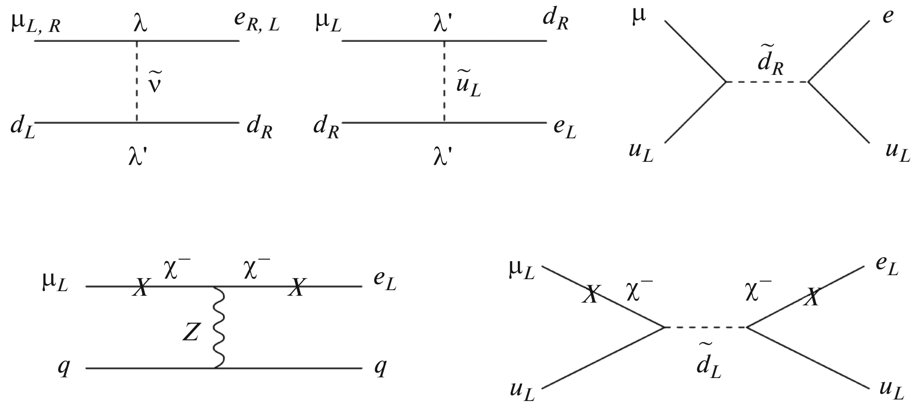


Fig. 17. Variants of the $\mu N \to eN$ process in the supersymmetric model with R parity violation. Top: exchange of sneutrinos $\tilde{\nu}$ and squarks $\tilde{u}_L$ and $\tilde{d}_R$ proportional to the R violation constants λ and λ'. Bottom: contribution to the $\mu - e$ conversion of the chargino χ^- mixing with charged leptons (marked with the cross X on the lepton line). From [146, 147].

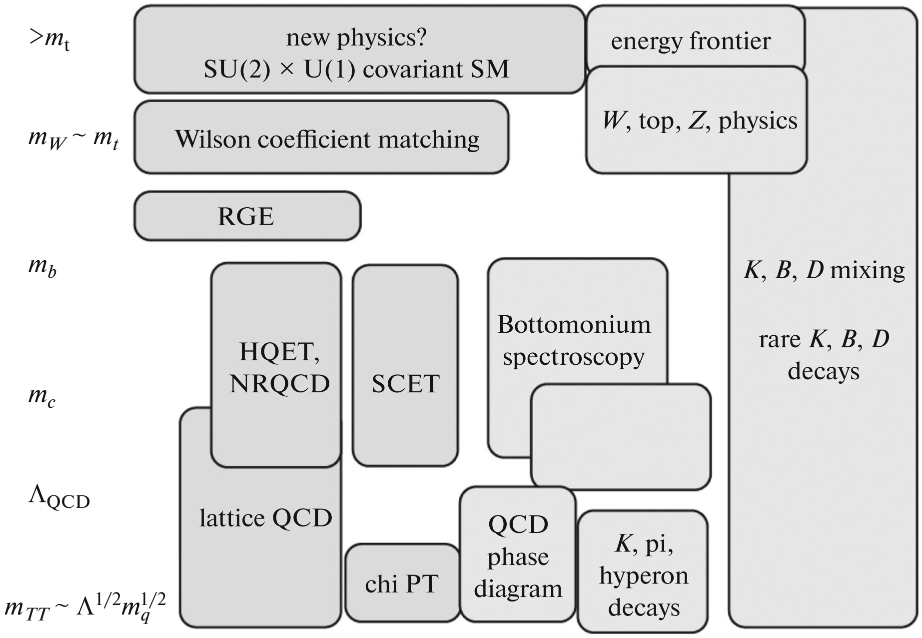
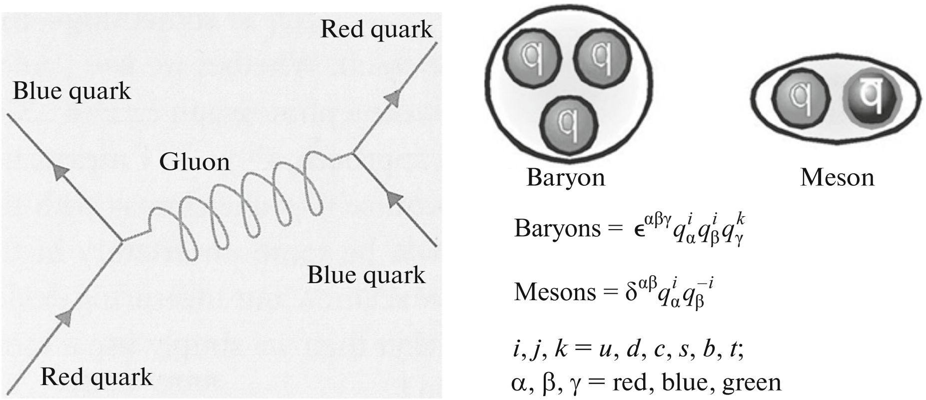


Fig. 18. Energy scales (from the pion mass to the top quark mass, left), research methods (from the chiral theory to entirely new theories, center), and physical observables (spectroscopy and rare decays, right) inherent in modern (hadron) flavor physic. From [136].

$\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$, and $\tau \to \mu\gamma$ (see for example [145]). However, extreme smallness of neutrino masses makes these processes entirely impossible in the Standard Model. As a result, searching for flavor transitions among charged leptons (unlike quarks) is the straightest way of probing new physics at the above-mentioned unique energy scales. As an example, Fig. 17 shows possible transitions of negative muons to electrons in their scattering by quarks within supersymmetric models with R-parity variation (see for example [146–149]). In other words, to investigate this sort of leptonic processes and obtain new probability limitations for them is always important because it allows us to constrain models of new physics or even to reject particular models (see for example [150–152]).

Though no statistically significant flavor deviations from the Standard Model predictions were observed at the LHC, it is flavor physics that still remains the primary tool for new physics searches since, as was already pointed out, it is potentially sensitive to much higher scales than those attainable in future high-energy accelerators [28, 29].

Figure 18 from [136] schematically summarizes energy scales, theoretical analysis methods, and key processes of modern flavor physics. It is seen that at low and intermediate energies (below the top quark



Baryons = $\epsilon^{\alpha\beta\gamma} q^{i}_{\alpha} q^{i}_{\beta} q^{k}_{\gamma}$

Mesons = $\delta^{\alpha\beta} q^{i}_{\alpha} q^{\bar{i}}_{\beta}$

$i, j, k = u, d, c, s, b, t$;
α, β, γ = red, blue, green

Fig. 19. Left: matter particles with a nonzero color charge (quarks, diquarks, etc.) interact via gluon exchange. Right: the observed hadrons (consisting of quarks), baryons and mesons, are colorless.

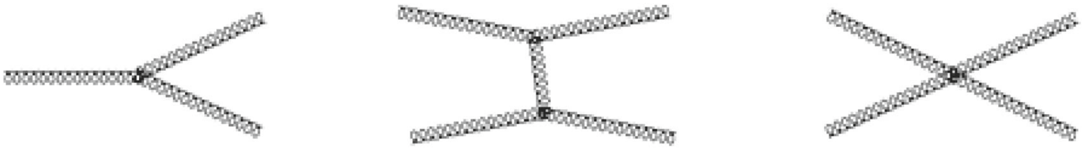


Fig. 20. Gluon self-interaction results in the asymptotic freedom, confinement effect, and generation of hadron masses.

mass) the main sources of information are rare decays of strange, charmed, and beauty mesons, mixing effects, and heavy-quark spectroscopy. Employed here are chiral field theory, lattice QCD, renormalization group equations, effective theories, etc. Higher energies open up new vistas of flavor physics, where the "main characters in the play" are gauge bosons and the top quark. Flavor physics (charmed and beauty quarks, direct CP violation) at colliders also remains significant [153–156]). Recently, possible lepton-flavor symmetry breaking (μ–e–τ universality) in Higgs boson decays like $H \to \mu\tau$ has aroused particular interest (see for example [157]).

In general, the major route for the new physics searches now runs in the "area of responsibility" of weak (or even extremely weak) interactions. However, the most important element of the Standard Model is quantum chromodynamics (QCD), a well-developed quantum-field theory of strong interactions (see for example [158–161] and references therein).

Unlike the case in the weak sector of the Standard Model, there is unbroken (color) gauge SU(3) symmetry and, as a consequence, masslessness and nonzero color charge of gluons, vector carriers of strong interactions.

Quarks (two upper lines in Fig. 6, left) exist in three different states symbolically labeled as red, blue, and green, i.e., they can have three different values of the quantum number (color) and interact with one another via gluons (Fig. 19, left), changing their color. Antiquarks accordingly have anticolor. Free (color) quarks are strictly localized inside hadrons, which is termed as color confinement. Summation of quantum colors in them yields white color (Fig. 19, right).

The SU(3) color symmetry requires eight different gluons with a double color charge $g_{\alpha\beta}$. The non-Abelian character of the unbroken (color) gauge SU(3) symmetry makes QCD drastically different from the electroweak elements of the Standard Model. Unlike photons (also massless), gluons interact with one another (Fig. 20), which leads to the asymptotic freedom and confinement effect and ensures dynamic breaking of chiral symmetry (masslessness of quarks) accompanied by generation of the hadron mass [159–163].

In high-energy hadron collisions, e.g., at the LHC, QCD is the main source for production of all particles, the basis for the verification of the Standard Model, and an unavoidable background in the search for "the new in the sea of the old" [25, 158]. A thorough understanding of the QCD effects is a necessary condition for correct interpretation of experimental data at high energies [26, 164]. Due to the asymptotic freedom effect (smallness of the strong interaction coupling constant) and the consequent justification of the perturbation theory method, perturbative QCD [162] is a set of efficient theoretical tools well describing quark–gluon processes at large transfer momenta (hard processes). For example, perturbative QCD calculations of hadron jet production cross sections agree with the

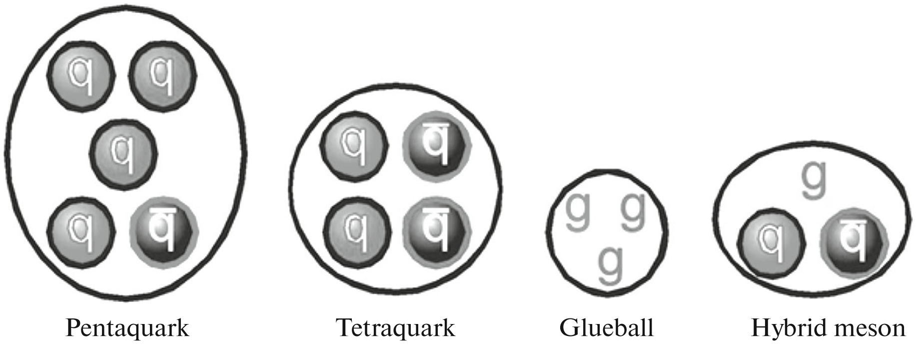


Fig. 21. Examples of multiquark and exotic hadron-like states.

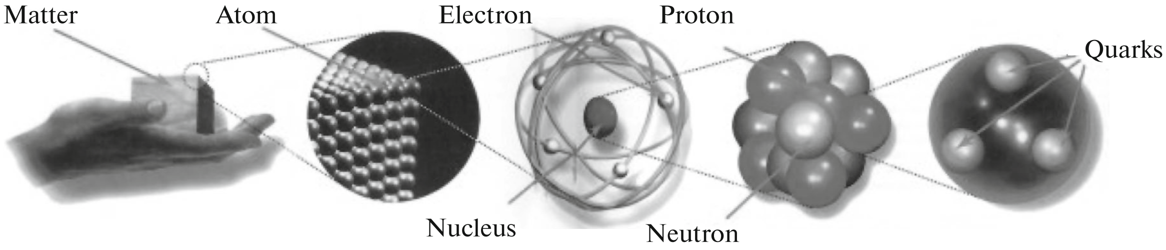


Fig. 22. Everything consists of quarks and gluons.

LHC data over many orders of magnitudes (see for example [25, 26]).

However, nonperturbative QCD [162] (when it is impossible to perform calculations within the perturbation theory) responsible for the confinement effect is inevitably manifested (though playing a supporting role) at high energies in the form of spin effects [165], parton (including transverse-spin TMD [166], nuclear [167], and other) distributions, fragmentation and recombination functions, and other "soft interactions" of hadrons [158, 159, 168, 169] that are usually considered in the framework of phenomenological models [166, 167].

Nonperturbative QCD plays an essential part in above-mentioned flavor physics, where it is an "unavoidable structural factor" (see for example [29, 170]) or "takes the form of a signal" of new physics, e.g., unusual valence-like (intrinsic) distributions of strange, charmed, and beauty quarks [57, 156, 171], and multiquark configurations of the type of tera- and pentaquarks (Fig. 21) [25].

The nonperturbative component of QCD is that extraordinary part of the Standard Model which is meant to explain from first principles (e.g., by complicated lattice calculations [172]) the dynamic breaking of chiral symmetry (which generates over 98% of the visible baryon mass of the Universe), confinement effect, and all nuclear physics [159, 163, 167, 168, 173]. In other words, it is necessary to understand how hadrons (pions, kaons, protons, neutrons) are formed on the basis of quarks and gluons and in their mutual interactions [159, 174, 175] and how they form the diversity of atomic nuclei [161, 168, 172, 173].

It is quite possible that nuclear physics does not uniquely stem from our current understanding of QCD [176], yet it is obviously bound to rely on QCD for the simple reason that all protons and neutrons, all nuclei, and all matter are "made" of quarks and gluons (Fig. 22).

To understand nuclear physics on the basis of QCD is a very complicated problem, and substantial advances in solving it can be made by gaining any new experimental information, especially that which can be obtained from the "problematic region" of the QCD phase diagram (Fig. 23), where quarks and gluons turn into hadrons and nuclei (see for example [160, 177]).

Apart from the above-mentioned soft nonperturbative QCD processes (see for example [178–180]), the main expectations are currently related to studies of heavy ion collisions at (rather) high energies [181], where conditions are systematically created for the formation and coexistence of hadron and hot quark–gluon matter (Fig. 24), that is, the confinement–deconfinement transition (see for example [160, 161, 177, 182–184], or [185]).

These studies are important for understanding the evolution of the early Universe after the Big Bang (see for example [186]), the formation of neutron stars, and the main phenomena arising in heavy ion collisions. Indeed, according to the theory of the Big Bang and

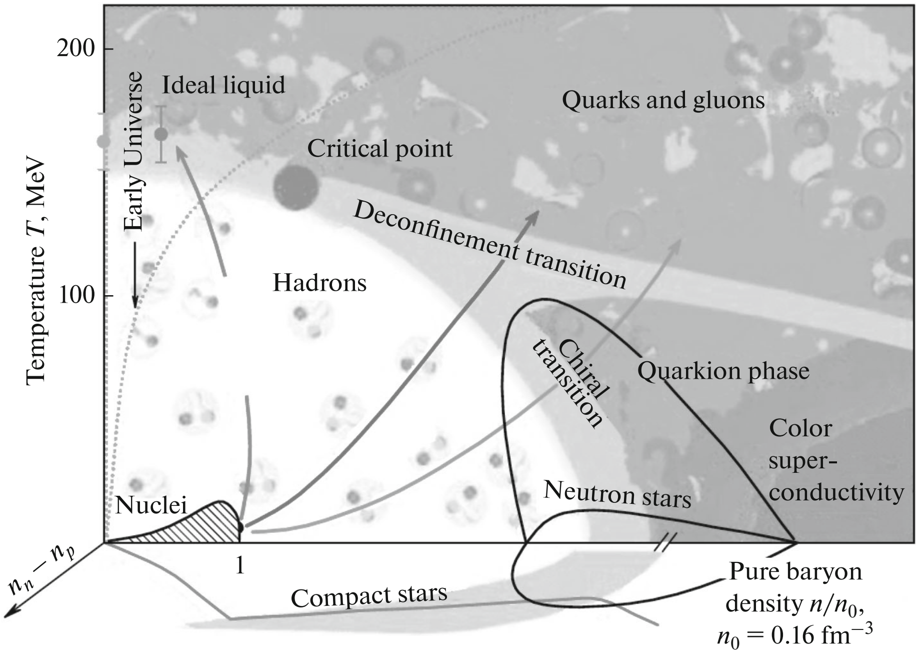


Fig. 23. Phase diagram of strongly interacting matter [399]: dependence of the temperature of a system of two colliding nuclei on pure baryon density (in units of nuclear matter density n_0). At high energy and low baryon density the transition from the quark-gluon phase to the hadron gas phase proceeds "almost unnoticeably" through the region of the so-called cross-over (at the critical point) [160].

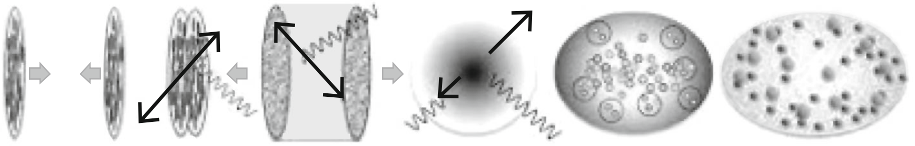


Fig. 24. Evolution of the system in the process of heavy ion collisions. Also shown are "probing" interactions that are capable of carrying information about the system at different phases of its evolution.

formation of matter in the Universe, in the course of its long evolution there inevitably was a specific phase where quarks and gluons existed without hadrons—the quark–gluon plasma (Fig. 25). It only remains to find it on the Earth and try to understand the nature of confinement.

By virtue of extreme complexity, transience, and diversity of the above processes, a correct, that is, adequate for the desired goals, set of physical observables is of great importance (see for example [187–190]).

Any experimental and theoretical information on rather stable and quite unusual hadron states—glueballs, (super)hypernuclei, highly neutron-rich light nuclei, di(tetra)baryons (see for example Fig. 21), and other nontrivial cluster configurations in nuclei—is highly important [180] for adequate formation of QCD in its nonperturbative region and for revealing the role of these states at the stage of nucleosynthesis in the early Universe.

This information can be gained from investigations of nuclear reactions induced by stable and radioactive beams of ions of (exotic) light elements [191–193], for example at the DRIBs complex [194] of the Flerov Laboratory of Nuclear Reactions, JINR (see also Section 6).

In the context of the JINR multidisciplinarity traditions, the physical object equally important from the viewpoints of new physics and the hadron structure is the neutron, the lightest neutral baryon without which atomic nuclei cannot exist. It justly occupies the exceptional place in elementary particle physics. As is known, the method of oil prospecting by neutron logging proposed and implemented in 1941 by Pontecorvo [195] "takes the first place in the chronology of important practical applications of the neutron," as Pontecorvo himself wrote [196]. The neutron is a remarkable source of new information from the point of view of fundamental verification of the Standard

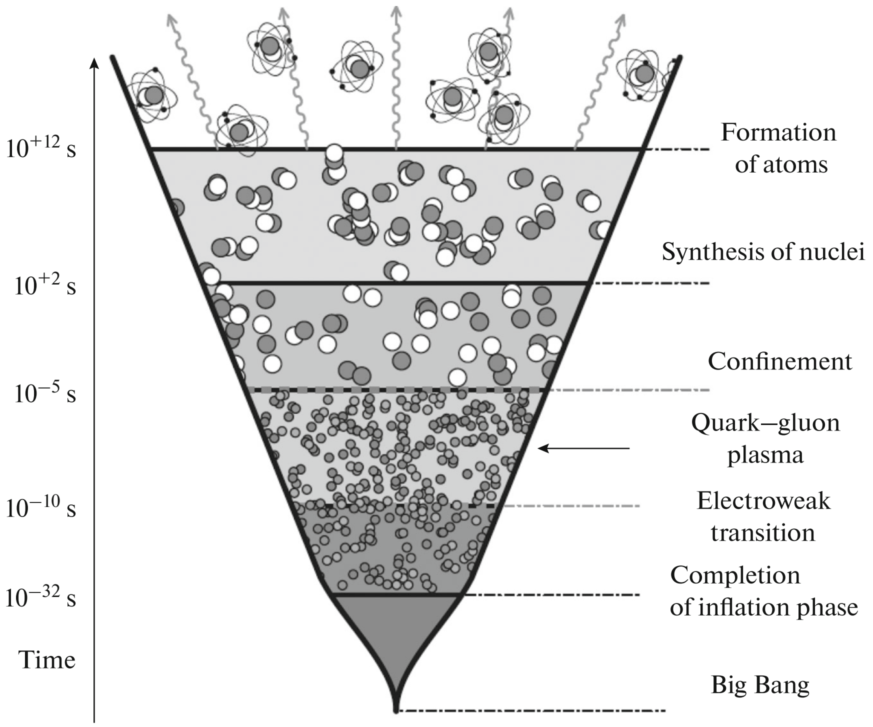


Fig. 25. Diagram of the evolution of the Universe from the Big Bang to the formation of atoms.

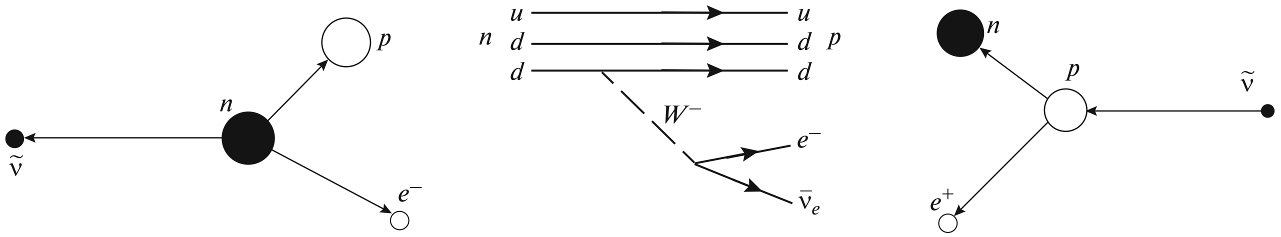


Fig. 26. Decay of the neutron into a proton, an electron, and an antineutrino (left), its typical quark diagram (center), and the inverse beta decay (right): absorption of the antineutrino.

Model in its QCD and electroweak sectors (see for example [197–199]) and as a unique tool for nuclear physics and condensed matter physics research.

Beta decay of the (free) neutron $n \to p + e^- + \bar{\nu}_e$ is the key (nuclear) process (Fig. 26) of particular interest for precision verification of the Standard Model, especially its charged weak current sector [199, 200].

Highly accurate measurements of neutron beta decay parameters (lifetime, angular correlations, form factors, etc.) are needed for determining the main characteristics of the Cabibbo–Kobayashi–Maskawa matrix and understanding the QCD structure of this baryon [201]. Properties of the neutron and nuclear reactions with its participation play a key role in many astrophysical processes, such as the genesis of light elements at the early development stage of the Universe, the production of isotopes of heavier elements in stars by neutron capture, etc. (see for example [128, 202]). Inverse neutron beta decay $\bar{\nu}_e + p \to n + e^+$ (Fig. 26, right) is the key process for detection of reactor antineutrinos (see for example [95, 102]).

Since nuclear fission is one of the most complex nuclear transformations related to deep redistribution of the initial nucleus mass and charge with the production of deformed and excited fragments that have a high spin and the energy sufficient for emission of a few neutrons and γ rays, investigation of various characteristics of spontaneous and induced nuclear fission under the effect of neutrons are of primary interest [203], especially with a modern high-intensity neu-

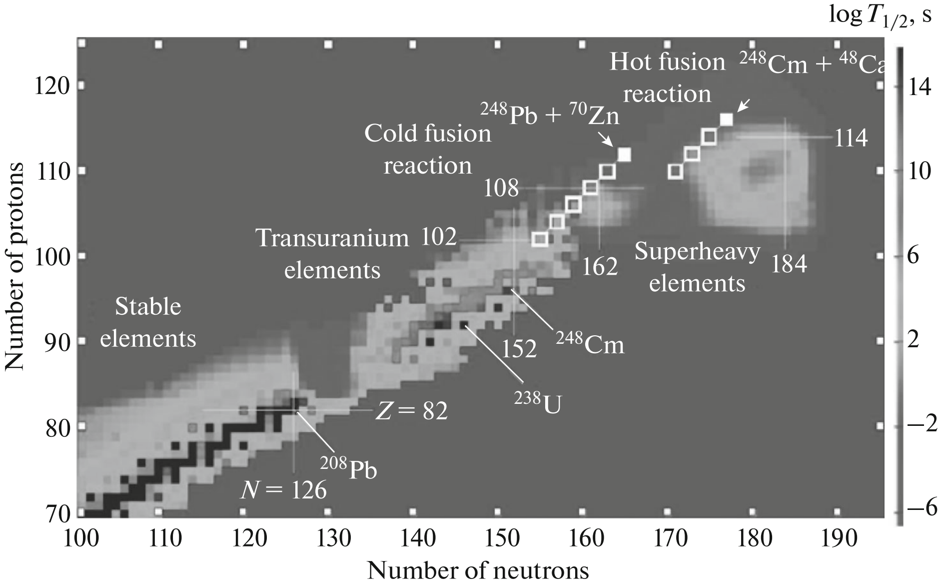


Fig. 27. Map of nuclear isotopes with large proton (Z) and neutron (N) charges near the island of stability of superheavy elements. From [215].

tron source (like the IBR-2M pulsed reactor [204] and the IREN facility [205, 206] at JINR).

An important line of basic research is physics of ultracold neutrons (see for example [207–209]) pioneered in Dubna in 1968 [210]. Here, one can measure such "fine" characteristics of neutrons as the precise value of their lifetime [211], electric dipole moment, which is a sensitive probe of new physics at PeV energy scales (see for example [25, 165, 212, 213]), or neutron–antineutron oscillations, which is a direct way to verify CPT universality (see for example [214]).

In the light of the concept of reducibility of nuclear physics to nonperturbative QCD it seems worth giving particular attention to superheavy element physics, or heavy ion physics (see for example [215]), which has now become the most extensively developing and most successful field of low- and intermediate-energy nuclear physics (see for example [216, 217]). The main experimental achievements are synthesis of transfermium elements($Z > 100$) and superheavy elements (SHE) and investigation of their nuclear, physical, chemical properties [218, 219], production of light exotic nuclei and investigation of their properties, investigation of fission–fusion and quasifission processes in interactions of particularly heavy ions, investigation of mechanisms for reactions with accelerated ions of stable and radioactive isotopes, etc. (see for example [8, 9, 192, 219]). At the same time, a fundamental achievement of microscopic nuclear physics is the prediction of the island of stability (Fig. 27) of superheavy elements [220–222]. Formation of these elements is a very rare event, its cross section is estimated to be in the range of a few picobarns [216, 221]. Moreover, predictions of the position and properties of the island itself strongly depend on the nuclear model.

Further advance in this direction is associated with the necessity of studying nuclear-physics properties of already observed superheavy elements with $Z = 113$–118 and synthesizing new isotopes with $Z = 119, 120$. In addition, it is necessary to obtain new data on nuclear level structures, which will allow refining parameters of the above-mentioned models, and data on nuclear fusion–fission cross sections, which is important for determining lifetimes of nuclei and optimizing their synthesis channels.

Impressive results of the past years obtained in synthesis of superheavy elements with $Z = 113$–118 are undoubtedly of continuing importance and will ever remain in the history of mankind in the form of filled-in periodic table element cells [223–226]. However, these unique researches are important also because they serve to verify and "bring to perfection" the most promising nuclear structure models, which must be eventually substantiated within nonperturbative QCD. It may be that this nuclear-physics information may require a substantial modification of the fundamental principles of QCD.

To sum up, it should be mentioned that the integrated program of international investigations into the above-mentioned fundamental problems of experimental physics relies on the contemporary achievements in the development of experimental facilities and advanced research methods, which can be rather arbitrarily grouped into four intertwining directions of research [37, 36, 38]. The first direction is related with the increase of accelerator energies (energy frontier).

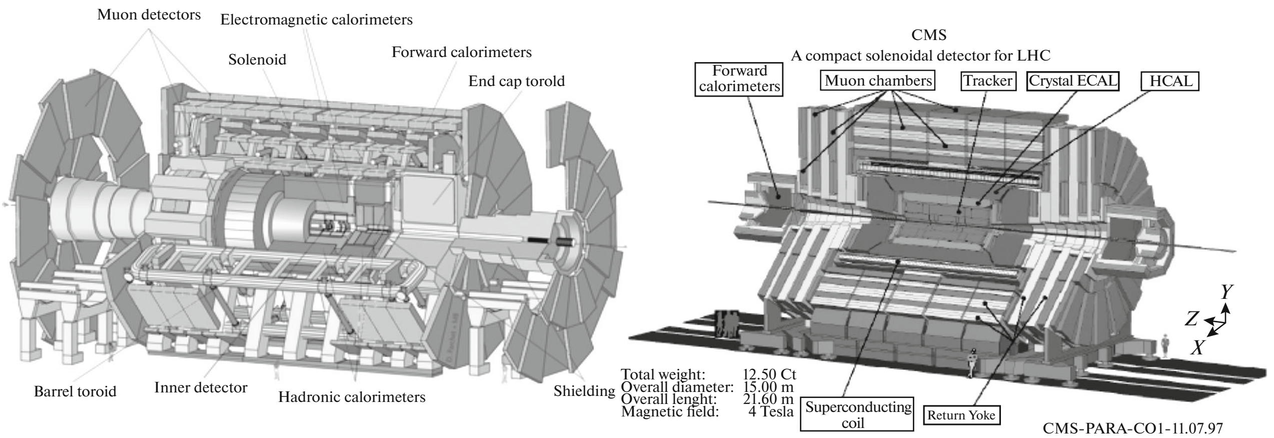


Fig. 28. General view of the ATLAS (left) and CMS (right) detector.

The main characteristic of the second direction is an appreciable increase in the accelerator beam intensity (intensity frontier). The third direction is essentially a considerable increase in the accuracy of nonaccelerator experiments (measurement accuracy frontier). The fourth direction is astrophysics and cosmology in relation to elementary particle physics (space research frontier). Only comprehension of the combined data from these fronts can lay a foundation for a new physical picture of the world free from the fundamental problems of the Standard Model.

3. JINR OBJECTIVES IN MODERN EXPERIMENTAL PARTICLE PHYSICS

This section briefly describes the main objectives of JINR at a new stage of its development in 2017–2023, which are aimed at solving the above-mentioned important problems of elementary particle physics and nuclear physics. The focus is placed on experimental particle physics since it takes the central place in the JINR research program due to is fundamentality and forms both the world vision basis and the methodology of all research carried out at JINR, ranging from quarks, nucleons, and nuclei to molecules and entirely new materials. Particle physics stimulates the work of JINR scientists in such related fields as information, communications, and computing technologies, radiochemistry, polymer, condensed matter, and complex compound physics, radiobiology, genetics, etc. It should be stressed that goals of the new JINR program discussed below are not randomly or arbitrarily chosen (“pulled out of a hat”). They are a logical consequence and natural continuation of the 60-year diverse successful research at the nuclear physics frontier carried out at JINR (see for example the previous JINR seven-year program [11]). It can be said that hard work and genius of several generations of JINR scientists and engineers underlie these objectives, and now, while preserving and increasing this heritage, it is necessary to start fulfilling these ambitious objectives. Actually, the scientific future of JINR is the improved continuation of its present.

3.1. JINR in Frontline LHC Research: ATLAS and CMS Experiments

As is known, the international collaborations ATLAS (A Toroidal LHC ApparatuS) [227] and CMS (Compact Muon Solenoid) [228] were specially established for carrying out diverse new-generation experiments to systematically study the fundamental properties of matter in proton–proton collisions with the maximum energy of 7–14 TeV at CERN’s LHC. As was already mentioned, the main goals of those studies were to find the Higgs boson and search for new physics effects beyond the Standard Model.

The ATLAS and CMS detectors (Fig. 28) are unrivalled, highly complex physical facilities that have accumulated the most advanced achievements in modern science, technology, and data processing and transmission methods. That is why they allow a maximum wide range of physics phenomena, including new and unexpected ones, to be investigated and ensure gaining absolutely new knowledge.

Therefore, participation in these large-scale international projects was considered indisputably necessary for JINR as an international research organization. The decision about the participation of JINR specialists in the ATLAS and CMS experiments at the LHC was officially taken in 1995. Since that time, a lot has been done by JINR in that field. For example, the ATLAS collaboration management stressed many times that JINR scientists made a substantial, sometimes decisive, contribution to the development, design, manufacture, mounting, and commissioning of the main ATLAS detector subsystems: the muon detection system, electromagnetic and hadron calorimeters, inner tracking detector, and data acquisition

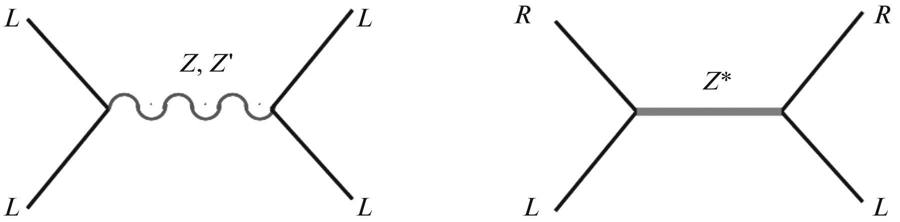


Fig. 29. Unlike the case of ordinary gauge bosons (left), the tensor interaction of fermions with chiral vector bosons does not conserve chirality (right), i.e., it mixes left-handed and right-handed fermions (labeled as L and R), which leads to unique experimental signatures [259, 260].

and primary processing systems (see for example [229–249]). In this connection, it should be specially noted that apart from JINR, only three participants in the ATLAS collaboration (Italy, United States, CERN) contributed to the development and adjustment of all main ATLAS detection systems. Participation of JINR had a similar impact in the CMS experiment (see for example [24, 228, 250–257]). In line with these works, traditions of the previous JINR seven-year program [11], and particle physics development directions formulated in the previous sections, the main strategic objective of JINR is to obtain, through full-scale participation in the international ATLAS and CMS experiments at the proton energy of 13 to 14 TeV (RUN-II LHC), fundamentally important results concerning the nature of the Higgs boson, structure and properties of quark–gluon QCD matter, the existence of new physics at the TeV energy scale, such as supersymmetry, extra dimensions of space, new types of particles and interactions, etc.

3.1.1. ATLAS experiment. The solution of the main strategic objective will be specified as a number of investigations proposed as a rule by the JINR participants in the ATLAS experiment [258]. An incomplete list of these investigations includes (i) the search for and study of characteristics of additional exotic (including chiral) Z^* and W^* bosons (Fig. 29) in two-jet, two-lepton, and other processes [258, 259, 261–268], (ii) the search for possible manifestations of supersymmetry in final states with a sufficiently large number of hadron jets accompanied by isolated leptons and large missing energy [269–272], (iii) the search for supersymmetric charged Higgs bosons by some of their particular decays [273–275] and study of the production of the Standard-Model Higgs boson in association with a $t\bar{t}$ pair, (iv) the search for manifestations of valence-like nonperturbative components of heavy quarks (intrinsic heavy flavor) in the proton on the basis of various possible final-state topologies [276–280], (v) the search for new and study of properties of known mesons and baryons containing heavy c and b quarks [281–286], (vi) the comprehensive study of the gluon structure of the proton [287–289], and (vii) the measurement of two-body Bose–Einstein correlations in proton–proton collisions at high multiplicities and energies [290].

3.1.2. CMS experiment. The main efforts for the fulfillment of the main objective will be concentrated on the directions traditional for the Dubna team. One is the investigation of muon pair production and multijet events aimed at verifying Standard Model predictions and searching for new physics [291–295]. More specifically, the JINR team concentrates on the investigation of regularities of muon pair production in Drell–Yan processes. In particular, considerable experience has already been gained in measurements of differential and double-differential muon-pair production cross sections in the range of invariant masses up to 2000 GeV/c^2 [253, 257], and asymmetry of forward–backward muon emission has been investigated [296–298]. Another direction is the study of the Higgs boson properties [299]. The team continues to work to improve the precision of the Higgs boson mass measurements and to determine its characteristics that will allow a conclusion to be made about its belonging to the Standard Model [254–256].

Apart from participating in these researches, the JINR scientists will continue fulfilling their obligations for routine operation of the ATLAS and CMS detectors (shifts, expert examinations, ensuring safety, software support and development, calibrations, data quality control, etc.) and taking part in their upgrading.

3.2. JINR in Modern Neutrino Physics

Investigations in the field of weak interactions, neutrino physics, and astrophysics have been carried out at the Dzhelepov Laboratory of Nuclear Problems (DLNP) by the personnel of the Scientific Experimental Department of Nuclear Spectroscopy and Radiochemistry and the Scientific Experimental Department of Elementary Particle Physics. This currently important (and not only for JINR) direction of research was pioneered by Pontecorvo, who came to Dubna in 1950 [3, 196], where many important results were obtained with his direct participation and under his supervision. Among them there are the discovery of the pion beta decay $\pi^+ \to \pi^0 e^+ \nu_e$ [300], substantiation of the existence of the muon neutrino and pro-

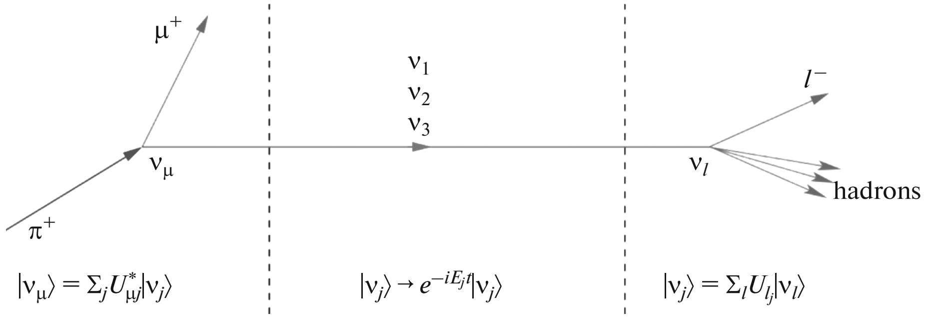


Fig. 30. Example of neutrino conversion from one type to another (neutron oscillations) at the diagram level: production of a muon-type neutrino (left), propagation of neutrino mass states in space, detection of a neutrino of another (not obligatory muon) type (right). From [309, 310].

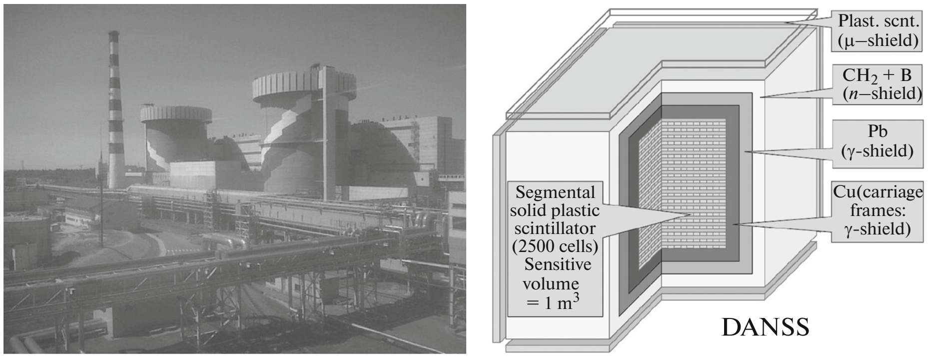


Fig. 31. Typical view of the nuclear power plant (left) and a schematic diagram of the DANSS plastic scintillator detector (right).

posal of an experiment for its observation [301, 302], observation of the recoil nucleus from the muon neutrino in the reaction $\mu^- + ^3\text{He} \to ^3\text{H} + \nu_\mu$ and estimation of the upper limit on the mass ν_μ [303, 304], confirmation of the *V–A* version and universality of the weak interaction by measuring the probability for muon capture by protons [305], measurement of the helicity of the electron neutrino from the ^{152m}Eu decay [306], and many others. As is known, it is in Dubna that Pontecorvo formulated the idea of neutrino oscillations, that is, transformations of neutrinos from one type to another (Fig 30) [307, 308], and in 2015 the Nobel Prize in physics was awarded for its experimental confirmation.

JINR physicists carry out experiments with almost all possible neutrino sources. Solar neutrinos are the subject for thorough studies in the BOREXINO experiment [311], where fluxes of solar beryllium, boron, *pep*, and *pp* neutrinos are measured, and limits are set for the effective magnetic moment of neutrinos, solar axion flux, violation of the Pauli exclusion principle, etc. [312–314]. In addition, the unique BOREXINO detector allowed measuring the geoneutrino flux from decays of natural radioactive isotopes in the Earth [98, 99, 314, 315].

JINR scientists use intense beams of accelerated neutrinos (and antineutrinos) in the NOvA experiment aimed at determining the neutrino mass hierarchy and solving the problem of CP violation in the neutrino sector (see for example [65, 316, 317]). The OPERA experiment has been successfully completed, in which five τ neutrinos produced in $\nu_\mu \to \nu_\tau$ oscillations in the ν_μ beam of the SPS (CERN) were observed for the first time [318].

Beams of reactor antineutrinos ($\bar{\nu}_e$ from nuclear reactors) are now the most intense of all available neutrino sources (Table 1). For this reason, they are constantly used (by JINR scientists as well) in a number of ambitious research projects [95].

At the Kalinin Nuclear Power Plant, one of such projects is the GEMMA experiment, in which the best limit on the antineutrino magnetic moment has been obtained [319, 320], and this result is expected to be noticeably improved.

Another experiment is DANSS [102, 321] aimed at directly detecting reactor antineutrinos for the reactor monitoring purposes and solving the problem of the existence of light sterile neutrinos [69]. In 2016, data taking began in that experiment. The main advantage of the DANSS detector (Fig. 31) is that it can detect up

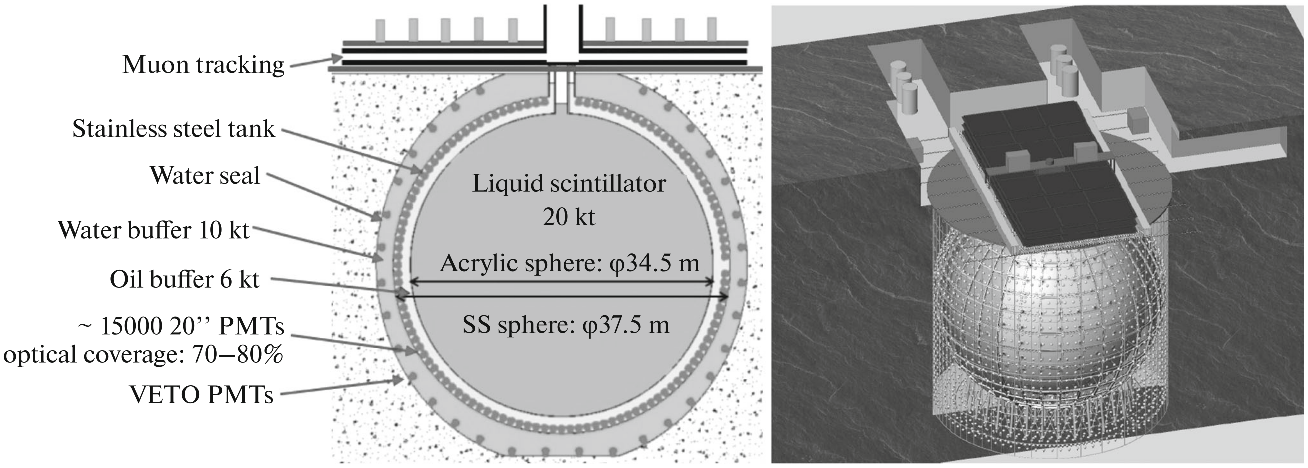


Fig. 32. Schematic diagram (left) and graphical design of JUNO, a new multifunctional detector of reactor antineutrinos.

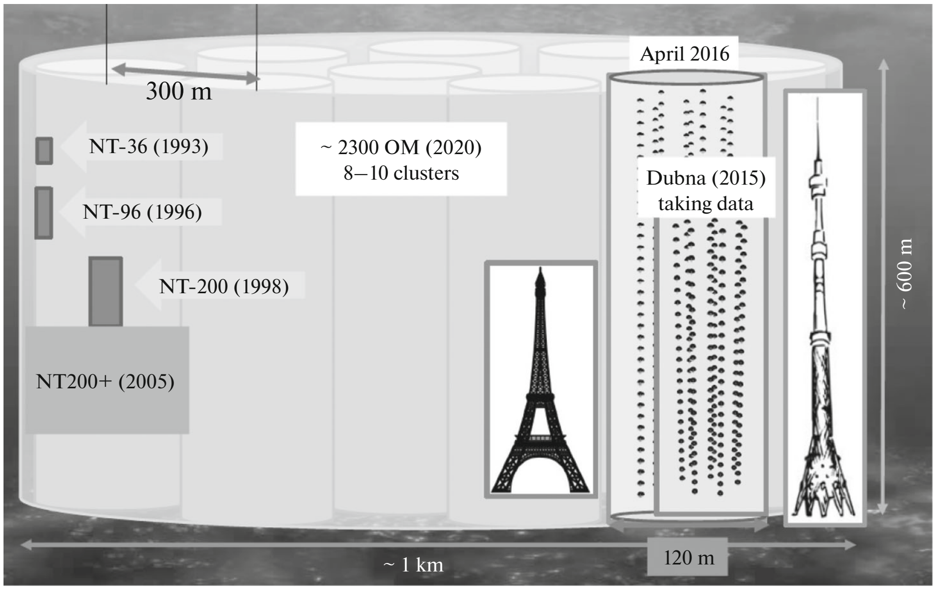


Fig. 33. Stages and planned further development of the cubic-kilometer BAIKAL–GVD project.

to 10000 antineutrino events a day due to being close to the center of the reactor. It is planned to employ these capabilities in the ν GEN experiment in the search for coherent (anti)neutrino scattering from nuclei using low-background and low-threshold Ge detectors of a new generation [322]. It should be stressed that JINR scientists are key figures in all the above experiments at the Kalinin Nuclear Power Plant.

As is known, in the international Daya Bay (China) experiment with ν_e neutrinos produced by the nuclear power plant where JINR participation is highly appreciated, the mixing angle θ_{13} was measured with a high accuracy for the first time [323], which became one of the most significant results in physics in 2012, and other important results were obtained [324–326]. Together with continuing the analysis of the Daya Bay data, the JINR team has concentrated its efforts on an even more ambitious international reactor antineutrino project JUNO (Jiangmen Underground Neutrino Observatory) [327] (Fig. 32), which involves a wide range of multifaceted experiments on neutrino physics and astrophysics.

To ensure full participation in this experiment, an entirely new infrastructure was built at JINR, for checking, testing, and certifying photomultiplier tubes.

Atmospheric neutrinos and especially neutrinos of astrophysical (galactic and extragalactic) origin are the main subject for investigation at the Baikal gigaton neutrino telescope BAIKAL GVD (Fig. 33), in which JINR has been taking part for more 25 years [329–332].

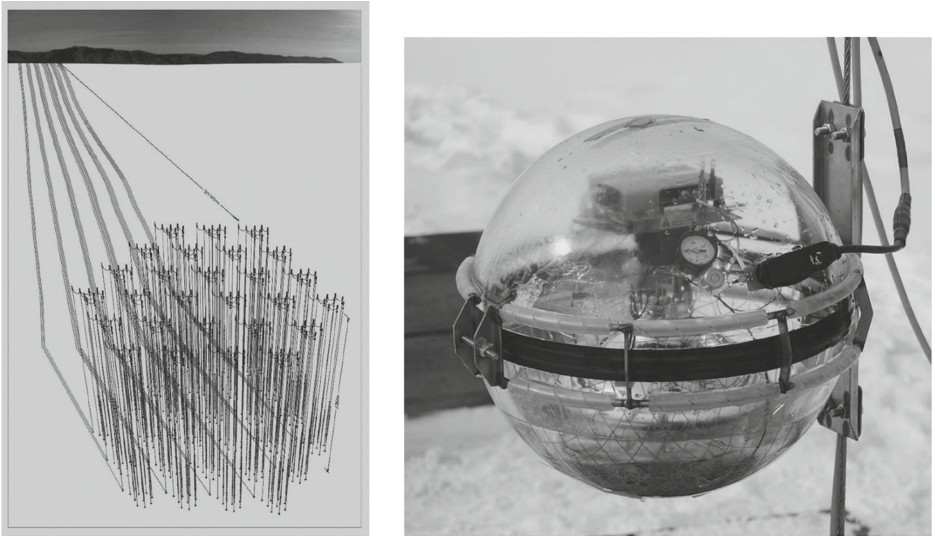


Fig. 34. Left: schematic view of the full-scale BAIKAL–GVD neutrino telescope. Right: photo of the optical module before submersion under ice. From [332].

This experiment gains importance in the light of the recent observation of extragalactic cosmic neutrinos with the energy 10^{15} eV by the IceCube collaboration [333, 334], which opens a new field in modern physics, neutrino astronomy. The upgraded BAIKAL GVD facility must play the vital role in this field of research (Fig. 34).

During the previous 25 years of intensive research and development, the technology for detection of neutrinos by large deep underwater detectors has been optimized, and a number of physical results have been obtained, e.g., atmospheric neutrino fluxes were measured [335]. In 2006–2010, all key elements and systems of the GVD (Gigaton Volume Detector) were developed, built, and tested. In 2015, the first Dubna cluster was mounted [336]. The BAIKAL GVD volume of about 1 km^3 [332, 337, 338] is planned to be achieved in the coming seven to ten years [339]. The BAIKAL GVD project together with KM3Net and IceCube is included in the Global Neutrino Network [340].

Neutrino sources important for basic research are weak nuclear processes, such as ordinary beta decay, K-capture of electrons, and double beta decay. Of most fundamental importance is the search for neutrinoless nuclear double beta decay because it is only possible when the lepton number conservation law is explicitly violated ($\Delta L = 2$) and is also extremely important for determining the nature of the neutrino (whether it is a Dirac particle, i.e., $\nu \neq \bar{\nu}$ or a Majorana particle, i.e., $\nu \equiv \bar{\nu}$) and the absolute scale of neutrino masses (Fig. 35).

JINR takes part in the SuperNEMO and GERDA (and also MAJORANA) experiments on the search for neutrinoless double beta decay. The NEMO-3 experiment (Fig. 36, left) aimed at simultaneously measuring tracks and energies of decay electrons (detector ≠ source) is completed at the low-background international laboratory LSM (Modane, France), which is supported in part by JINR.

Many important results were obtained in the experiment, in particular, a new limit was set for the neutrinoless double beta decay lifetime of the ^{100}Mo nucleus [341, 342]. Still adhering to the main idea of simultaneous tracking and calorimetry, the NEMO collaboration is now developing the first demonstration module of the SuperNEMO detector (Fig. 37).

In the GERDA experiment (Fig. 36, right) based on a different principle “detector = source” the two-neutrino double beta decay lifetime of the ^{76}Ge nucleus was measured and a new limit on its neutrinoless double beta decay lifetime was obtained with the participation of JINR scientists [343–345]. Successful continuation of the GERDA experiment for the coming five to seven years will allow confirmation or refutation at a high confidence level [346, 347] of the unique result of the Heidelberg–Moscow experiment [348, 349].

It is worth noting that after the above-mentioned outstanding advances in the experimental searches for and investigations of neutrino oscillations, which must undoubtedly be continued at least for solving the problem of the neutrino mass hierarchy and the character of the CP symmetry breaking in the lepton sector, the top-priority objective now becomes determination of the nature, absolute mass scale, electromagnetic properties, and cosmic sources of neutrinos. This is where additional efforts should be made and important experimental results ought to be expected.

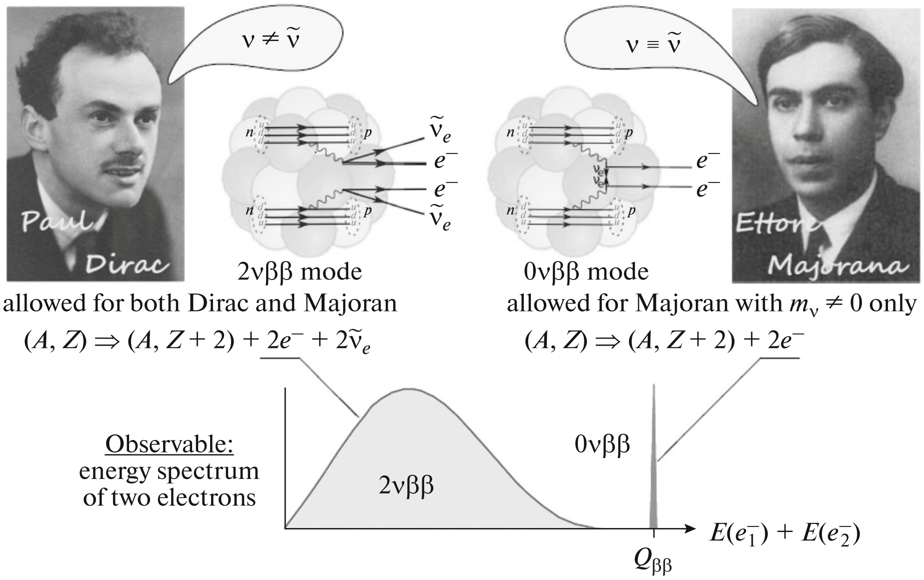


Fig. 35. Two main modes of double beta decay, two-neutrino mode 2νββ and neutrinoless mode 0νββ. The 0νββ probability depends on the absolute neutrino mass scale $m_{ee} = \left|\sum_i^3 m_i V_{ei}^2\right|$. Drawing of V.G. Egorov from [339].

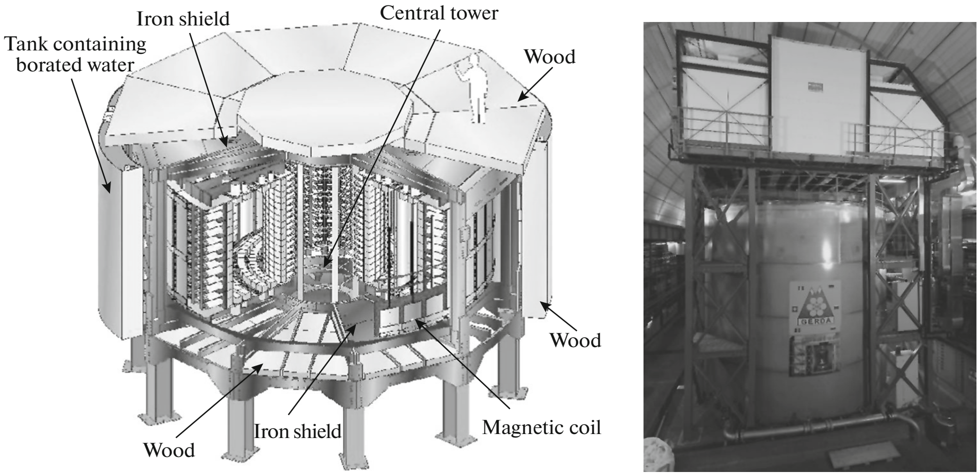


Fig. 36. NEMO-3 detector employed at the LSM laboratory in Modane (left) and the GERDA detector in one of the Gran Sasso laboratory, Italy (right).

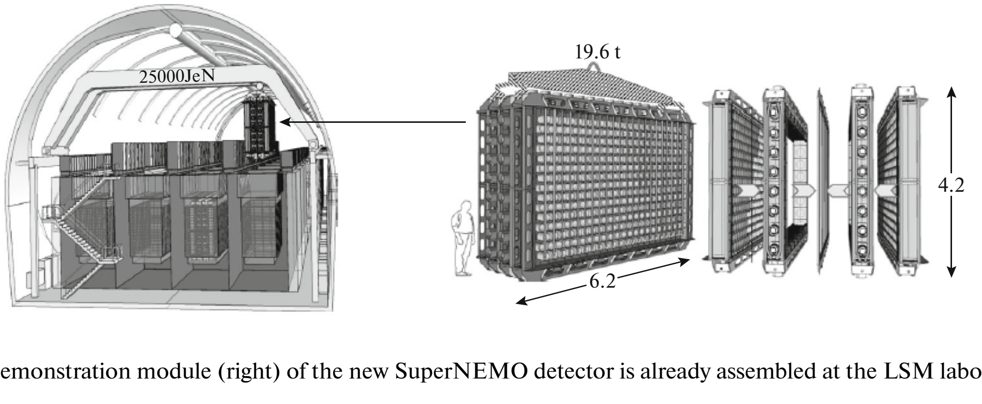


Fig. 37. First demonstration module (right) of the new SuperNEMO detector is already assembled at the LSM laboratory (left).

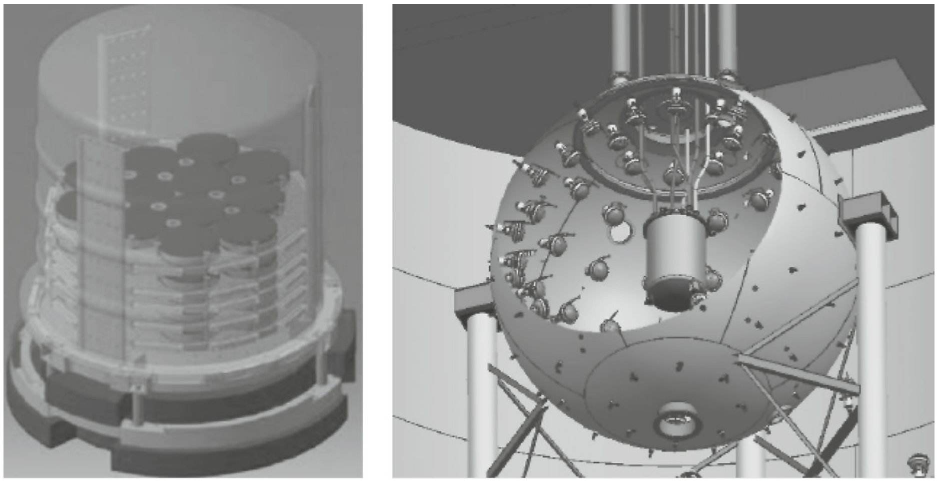


Fig. 38. Cryostat of the EDELWEISS-3 detector (left) and the Darkside-50 detector (right) [353].

In the Modane underground laboratory, JINR scientists make a considerable contribution to the EDELWEISS experiment (Fig. 38, left) with a set of bolometric high-purity germanium detectors, which has a goal of the direct search for dark matter [350, 351]. Within the above-mentioned BOREXINO collaboration, the JINR team participates in the DarkSide experiment on the search for dark matter (Fig. 38, right) with a time-projection liquid-argon chamber [352, 353].

The planned increase of an array of high-precision germanium detectors in the EDELWEISS experiment seems to be strategically important from the perspective of having a possibility of detecting the yearly signal modulation, which is a distinctive characteristic of interactions between particles of galactic dark matter [115].

All projects described in the section constitute the basis for the JINR Neutrino Program (see the White Book [339] for detail). Within this program, JINR expects results of primary importance to be obtained in experiments both in Russia and abroad. At the same time, it is believed to be necessary for JINR to participate in important international neutrino physics projects, where the contribution of JINR scientists is highly important if not decisive. These are, first, the above-mentioned JUNO, NOvA, EDELWEISS, SuperNEMO, BOREXINO, and GERDA experiments.

Thus, according to the new Neutrino Program [77, 339, 354], the main objective is to ensure the leading position of JINR in neutrino physics and astrophysics both through the astrophysical researches at the unique BAIKAL–GVD neutrino telescope and the multifaceted (fundamental and applied) investigations with antineutrino beams at the Kalinin Nuclear Power Plant and through the decisive contribution of JINR scientists to the advanced international experiments (such as JUNO, EURECA [355], etc.) and creation of the advanced research infrastructure in Dubna.

3.3. JINR in Flavor Physics: Indirect Search for New Physics

The notion of the lepton number (discriminating charged leptons) arose [302, 356, 357] in fact from the negative result (1949–1950) of Pontecorvo and Hincks's pioneering works [358, 359] on the search for conversion of one charged lepton (muon) to another charged lepton (electron) without neutrino emission ($\mu \to e\gamma$).

Later, initiated by Pontecorvo, the first experiments were performed at JINR for determining probabilities of decays forbidden by the lepton number conservation law. At the ARES facility, a record limitation on the probability of the $\mu \to 3e$ decay was obtained [360]. In 1957, Pontecorvo came up with an idea of possible transitions of the muonium (an atom consisting of two leptons, $M \equiv \mu^+e^-$) to the antimuonium (μ^-e^+) [307]. In this process the lepton number changes by two ($\Delta L = 2$), and the transition $\mu^+e^- \to \mu^-e^+$ is completely forbidden in the Standard Model. In 1993, the upper limit for the probability of $M \to \bar{M}$ transition was set at the DLNP Phasotron [361, 362].

The tradition of searching for rare transitions between charged leptons with flavor conservation violation is maintained at JINR by participation in the corresponding ambitious international projects, such as the search for the $\mu \to e\gamma$ decay at a record accuracy level at the PSI (MEG project) [363, 364], measurement of the anomalous muon magnetic moment at Fermilab (Muon $g - 2$ project) [365], and the high-precision search for muon-to-electron conversion in

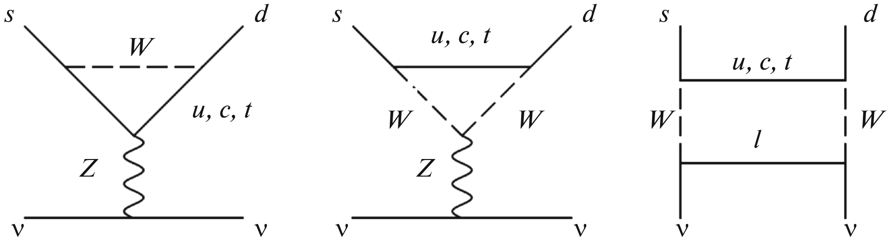


Fig. 39. Examples of diagrams contributing to the $K^+ \to \pi^+\nu\bar{\nu}$ decay in the Standard Model.

nuclear targets $\mu^- A \to e^- A$ (experiments Mu2e [366–368] and COMET [369–371] which are conceptually different).

Of particular interest is the possibility of searching in the Mu2e experiment for the muon-to-positron conversion $\mu^- A \to e^+ A$ [372–374], which is completely forbidden in the Standard Model because the lepton number is violated in it by two units ($\Delta L = 2$). In this sense, the $\mu^- \to e^+$ conversion is a direct (accelerator) analogue of neutrinoless double beta decay $0\nu\beta\beta$ and it is also sensitive to the absolute neutrino mass scale, though in a different combination $m_{\mu e} = \left|\sum_i^3 m_i V_{\mu i} V_{ei}\right|$ (cf. Fig. 35).

Hadron flavor physics studies were started at JINR by Pontecorvo with his searches for joint production of kaons and neutral hyperons at the LNP synchrocyclotron in 1951–1960 [375, 376]. As a result, the notion of strangeness appeared [377], and for a long time LNP scientists extensively studied properties of hadrons that possessed this quantum number. They took part in the experiments HYPERON (see for example [378–381]) and EXCHARM (see for example [382, 383]) at the Serpukhov accelerator [384]. Recently, they have concentrated on the E391a experiment (Japan) aimed at searching for very rare decays of neutral kaons (see for example [385–388]).

In the JINR Laboratory of High Energies, investigations of decay properties and characteristics of neutral K-mesons [389, 390] started in the 1960s. Now scientists of this laboratory noticeably contribute to the NA62 experiment on the study of a particularly important decay $K^+ \to \pi^+\nu\bar{\nu}$ (Fig. 39) at a new accuracy level (see for example [391–394]).

Apart from strangeness studies, JINR physicists participated in investigations of rare decays and conversions of charmed (containing c quarks) and beauty (containing b quarks) hadrons. For example, the lepton decay of the charmed meson $D^0 \to \mu^+\mu^-$ was searched for at CERN [395], polarization of the Λ and $\bar{\Lambda}$ hyperons was measured in the NOMAD experiment [396], transition rate in the system $B_s^0 - \bar{B}_s^0$ was determined in the CDF experiment [397], etc.

Thus, the main objective of JINR in indirect searches for new physics is to continue its traditional investigations in quark and lepton flavor physics by full participation in such world-class experiments as the study of rare CP-violating kaon decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$ [398] and the precision search for muon-to-electron (positron) conversion on nuclei $\mu^- A \to e^\pm A$.

3.4. NICA is the Future of JINR in Relativistic Heavy Ion Physics

The fundamental strategic goal of NICA (Nuclotron based Ion Collider Facility, Fig. 40) is to gain unique information on QCD (including the nonperturbative mode) through experimental investigations of hot and dense strongly interacting QCD matter and search for manifestations of the mixed phase and the critical point of the QCD phase diagram (Fig. 23) in collisions of heavy ions (see for example [399–402]).

The NICA energy range NICA ($\sqrt{s_{NN}} \simeq 5$ GeV) appears to be of particular interest, being considerably lower than the LHC energy but corresponding to the energy (Fig. 23) where the freezing-out density of baryons is expected to be at maximum. In this energy range, the system occupies the maximum space–time volume in the form of the mixed phase of quark–hadron matter (coexistence phase of hadrons and quarks–gluons). The NICA energy range opens access to analysis of highest-density baryon matter under laboratory conditions [182, 184, 403–406].

The NICA megaproject consists of two rather long stages. The first and main stage (2016–2023) is construction of the entire accelerator–detector complex, its commissioning, and subsequent upgrading of the collider and detectors for obtaining the design parameters. The further objective of JINR physicists will be to get, through multifaceted investigations, the fullest possible answers to all those important questions, which gave rise to the project. Entirely new information should eventually be obtained, which will allow a

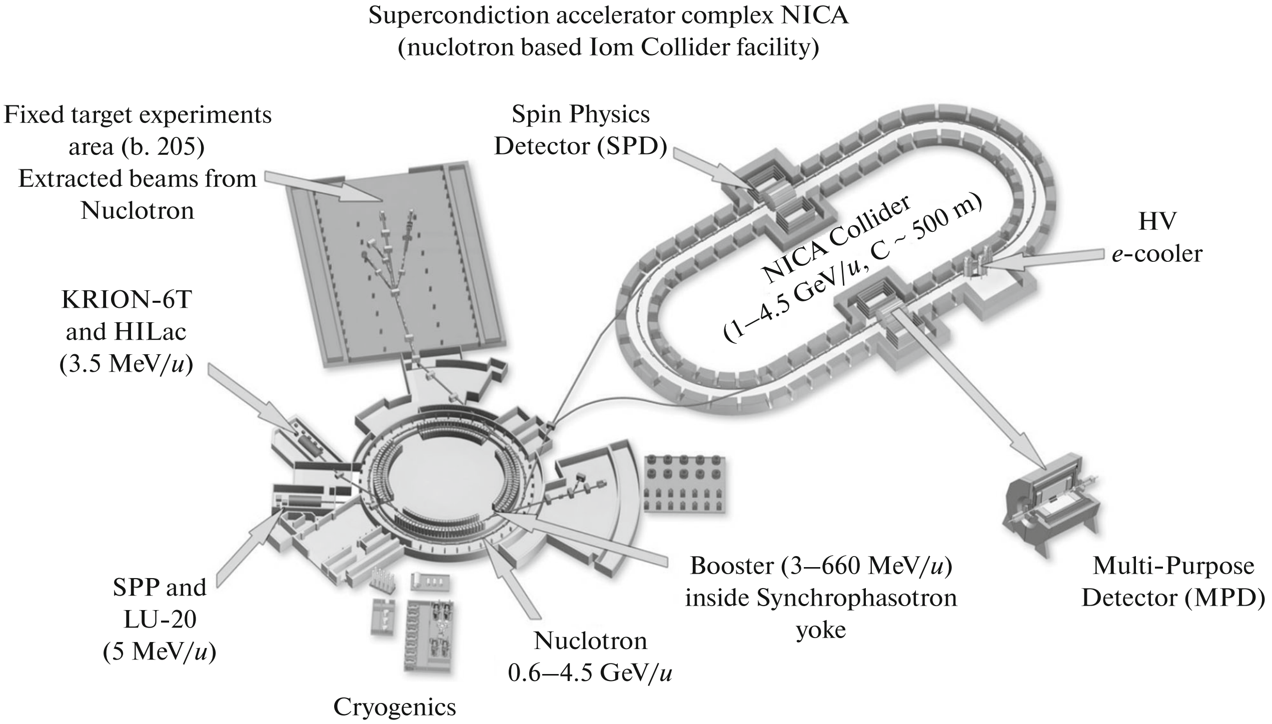


Fig. 40. Schematic view of the NICA fascility at LHEP, JINR.

better insight into the underlying fundamentals of QCD, the modern theory of strong interactions.

In the coming seven years, while NICA and the multipurpose detector (MPD) will be under construction, it is planned to commission the BM@N (Baryon matter at Nuclotron) facility at the Laboratory of High-Energy Physics (LHEP), JINR. This facility [407–410] is expected to yield new results in systematic investigations of dense baryon matter and will allow JINR scientists to gain invaluable experience in this field, which will undoubtedly be helpful at the second stage of the NICA project. It should be noted that LHEP physicists also acquire this kind of experience, participating in such relativistic heavy ion physics experiments as ALICE (see for example [411, 412]) at the LHC and STAR (see for example [413, 414]) at RHIC. In addition, JINR takes part in preparation of a new CBM (Compressed Baryonic Matter) experiment on the investigation of dense baryonic matter at the GSI accelerator complex (see for example [415–417]). The widely discussed program for spin physics studies at the NICA collider is also part of deep traditions at LHEP. This program provides for the development of a special detector, SPD, for these studies (see for example [418]).

3.5. JINR in Studies of Nucleon Structure and QCD Fundamentals

Research in this field began immediately after the commissioning of the LNP synchrocyclotron in 1949 and still goes on due their fundamental importance. It suffices to mention that experiments on elastic and inelastic nucleon–nucleon scattering at this accelerator in the first years of its operation proved the validity of the main strong-interaction symmetry principles, which are charge independence of nuclear forces and their isotopic invariance at high energies (see for example [419, 420]). In 1957, a phenomenon of quasi-elastic knockout of deuterons from nuclei was observed at the synchrocyclotron, which was interpreted by D.I. Blokhintsev based on the idea of fluctons, fluctuations of nuclear matter density, and later became typical of relativistic nuclear physics. It was registered as a discovery (see for example [8]). Investigations of charge-exchange scattering of π and K mesons on a nuclear target with production of an η meson revealed the phenomenon of color transparency of nuclei (see for example [421, 422]). The list of achievements in this field is quite long (see for example [9]); in addition, we only mention unique muon catalysis investigations [423].

Now the JINR “key players” in this field are participants in the COMPASS, BESS-III, and PANDA experiments and in the fundamental (ultracold) neutron physics research at the upgraded IBR-2M reactor of the Frank Laboratory of Neutron Physics (see for example [207, 424, 425]).

The physics program of the COMPASS experiment (at the SPS, CERN) includes investigation into the (nonperturbative) QCD structure of hadrons—generalized parton distribution functions, polarized

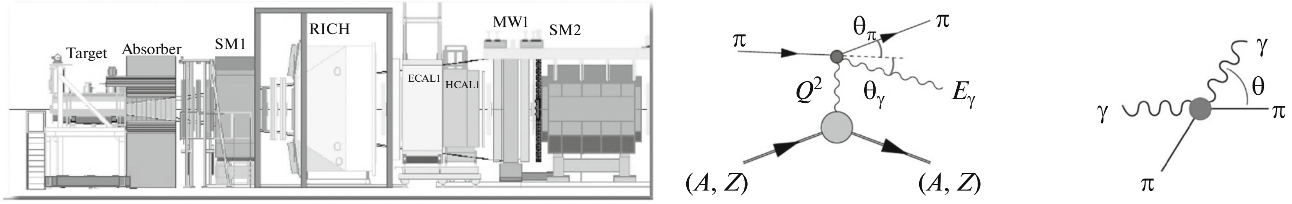


Fig. 41. Schematic view of the COMPASS detector (left) and Primakov effect diagrams allowing pion polarizability to be measured (right).

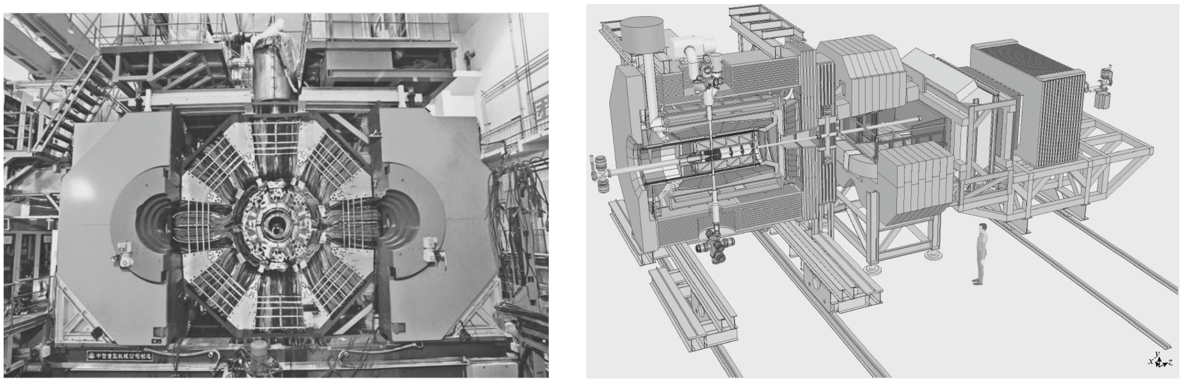


Fig. 42. BESS-III facility (left) and the schematic view of the PANDA facility (right).

structure functions, pion and kaon polarizabilities, hadron form factors, etc.—by systematically studying a wide range of inclusive and (semi)inclusive muon and hadron scattering from polarized hadron targets.

This program also includes analysis of Primakov reactions (Fig. 41) and diffraction processes and search for new bound quark and gluon states, including those containing heavy quarks (see for example [4, 28, 426, 427, 429, 430]). Many of these objectives were proposed by the JINR scientists.

The main goals of the BESS-III experiment (Fig. 42, left) at the BEPC-II electron–positron collider (Beijing) are accurate measurements in the region of tau-lepton pair and charmonium resonance production, search for exotic states (glueballs, hybrids, multiquark), etc. The fundamental goal of these investigations is the precision verification of the Standard Model and QCD predictions in lepton decays of charmed mesons (see for example [154, 431–433]).

Exotic states of nuclear matter and the nucleon structure are planned to be further studied in the PANDA experiment (Fig. 42, right) at the FAIR accelerator complex (see for example [434–436]). Preparations for these studies are well under way.

At the Frank Laboratory of Neutron Physics, a wide range [425, 437] of basic and applied research [204, 438, 439] is carried out with neutron beams of the IBR-2M pulsed reactor (Fig. 43), and development of a promising new-generation intense neutron source started [209, 440].

Thus, the JINR objectives in the field of perturbative and nonperturbative QCD are the full participation in the most promising international experiments aimed at studying the hadron, nuclear, and spin structure of hadrons (COMPASS, BESS-III, PANDA, etc.), continuation of basic research in neutron physics, including measurement of fundamental beta decay parameters of the neutron, its lifetime, and electric dipole moment, and verification of the equality of inertial and gravitational neutrino masses both at external sources of ultracold neutrons within international collaboration [441] and at the IBR-2M pulsed reactor.

3.6. QCD-Based Objectives of JINR in Nuclear Physics

It is universally acknowledged that the above-mentioned synthesis of superheavy elements with $Z = 113–118$ and filling-in of line 7 in the periodic table of elements [223, 224] would be impossible without the decisive contribution of scientists from the Flerov Laboratory of Nuclear Reactions (FLNR), JINR. Though no explicit relation between these outstanding results and fundamentals of nonperturbative QCD is seen yet, it undoubtedly exists, and one of the objectives important for future development of elementary particle physics is to reveal this relation. It

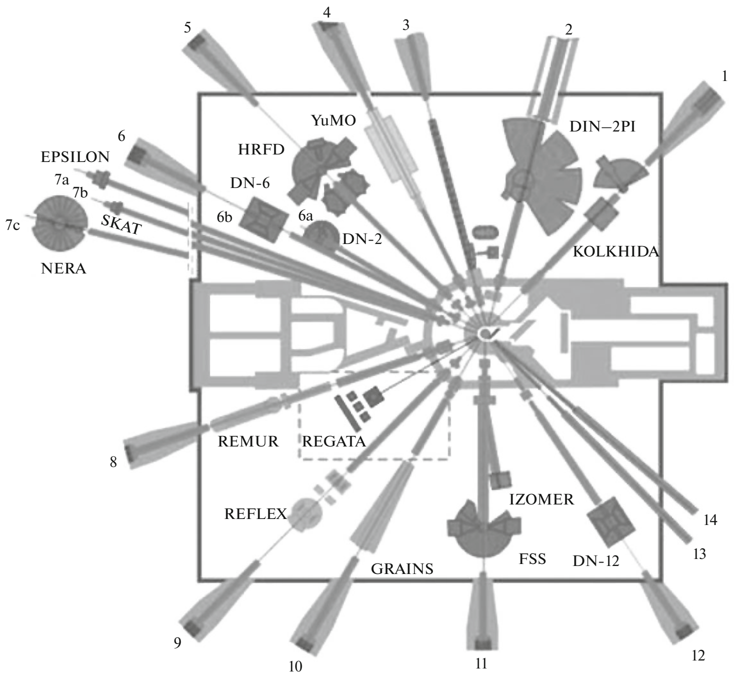


Fig. 43. Layout of spectrometers in the beamlines of the IBR-2M pulsed reactor. They are used for solving both fundamental and applied problems.

may well turn out that this information will be of decisive importance for solving the problem of confinement and will help explain how quarks are assembled into nucleons and the latter inevitably form atomic nuclei.

In this connection, in the coming seven years it is necessary to maintain and strengthen the leading position of JINR in the physics of superheavy elements by carrying out diverse research at the new JINR Superheavy Element Factory. This research should include synthesis and study of nuclear physics and chemical properties of isotopes of superheavy elements, investigation of the reaction mechanisms in stable and radioactive nuclei, searches for new modes of nuclear decays, etc. In addition, FLNR scientists are to bring studies of light exotic nuclei near the drip line to a new level using the Dubna radioactive-ion accelerator complex [442].

3.7. JINR Objectives in Condensed Matter Physics

Apart from elementary particle physics and nuclear physics, the third important direction of research at JINR is condensed matter physics [9, 11]. Its relation to the fundamental objectives of elementary particles is even more difficult to trace than for nuclear physics, and it is probably unnecessary. Therefore, just to round out the picture, only the main directions of research in this area are given below in accordance with the new seven-year JINR development plan [443].

At JINR, among strategic investigations are those in physics and chemistry of new functional materials, which include investigation of the structure and properties of these materials, under extreme conditions as well, investigation of fundamental regularities of transition processes in condensed matter, and computer simulation of physicochemical properties of new crystalline and nanostructured materials [444].

Another field is physics of nanosystems and nanoscale phenomena, where investigations are performed to study magnetic properties of layer nanostructures, the structure of carbon-containing and silicon-containing nanomaterials, and their molecular dynamics.

The physics and chemistry of complex liquids and polymers with an emphasis on the comprehensive study of magnetic colloidal systems and structural analysis of polymeric nanodispersion materials are also of great interest.

Another, no less important, area is considered to be molecular biology and pharmacology, which include investigations of the supramolecular structure and functional characteristics of biological materials, properties of lipid membranes and lipid complexes, interaction features of nanoparticles and their functional complexes with biological macromolecules, and the effect of structural and cluster stability of nanosystems on biological compatibility of complex solutions. One should also mention investigations of membrane proteins, cells, and organisms using spectral microscopic imaging.

Of more applied character is the materials science and engineering research focused mainly on investigations of the structure and properties of minerals, rocks, and structural materials and nondestructive testing of industrial products, structural materials, etc. for internal stresses.

Further progress in radiation physics and radioisotope research is now associated with thorough investigations of effects produced by heavy ions in materials (with a view to developing nanotechnological applications of accelerated ion beams), radiation hardness of materials (including tests of microelectronic circuits for space equipment), the development of a new-generation track membranes and nanoobjects with unique prescribed properties, the development of hybrid nanotechnologies, the production of radioisotopes for nuclear medicine and radio-ecological investigations with beams of γ rays, neutrons, α particles, and heavy ions [445, 446].

Setting up the experiments at new-generation accelerators (ILC, CLIC) requires development of completely new detectors capable of operating for a long time in a high rate environment and ensuring the desired detection accuracy and reliability. Development of these detectors is important not only for high-energy physics. The future of biology, materials science, geophysics, and medicine is now closely associated with investigations using sources of synchrotron light and X rays and other nuclear physics techniques. This will require high-resolution recording systems and image sensors [443].

It should be noted that these and many other (not mentioned here) investigations in the field of condensed matter form the basis for applied research and completely new developments, technologies, and materials, which in turn are intended to improve the quality of life and its safety.

4. CONCLUSIONS

In 60 years, JINR has come a successful way of research in elementary particle physics, nuclear physics, and condensed matter physics, relying on traditions of internationality, diversity, and fundamentality—a triune basis of stable development of fundamental science laid by the founding fathers of JINR.

In this review, an attempt is made to look into the future and show the role of JINR in fulfilling important objectives for development of the most fundamental area of modern natural science—elementary particle physics. Indeed, these main objectives, searching for new phenomena beyond the Standard Model and investigating the QCD nature of strong interactions, justify the name of the Joint Institute because through the common goal they actually unify all multifaceted investigations "under the same roof": all JINR laboratories make a worthy contribution to the fulfilment of the common objective.

Our intention was to review the experimental program. This glance at JINR from the "windows of the Laboratory of Nuclear Problems" is quite justified, on the one hand, since it is the diversity of LNP which our institute has stemmed from. On the other hand, famous investigations of the Dubna theorists, biophysicists, genetic scientists, radiobiologists, information technology specialists, and many others are undoubtedly worth noting. In the past 60 years, important results were obtained in these fields, which are still awaiting a description. We only wanted to underline the main thing, that is, the advances and prospects of JINR in the experimental area of modern elementary particle and nuclear physics.

Thus, JINR is a unique international organization carrying out investigations at the frontier of modern fundamental science. Its future is quite optimistic, since it has a good potential to make a decisive contribution in almost all important fields of research.

ACKNOWLEDGMENTS

Materials prepared by the JINR laboratories for the new seven-year program are used in the review. All details (scientific, financial, resource-related, infrastructural, etc.) can be found in the special booklet Seven-Year Plan for the Development of JINR for 2017–2023 [443].

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