

Nuclear reactions at JINR: from heavy-ion cyclotrons to the frontiers of superheavy and exotic nuclei

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Abstract

The seventieth anniversary of the Joint Institute for Nuclear Research provides a unique opportunity to trace the development of heavy-ion physics at the Flerov Laboratory of Nuclear Reactions (FLNR). This review outlines the major stages in the development of the FLNR experimental facilities, from the first U-300 and U-200 cyclotrons to the present-day U-400 and U-400M accelerators and the DC-280 cyclotron complex at the Superheavy Element Factory. Particular attention is paid to how the increase in beam intensities, the expansion of the range of accelerated ions, and advances in separation and detection systems have enabled studies of progressively rarer nuclear processes.

The review presents results on the synthesis and investigation of superheavy nuclei in “hot-fusion” reactions induced by ^{48}Ca , including the production of nuclei with atomic numbers up to $Z = 118$. Recent studies of new isotopes at the Superheavy Element Factory and prospects for further advances toward heavier nuclei are also discussed. Particular emphasis is placed on the prospects for using ^{50}Ti and ^{54}Cr beams in the synthesis of elements 119 and 120, studies of light exotic nuclei at ACCULINNA and ACCULINNA-2, and investigations of fusion, quasifission, and multinucleon-transfer processes. The development of applied research using heavy-ion beams is also highlighted.

1 Introduction

Over the past seven decades, nuclear and particle physics have undergone substantial changes not only in the range of scientific problems being addressed, but also in the organization of experimental research itself. The increase in beam energies and intensities, together with advances in accelerator technology, detector systems, and computational methods, has gradually led to the development of large specialized research facilities. The capabilities of modern experimental installations are determined not only by the maximum attainable energy, but also by the types of accelerated particles, beam luminosity, time structure and polarization, detector performance, and the ability to identify relatively rare processes against the background of large volumes of experimental data. The history of the Joint Institute for Nuclear Research (JINR) provides an opportunity to trace this evolution over nearly its entire course, from the accelerators of the 1950s to present-day research facilities.

The Joint Institute for Nuclear Research (JINR) was established on March 26, 1956, as an international intergovernmental research organization for fundamental studies in nuclear and high-energy physics [Fig. 1(a)]. The agreement establishing JINR was signed by eleven founding states: Albania, Bulgaria, Czechoslovakia, the German Democratic Republic, Hungary, Mongolia, the Democratic People's Republic of Korea, the People's Republic of China, Poland, Romania, and the USSR. Vietnam joined JINR later in 1956, while Cuba became a Member State in 1976. Following the political transformations of the early 1990s, the membership structure of JINR changed substantially, with several newly independent states joining the Institute. Egypt became a full Member State in 2019.

At present, JINR comprises 15 Member States: Armenia, Azerbaijan, Belarus, Bulgaria, Cuba, Egypt, Georgia, Kazakhstan, Mongolia, the Democratic People's Republic of Korea, Romania, Russia, Slovakia, Uzbekistan, and Vietnam. In addition, JINR maintains formal cooperation with Associate Members and partner countries, further extending the geographical scope of its international scientific activities.

At the time of its establishment, the Institute included the already operational 680-MeV proton synchrocyclotron [Fig. 1(b)] and the 10-GeV synchrophasotron then under construction [Fig. 1(c)]. The first laboratories were established at the same time, covering theoretical physics, nuclear problems, high-energy physics, and neutron physics. Shortly thereafter, the Laboratory of Nuclear Reactions was founded, with its scientific program developing under the leadership of G. N. Flerov. From that time onward, heavy-ion reaction studies became an independent and rapidly developing component of the JINR scientific program.

Research at the Flerov Laboratory of Nuclear Reactions (FLNR) has always been closely linked to advances in accelerator technology. The early facilities were successively complemented and replaced by the U-300, U-400, and U-400M cyclotrons, followed later by the construction of the DC-280 cyclotron. With each new accelerator, the range of available ion beams was expanded and their intensities increased, making it possible to investigate increasingly rare nuclear-reaction products. The next major step was the establishment of the Superheavy Element Factory, designed for the synthesis of new superheavy nuclei and for more detailed studies of their properties. The current status of this program and the capabilities of the new



Figure 1: Early activities of the Joint Institute for Nuclear Research. (a) Signing of the Agreement on the establishment of JINR on March 26, 1956. Buildings of (b) the synchrocyclotron and (c) the synchrophasotron, which formed the initial accelerator infrastructure of the Institute. *Photographs courtesy of the JINR Press Office.*

experimental infrastructure are discussed in Refs. [1–3].

One of the principal fundamental questions driving the development of this program concerns the limits of existence of atomic nuclei. As the number of protons increases, the Coulomb repulsion becomes stronger, opposing the formation of a stable bound system. At the same time, shell effects can substantially enhance the stability of certain heavy nuclei against spontaneous fission. These effects make possible the existence of superheavy nuclei in a region where a purely macroscopic description would no longer predict appreciable lifetimes. The predicted region of enhanced stability of superheavy nuclei has therefore provided one of the main motivations for the long-standing experimental search for new elements and their isotopes [2, 3].

A particularly important role in these studies has been played by complete-fusion reactions induced by ^{48}Ca beams on actinide targets. The relatively large neutron excess of ^{48}Ca , combined with its favorable structural properties, made it possible to form comparatively neutron-rich compound nuclei and to extend experimental studies substantially into the region of superheavy elements. One of the key results of this program was the observation, in the $^{249}\text{Cf} + ^{48}\text{Ca}$ reaction, of decay chains attributed to ^{294}Og [4]. Together with the results obtained in other ^{48}Ca -induced reactions, these experiments substantially expanded the known region of superheavy nuclei and provided new information on their lifetimes, decay modes, and the role of shell effects.

The present-day objectives, however, are no longer limited to the production of the next new element. As experimental statistics have improved, increasing emphasis has been placed on studies of the properties of superheavy nuclei, the search for new isotopes, and progress toward more neutron-rich species. At the same time, the development of the accelerator infrastructure has broadened the scope of applied research. The construction of the Superheavy Element Factory was motivated to a large extent by the need to increase the efficiency of such experiments. The DC-280 cyclotron was designed to provide substantially more intense heavy-ion beams, while the new DGFRS-2 gas-filled recoil separator provides more efficient separation of complete-fusion reaction products. The first experiments at the Factory demonstrated the capabilities of the new complex, in particular in studies of the $^{243}\text{Am} + ^{48}\text{Ca}$ reaction, in which ^{288}Mc nuclei were produced and the new isotope ^{264}Lr was identified [5].

The next major step is the search for elements with $Z > 118$. The experimental

situation in this region is considerably more challenging. The use of ^{48}Ca is limited by the availability of sufficiently heavy target nuclei, and the synthesis of elements 119 and 120 therefore requires a transition to heavier projectile ions. Among the most important candidates are ^{50}Ti and ^{54}Cr beams. At the same time, the expected production cross sections decrease, while the requirements on beam intensity, target stability, reaction-product separation efficiency, and the reliability of single-event detection become substantially more stringent [6]. Thus, further extension of the Periodic Table is no longer determined by a single performance parameter, but rather by the efficiency of the entire experimental chain.

Research at FLNR, however, is not limited to the region of superheavy elements. A second major direction concerns nuclei located far from the line of beta stability. In light neutron- and proton-rich systems, the effects of weak binding, unusual spatial nucleon distributions, cluster configurations, and exotic modes of radioactive decay become particularly pronounced. To investigate such systems, FLNR has developed methods for the production of radioactive beams and the separation of secondary nuclei; one of the modern instruments in this field is the ACCULINNA-2 fragment separator [7]. The study of nuclei near the limits of nucleon stability is of fundamental interest in its own right, since phenomena such as two-proton radioactivity and other exotic decay modes emerge in this region and are directly related to the structure of weakly bound nuclei [8].

The development of the Laboratory of Nuclear Reactions can be viewed in terms of three closely related directions: advances in heavy-ion accelerators, studies of heavy and superheavy nuclei, and investigations of light exotic nuclei near the limits of nucleon stability. These areas are united by a common experimental challenge: the production and study of nuclei formed with very low probabilities and often characterized by short lifetimes.

The present review focuses on the evolution of these experimental capabilities, from the first cyclotrons to the Superheavy Element Factory and modern facilities for exotic-nuclei research. Particular attention is given to the synthesis of superheavy elements, the role of ^{48}Ca -induced reactions, the search for elements 119 and 120, and the prospects for producing new neutron-rich nuclei.

The seventieth anniversary of JINR provides an appropriate occasion to assess both the progress achieved and the challenges ahead, including the extension of the Periodic Table, studies of the structure and decay of superheavy nuclei, and the development of reaction mechanisms capable of accessing still unexplored regions of the nuclear chart.

2 The FLNR accelerator complex

The history of the Flerov Laboratory of Nuclear Reactions closely parallels that of JINR itself. From the outset, heavy-ion reactions were recognized as a powerful tool for exploring nuclear properties. Compared with reactions induced by light charged particles, collisions between complex nuclei provide access to a much broader range of reaction mechanisms, including multinucleon transfer, fusion and fission, and the formation of highly excited and strongly deformed nuclear systems. They also make it possible to produce nuclei that do not occur naturally. These opportunities formed the basis of the heavy-ion research program at JINR.

On May 17, 1957, G. N. Flerov presented a program of heavy-ion research to

the JINR Scientific Council. The Laboratory of Nuclear Reactions was established three days later, on May 20, with Flerov as its director. He headed the Laboratory for more than three decades. The new laboratory grew out of earlier work on the acceleration of multiply charged ions and their interactions with nuclei. According to the review by Yu. Ts. Oganessian and B. I. Pustynnik, Flerov's group had already carried out the first experiments of this kind in 1956 at the cyclotron of the Institute of Atomic Energy in Moscow [9]. The establishment of the Laboratory in Dubna made it possible to develop these studies into a systematic experimental program.

This program required a dedicated accelerator capable of delivering intense heavy-ion beams over a broad mass range. The choice of projectile and beam energy strongly affects both the reaction mechanism and the products formed. Accelerator development was therefore closely tied to the scientific goals of the Laboratory, a connection that has remained characteristic of FLNR research ever since.

The first major accelerator built for the new laboratory was the three-meter U-300 cyclotron. The project was initiated by G. N. Flerov, and the main accelerator components were manufactured at the Elektrosila plant in Leningrad. The first nitrogen-ion beam was accelerated on September 9, 1960, reaching energies of about 10 MeV per nucleon. At that time, the U-300 offered high beam intensities and access to a broad range of heavy ions.

The U-300 considerably expanded the experimental program of the Laboratory. It allowed long experimental runs and systematic studies of reactions between complex nuclei. The accelerator was used for investigations of heavy-element synthesis, radioactive nuclei, and nuclear-reaction mechanisms. Many of the research directions that later became central to FLNR were established during this period [9, 10].

As the research program grew, so did the demands on the accelerator complex. Experiments required a wider range of ion species and energies, higher beam intensities, and more reliable operation over long periods. The U-300 could no longer meet all of these requirements. The next step was the U-200 isochronous cyclotron, commissioned in 1968. The U-300 and U-200 were later operated as complementary facilities, providing different beam conditions for heavy-ion experiments [10].

A major qualitative advance came with the commissioning of the U-400 cyclotron in 1978. The U-400 was a powerful isochronous cyclotron with an azimuthally varying magnetic field and was capable of accelerating a broad range of heavy ions. Compared with the previous generation of accelerators, its capabilities were better suited to the problems that had become central by that time: the synthesis of heavy nuclei, studies of fusion and fission processes, and investigations of nuclei far from the region of stability.

During the following decades, the U-400 underwent several upgrades. Of particular importance was its capability to deliver sufficiently intense ^{48}Ca beams at energies optimized for complete-fusion reactions with heavy actinide targets. In long-term experiments, beam intensities reached approximately 1 pμA at energies of about 5.3–5.7 MeV per nucleon [11]. A substantial fraction of the experiments that shaped the modern superheavy-element program were subsequently performed at the U-400.

The U-400 stage also clearly demonstrated a key feature of experiments aimed at the synthesis of new nuclei: reaching the required beam energy alone is not sufficient. When the reaction cross section is small, beam intensity and stability, the duration of continuous accelerator operation, target performance, and the efficiency of

reaction-product detection become decisive factors. Accelerator development therefore evolved not only toward a broader energy range, but also toward higher beam intensities and greater operational reliability.

By the beginning of the 1990s, another major accelerator, the U-400M, had been commissioned at FLNR. It entered operation in 1991 and was initially designed to accelerate heavy ions to energies of up to several tens of MeV per nucleon. This energy range was particularly suitable for studies of nuclear-reaction mechanisms and for the production of secondary radioactive beams. The capabilities of the facility were gradually expanded through the introduction of new ion sources and improved beam-injection and extraction systems [11].

The U-400M also played an important role in studies of light exotic nuclei. Stable beams provide access to only a limited part of the nuclear chart, whereas investigations near the proton and neutron drip lines require radioactive beams. Such beams are typically much less intense, and the nuclei of interest may have very short lifetimes. Their production, separation, and transport therefore require specialized experimental techniques.

This concept was further developed within the DRIBs (Dubna Radioactive Ion Beams) project. In one of the schemes, the U-400M beam was used to produce radioactive nuclei, which were then separated and injected into the U-400 for further acceleration. This approach made it possible, in particular, to obtain ${}^6\text{He}$ beams and to study reactions with them at energies near the Coulomb barrier [11, 12].

This line of research was further developed with the construction of the ACCULINNA and ACCULINNA-2 fragment separators. ACCULINNA-2 was commissioned at the U-400M in 2017 and was designed for experiments with secondary radioactive beams of light nuclei.

By the end of the 2000s, the capabilities of the U-400 no longer fully met the requirements of the developing superheavy-element program. Experiments with ${}^{48}\text{Ca}$ had demonstrated the effectiveness of the chosen synthesis approach, but further progress required a substantial increase in the number of detected events. This was necessary both for searches for new elements and for more detailed studies of known superheavy nuclei. Beam intensity had become one of the main limiting factors. In long-term experiments, the U-400 provided ${}^{48}\text{Ca}$ beam intensities of about $1\text{ p}\mu\text{A}$, while further upgrades could offer only a limited increase.

In 2009, FLNR therefore initiated the development of a new accelerator capable of delivering beam intensities of up to $10\text{ p}\mu\text{A}$ for ions with masses up to approximately $A = 50$. These requirements formed the basis of the DC-280 project [11, 13], shown schematically in Fig. 2. Development of the DC-280 began in 2010 and drew on the Laboratory's extensive experience in cyclotron technology, multiply charged ion sources, and beam injection, acceleration, and extraction systems. At the same time, the new accelerator represented a substantial step forward in performance. Its design beam intensities for medium-mass ions were expected to exceed those routinely achieved at the U-400 by approximately an order of magnitude [13].

The first ${}^{84}\text{Kr}^{14+}$ beam was accelerated by the DC-280 on December 26, 2018. In January 2019, the beam was extracted into the transport line, and the accelerator was commissioned in March of the same year [13]. In parallel, a new experimental building and dedicated systems for the separation and detection of reaction products were constructed. The result was not simply a new cyclotron, but a specialized research complex, the Superheavy Element Factory. The term "Factory" reflects

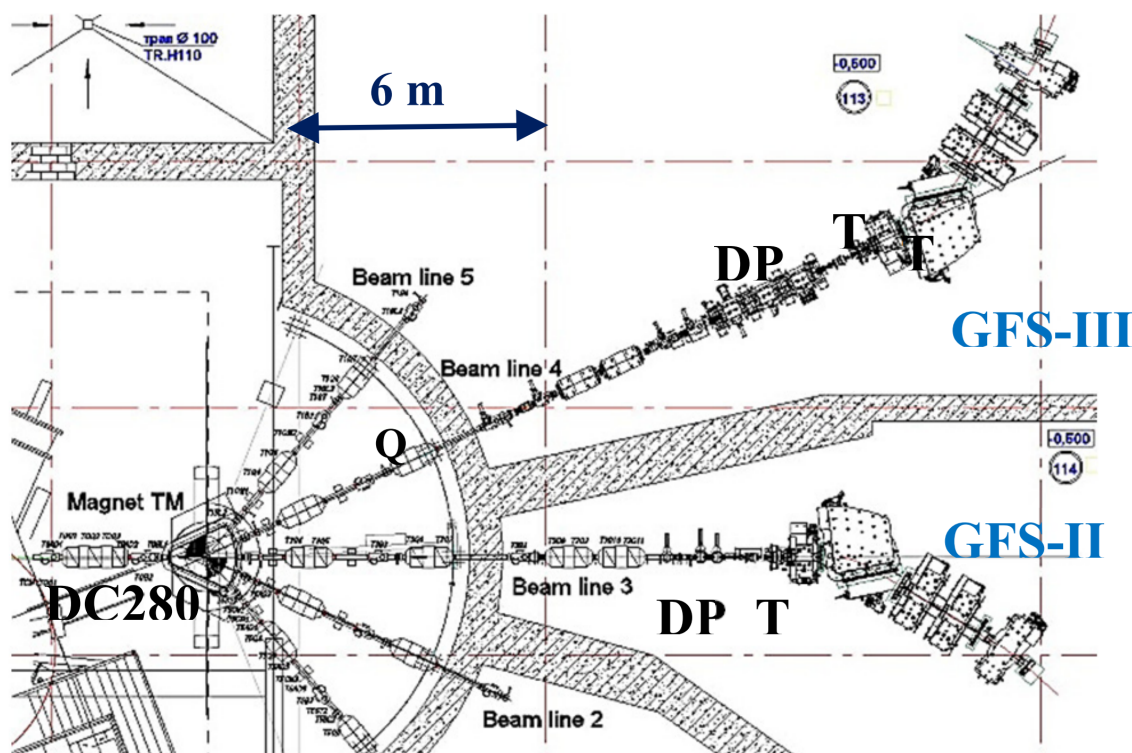


Figure 2: Layout of the beam lines at the FLNR JINR Superheavy Element Factory. Beams from the DC-280 cyclotron are transported to the gas-filled separators GFS-II and GFS-III through beam lines No. 3 and No. 4, respectively. Q denotes quadrupole lenses, DP the differential pumping system, and T the targets. Adapted from Ref. [14] under the CC BY 3.0 license.

the main concept of the project. Because superheavy nuclei are produced with extremely low yields, the observation of even a few atoms requires prolonged irradiation with high-intensity beams together with efficient suppression of background events. Increasing the beam intensity alone is therefore insufficient. Target systems, recoil separators, detectors, and data-acquisition systems must be improved accordingly. The DC-280 is thus the central component of the Factory, but its performance depends on the capabilities of the entire experimental setup.

The construction of the DC-280 did not replace the other FLNR accelerators. The present research program requires facilities with different beam characteristics. Studies of superheavy nuclei demand intense beams of relatively heavy ions at energies near the Coulomb barrier, whereas experiments with light exotic nuclei require a different energy range and the production of secondary radioactive beams. Applied studies impose additional requirements on ion species, beam energies, and operating modes. For this reason, the FLNR accelerator complex has evolved toward several specialized facilities.

A major upgrade of the U-400M was carried out in 2020–2024. The magnetic, vacuum, and control systems, as well as the beam-extraction system, were substantially modernized [15, 16]. In May 2024, beams of ^{16}O , ^{40}Ar , and ^{132}Xe were accelerated and transported after completion of the upgrade. The first physics experiments followed in the autumn of 2024 and included studies of correlations in reactions involving helium nuclei [17].

At the same time, the U-400 reconstruction program was launched as part of the U-400R project. The upgrade is intended to provide a wider and more smoothly adjustable range of heavy-ion energies and to establish a new experimental hall with modern beam-transport lines. This will extend the possibilities for studies of heavy-ion reaction mechanisms, including multinucleon-transfer reactions that may provide access to new neutron-rich heavy nuclei [18, 19]. As of 2026, work on the U-400R complex is ongoing [20].

FLNR has also developed dedicated accelerators for applied research. For many years, the IC-100 cyclotron was used for this purpose, including irradiation of polymer films and production of track membranes [21]. In 2020, construction of the new DC-140 accelerator complex began. The facility is intended to take over the applied-research program previously supported by the IC-100 and U-200 [22, 23]. The first accelerated krypton beam was obtained at the DC-140 on August 4, 2026 [23].

The evolution of the FLNR accelerator complex has closely followed the changing requirements of the research program. The production of new nuclei called for higher beam intensities and improved stability, while studies near the limits of nuclear stability required radioactive beams and efficient separation systems. Experiments with very low production cross sections, in turn, placed increasing demands on the overall efficiency of the experimental setup [11, 18, 24]. Accelerator development and research on heavy and superheavy nuclei have therefore progressed in close connection with one another.

3 Studies of superheavy and exotic nuclei

One of the main directions of FLNR research throughout its history has been the production and study of nuclei far from the region of stability. In this respect, the programs devoted to superheavy and light exotic nuclei address closely related questions, although they rely on very different experimental methods. Superheavy-nucleus studies explore systems with extremely large charge and mass, where nuclear stability is governed by the competition between Coulomb repulsion and shell effects. Light exotic nuclei are studied near the proton and neutron limits of stability, where weak binding, few-body correlations, and unusual modes of radioactive decay become especially important. In both cases, reactions induced by heavy or radioactive ions provide access to nuclei that do not occur naturally.

Some of the most prominent results obtained at FLNR are associated with the synthesis of superheavy nuclei. Major progress was achieved using ^{48}Ca beams and actinide targets. These reactions made it possible to produce a number of relatively neutron-rich isotopes of superheavy elements and to trace their successive α decays and spontaneous fission. One of the key experiments involved the $^{249}\text{Cf} + ^{48}\text{Ca}$ reaction, in which three decay chains were assigned to ^{294}Og [4]. This experiment was an important part of the program that extended the Periodic Table up to $Z = 118$.

The success of the ^{48}Ca program is not due solely to the relatively large neutron excess of this nucleus. In the synthesis of superheavy nuclei, the final yield is determined by several consecutive stages: capture, formation of a compound nucleus, and its subsequent survival against fission. In general, the evaporation-residue cross section can be written as [25]

$$\sigma_{\text{ER}}(E) = \sum_J \sigma_{\text{cap}}(E, J) P_{\text{CN}}(E, J) W_{\text{sur}}(E^*, J), \quad (1)$$

where σ_{cap} is the partial capture cross section, P_{CN} is the probability of compound-nucleus formation after capture, and W_{sur} is the probability that the excited compound nucleus survives against fission during deexcitation. A large capture cross section alone therefore does not guarantee a large yield of superheavy nuclei. The final yield is also strongly affected by competition with quasifission and by fission of the excited compound nucleus [26, 27]. The use of the doubly magic and relatively neutron-rich ^{48}Ca projectile together with actinide targets proved particularly favorable for both compound-nucleus formation and its subsequent survival against fission. Hot-fusion reactions induced by ^{48}Ca made it possible to produce elements with $Z = 114$ – 118 with cross sections in the picobarn range [2–4]. The magnitude of these cross sections is governed to a large extent by the survival probability of the excited compound nucleus, which is highly sensitive to shell effects. This dependence is illustrated by comparing the measured cross sections with the quantity $B_f - B_n$, where B_f is the fission-barrier height and B_n is the neutron separation energy, as shown in Fig. 3 [28].

New experiments with DGFRS-2 at the Superheavy Element Factory provided more detailed information on this systematics. In the $^{242}\text{Pu}(^{48}\text{Ca}, 3n)^{287}\text{Fl}$ reaction, the maximum cross section was measured to be $10.4^{+3.5}_{-2.1}$ pb [29, 30]. For the $^{243}\text{Am}(^{48}\text{Ca}, 3n)^{288}\text{Mc}$ reaction, the corresponding value was $17.1^{+6.3}_{-4.7}$ pb [5]. These results show that production cross sections of superheavy isotopes in the region $Z = 114$ – 115 can reach about 10–20 pb. The high beam intensity of the DC-280, together with the new gas-filled separators, has made it possible to study excitation functions and reaction products from ^{48}Ca -induced reactions in much greater detail (Fig. 2). The relatively large cross sections observed in this region are related, in part, to the enhanced survival probability of the compound nuclei due to shell effects. With increasing Z , the evaporation-residue cross sections decrease, and for $Z = 118$ the maximum measured values are already only a few picobarns [28].

The Superheavy Element Factory has also made it possible to study superheavy nuclei with much better statistics. In the first experiment with the DC-280 and DGFRS-2, using the $^{243}\text{Am} + ^{48}\text{Ca}$ reaction, 55 decay chains of ^{288}Mc and six chains assigned to ^{289}Mc were observed. The same experiment also provided the first observation of the α decay of ^{268}Db and led to the identification of the new isotope ^{264}Lr [5]. Later experiments showed that the new facility can also be used effectively to search for previously unknown isotopes. In 2024, the isotope ^{275}Ds was synthesized for the first time in the $^{232}\text{Th}(^{48}\text{Ca}, 5n)^{275}\text{Ds}$ reaction and identified from correlated α -decay chains [31]. The present FLNR program therefore includes not only the search for new elements, but also systematic studies of superheavy isotopes, their lifetimes, and their decay modes.

Studies of heavy nuclei at FLNR also include detailed spectroscopy of transfermium isotopes produced in complete-fusion reactions. Experiments at the SHELS separator have been used to study the decay properties of Rf and No isotopes. In particular, the neutron-deficient isotope ^{249}No was produced for the first time in the $^{204}\text{Pb}(^{48}\text{Ca}, 3n)^{249}\text{No}$ reaction, and its decay properties were studied with the GABRIELA detection system [32].

At such small reaction cross sections, the result of an experiment depends on the

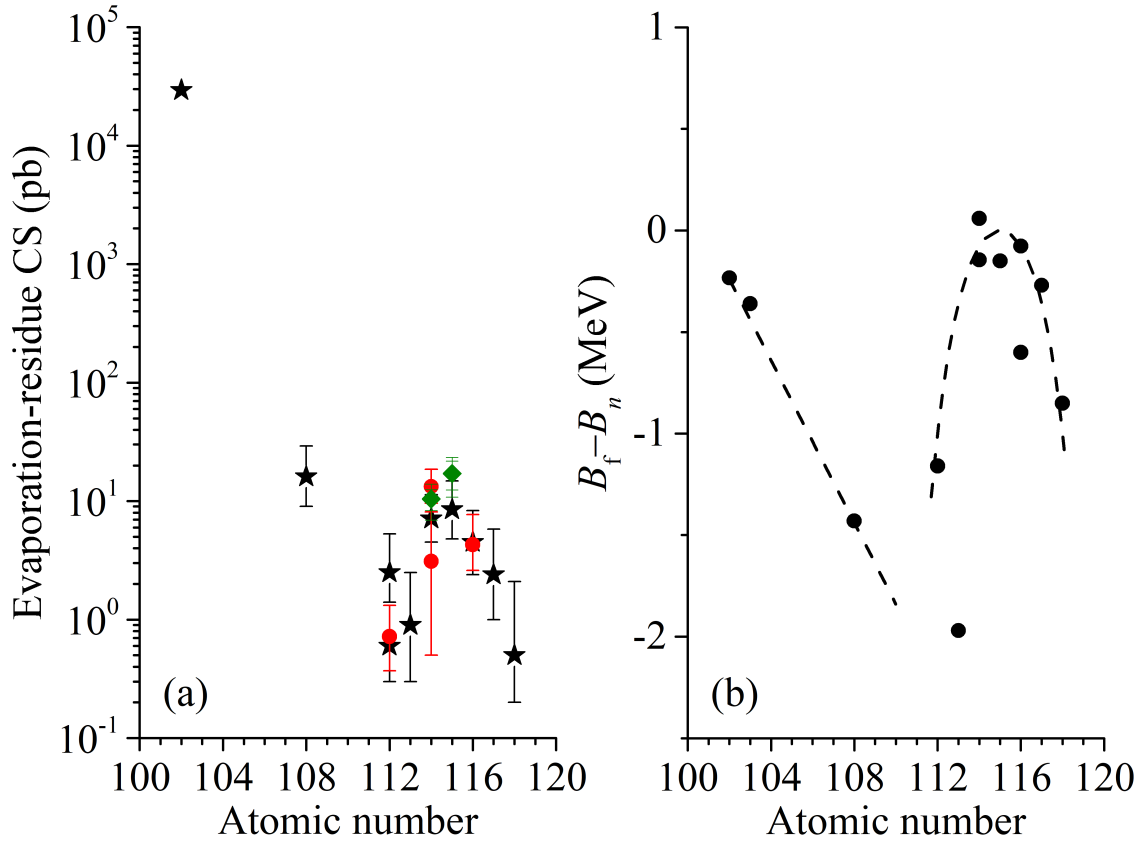


Figure 3: (a) Maximum production cross sections for heavy and superheavy nuclei in ^{48}Ca -induced reactions. Stars show the experimental data obtained with DGFRS, red circles show the SHIP, BGS, and TASCA results from Ref. [28], and green diamonds show the results obtained with DGFRS-2 at the Superheavy Element Factory [5,30]. (b) Difference between the fission-barrier height B_f and the neutron separation energy B_n for the corresponding compound nuclei. Dashed lines are shown as guides to the eye.

performance of the entire setup, including beam intensity, target stability, separation efficiency, and reliable detection of decay chains. At the Superheavy Element Factory, reaction products formed in the target by the DC-280 beam are separated from the primary beam and other reaction products by the DGFRS-2 gas-filled separator. They are then implanted into a detector at the focal plane. New nuclei are identified from spatial, time, and energy correlations between the implanted recoil nucleus and its subsequent α decays or spontaneous fission. Compared with the previous DGFRS-1 separator, the transmission efficiency of DGFRS-2 was increased by about a factor of two, while the background level was reduced by about a factor of 200 [33]. The combination of high beam intensity and strong background suppression made systematic studies of reactions with subpicobarn cross sections possible.

The transition from ^{48}Ca to heavier projectiles is one of the main challenges of the current superheavy-element program. A direct comparison was performed at the Superheavy Element Factory using the $^{242}\text{Pu} + ^{50}\text{Ti}$ and $^{238}\text{U} + ^{54}\text{Cr}$ reactions, which form the same compound nucleus, ^{292}Lv . For the ^{50}Ti -induced reaction

at $E^* \approx 41$ MeV, the measured cross sections for the $3n$ and $4n$ channels were about 0.32 and 0.22 pb, respectively. For the ^{54}Cr -induced reaction at a similar excitation energy, the $4n$ -channel cross section was about 32 fb. The total yield in the ^{50}Ti reaction was therefore about 15 times higher. This result supports the use of ^{50}Ti rather than ^{54}Cr as a promising projectile for searches for elements 119 and 120 [34, 35]. The new isotopes ^{288}Lv , ^{289}Lv , and ^{280}Cn were also identified in these experiments.

The situation, however, is more complicated than a simple comparison of the maximum cross sections. In the 2026 experiment, the excitation energy of the $^{242}\text{Pu} + ^{50}\text{Ti}$ system was reduced by 5 MeV. The total fusion-evaporation cross section then decreased by about an order of magnitude, from approximately 540 to 54 fb. This behavior differed from several calculations that predicted the maximum of the $3n$ channel at lower excitation energies [36]. Thus, even for a promising beam-target combination, the position and shape of the excitation function remain an important source of uncertainty when planning experiments aimed at the synthesis of elements with $Z > 118$.

Another major area of research at FLNR is the study of light exotic nuclei. Nuclei close to, or beyond, the limits of nucleon stability are characterized by low binding energies, strong coupling to the continuum, and pronounced few-body correlations. Radioactive beams produced with the ACCULINNA and ACCULINNA-2 separators have been used to study a number of such systems. One example is the study of low-lying states in ^{10}He . In the $^3\text{H}(^8\text{He}, p)^{10}\text{He}$ reaction, the ground state was observed about 2.1 MeV above the $^8\text{He} + n + n$ decay threshold. Analysis of the decay correlations also indicated an unusual ordering of the low-lying states and a continuation of the $N = 8$ shell breaking in ^{10}He [37].

The extremely neutron-rich ^7H system, which decays into $^3\text{H} + 4n$, is of particular interest. Experiments at ACCULINNA-2 with a radioactive ^8He beam provided information on the ^7H spectrum. In 2020, evidence for the ground state was obtained together with the first information on an excited state [38]. A later analysis provided a more detailed description of the observed spectrum and the possible resonant states of ^7H [39]. These studies are important not only for the spectroscopy of very neutron-rich nuclei, but also for understanding correlated multineutron decay.

As a continuation of this program, a search for a low-energy four-neutron continuum was carried out in 2025 using reactions of ^8He on deuterium. An enhancement of the yield was observed at energies around 3–4 MeV [40]. Its interpretation is still not clear, and further studies are needed before this structure can be associated with a bound tetra-neutron or a specific tetra-neutron resonance.

Another aspect of studies near the limits of stability is related to unusual few-body decay modes. In true two-proton radioactivity, the decay is a three-body process with a daughter nucleus and two protons in the final state. Measuring only the decay energy is therefore not sufficient. Energy and angular correlations between all three decay products contain important additional information. A three-body approach to this problem was developed by L. V. Grigorenko and coauthors, making it possible to calculate these correlations at large distances and compare them directly with experiment [8, 41]. These studies showed that the correlations between the decay products provide information on both the dynamics of the three-body system and the structure of the initial state.

Studies of heavy and exotic nuclei are also closely connected with the mech-

anisms of heavy-ion reactions. Even at similar collision energies, several processes may compete, including complete fusion, quasifission, compound-nucleus fission, and multinucleon transfer. The balance between these channels has a strong influence on the probability of forming a given nucleus. This is especially important in the synthesis of superheavy elements, where quasifission can strongly reduce the probability of compound-nucleus formation. Experimental studies at FLNR have shown that the relative contributions of fusion-fission and quasifission depend strongly on the entrance channel, excitation energy, and properties of the interacting nuclei [26,42,43]. More recent analyses have extended these studies to the systematics of formation cross sections for heavy and superheavy nuclei [27,44].

Multinucleon transfer reactions provide another possible way to produce new nuclei. In this case, the two nuclei separate after contact, exchanging several protons and neutrons. Early calculations showed that low-energy multinucleon transfer reactions may provide access to neutron-rich heavy nuclei that are difficult to reach in complete-fusion reactions [18]. This idea was further developed using dynamical models based on Langevin equations. Calculations by V. V. Saiko and A. V. Karpov studied the role of nuclear deformation and entrance-channel orientation and examined the production of neutron-rich transuranium nuclei [45,46]. More recent calculations extended these studies to neutron-rich nuclei near the closed neutron shell $N = 126$ using radioactive-ion beams [47]. This possibility is also being studied experimentally. A detailed investigation of the $^{136}\text{Xe} + ^{238}\text{U}$ reaction, published by FLNR researchers in 2024, examined the mass and energy distributions of transfer products and the formation of heavy nuclei [48].

A series of experiments at the U-400 cyclotron was devoted to nucleon- and cluster-transfer reactions [49–52]. The $^{18}\text{O} + ^{181}\text{Ta}$, $^{48}\text{Ca} + ^{197}\text{Au}$, and $^6\text{Li} + ^9\text{Be}$ reactions were used to study neutron transfer and the production of neutron-rich nuclei. These measurements provided new information on direct-reaction mechanisms and showed that multinucleon and cluster transfer can be useful for producing nuclei far from the line of stability.

4 Applications of heavy-ion beams

Alongside fundamental nuclear physics, FLNR also has a broad program of applied research. It includes radiation materials science, nanotechnology, surface modification, and track-membrane technologies. Much of this work is based on studies of the interaction of heavy ions with matter. The high density of electronic excitations along the ion path can produce local radiation damage and latent tracks [53]. This makes it possible both to study the radiation resistance of materials and to use ion irradiation to modify their structure and properties. Such experiments have been carried out at the U-400, U-400M, and IC-100 cyclotrons.

Radiation materials science is one of the main applied directions. At the U-400 and IC-100, the radiation stability of oxide-dispersion-strengthened (ODS) alloys was studied under irradiation with swift Xe and Bi ions. Electron microscopy showed that high electronic energy losses can lead to amorphization of oxide and carbide nanoparticles, with their stability depending strongly on composition and particle size [54]. These results are important for materials intended for use under intense irradiation. Related experiments studied the radiation resistance of nanostructured zirconium nitride (ZrN) coatings irradiated with Xe, Kr, and Bi

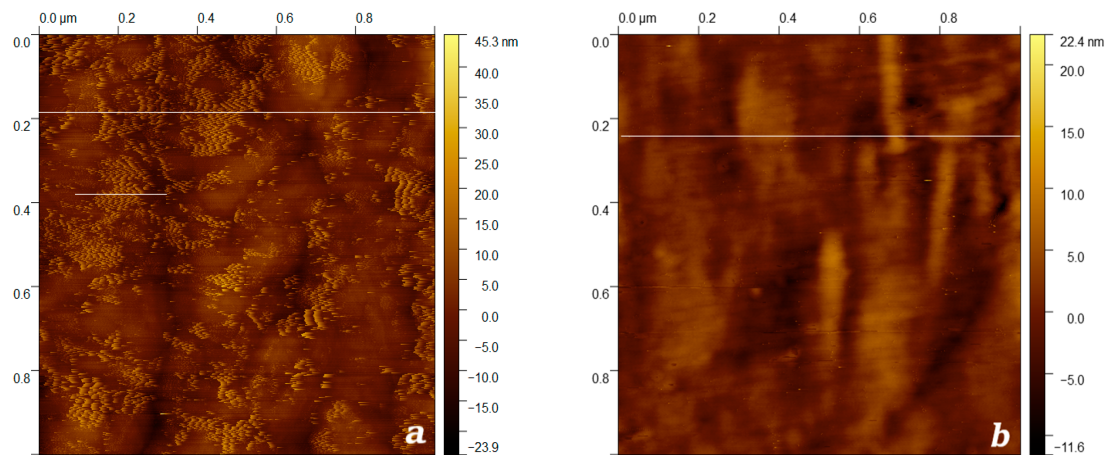


Figure 4: AFM images of the surface of thermoradiation-modified PTFE (a) before and (b) after irradiation with accelerated ^{132}Xe ions at the IC-100 cyclotron. Reproduced from Ref. [66] under the CC BY 4.0 license.

ions. Such measurements were also used to simulate the effects of fission fragments on materials [55]. These studies were later extended to a wider range of ceramic and functional materials. The formation and evolution of swift-heavy-ion tracks in dielectric materials have also been investigated using combined numerical and experimental approaches [56]. At the U-400, ion-track formation and its dependence on material composition were investigated [57]. In crystalline materials, the formation of latent tracks was studied as a function of stopping power and temperature [58]. More recent experiments with ZnO showed that irradiation with swift Bi ions can significantly affect thermal transport through the formation of radiation-induced defects [59].

Another area of research is the modification of materials with swift heavy ions. The interaction of energetic ions with thin films can produce different types of nanoscale surface modification, depending on the film thickness and irradiation conditions [60]. At the U-400, titanium was irradiated with Kr and Xe ions, producing changes in the structure and properties of the surface layer [61]. In silicon, irradiation with Kr and Bi ions was used to study changes in boron diffusion and electrical activation caused by radiation defects [62].

When heavy ions pass through a polymer, they produce latent tracks that can later be converted into pores of controlled size by chemical etching. At the U-400, different methods for forming and modifying pores in PET membranes were studied [63–65]. Similar studies were later continued at the IC-100 with other polymer materials, as illustrated in Fig. 4 [66].

FLNR accelerators are also used for radiobiological studies. At the U-400M, DNA damage caused by heavy-ion irradiation of cells was investigated. These studies showed that both the complexity of the damage and the efficiency of its repair depend not only on the linear energy transfer, but also on the structure of the ion track [67].

A further step in the applied-research program is the new DC-140 accelerator complex. The facility is intended to provide dedicated heavy-ion beams for materials science and technological applications, replacing the IC-100 and U-200 in this part of the FLNR program [22, 23]. The first accelerated krypton beam was obtained at

Table 1: Examples of international organizations and institutions with which JINR has concluded memoranda of understanding.

Organization or institution	Year
Government of the Republic of South Africa / Department of Science and Technology	2005
Arab Atomic Energy Agency (AAEA)	2016
China Institute of Atomic Energy (CIAE)	2018
Ministry of Science, Technology and Innovation of Brazil (MCTI)	2025
Federal University of Rio Grande do Sul (UFRGS), Brazil	2025
Institute of Plasma Physics, Chinese Academy of Sciences	2025
Latin American Centre for Physics (CLAF)	2026

the DC-140 in August 2026 [23].

Together with the upgraded U-400M, the DC-140 will broaden the range of irradiation conditions available for applied studies. The FLNR applied program therefore remains closely connected with the development of its accelerator facilities, with current work focused on radiation effects in materials, ion-beam modification, track-membrane technologies, and radiobiology.

5 International collaboration and future directions

The main research directions at FLNR are closely connected through the common goal of studying nuclei far from stability. This includes the synthesis of superheavy elements, studies of light exotic nuclei, and investigations of heavy-ion reaction mechanisms. Together, these areas define much of the present scientific program of the Laboratory.

The international status of JINR is reflected not only in its membership structure but also in a broad network of formal agreements with governmental, scientific, and educational organizations. These agreements provide an institutional framework for joint experiments, exchange of researchers, development of research infrastructure, and education and training programs. Examples of organizations and institutions with which JINR has concluded memoranda of understanding are summarized in Table 1.

A significant part of this work has been carried out in international collaboration. One of the best-known examples is the long-standing cooperation between JINR and Lawrence Livermore National Laboratory in experiments on the synthesis of superheavy elements [4]. Cooperation with Oak Ridge National Laboratory has also been important, particularly for the preparation of rare actinide target materials [6]. This international character is also seen in recent experiments at the Superheavy Element Factory. The studies with ^{50}Ti and ^{54}Cr beams involved researchers from JINR together with colleagues from Kazakhstan, the Czech Republic, and China [34]. Recent work at the GRAND separator, including studies of the new isotope ^{227}Pu , has also been carried out with researchers from Kazakhstan and China [68].

The next stage of the superheavy-element program is connected mainly with attempts to reach nuclei beyond $Z = 118$. Recent experiments with ^{50}Ti and ^{54}Cr

beams provide important information for choosing reactions for future searches for elements 119 and 120 [34,36]. At the same time, experiments with known superheavy nuclei will continue, with the aim of producing new isotopes and obtaining more detailed information on their decay properties.

Another important direction is the production of neutron-rich nuclei. Multinucleon transfer reactions provide a possible way to reach heavy neutron-rich isotopes that are difficult to produce in complete-fusion reactions [18,19]. This approach has been further developed in theoretical studies of transfer dynamics and the production of neutron-rich transuranium nuclei [45,46]. More recent calculations have also considered the production of neutron-rich nuclei near the closed neutron shell $N = 126$ using radioactive-ion beams [47]. Experimental studies have also been carried out in international collaboration. In particular, products of the $^{48}\text{Ca} + ^{248}\text{Cm}$ multinucleon transfer reaction were studied with the SHIP separator at GSI [69]. The reconstruction of the U-400 within the U-400R project, together with the development of new separation systems, is expected to extend the possibilities for such experiments [20].

Also, the upgraded U-400M and further development of ACCULINNA-2 provide new opportunities for experiments with light exotic nuclei near and beyond the neutron drip line [7,15,16]. The ACCULINNA-2 experimental program is carried out in close international collaboration, with participation of researchers from JINR and partner institutes in Europe and Asia [70]. This cooperation supports experiments with radioactive beams and the development of new experimental methods. These studies will continue to address weakly bound systems, few-body correlations, and unusual decay modes.

The future FLNR program therefore combines several complementary directions: searches for new superheavy elements, studies of known superheavy isotopes, production of neutron-rich nuclei, and experiments with light exotic systems. Progress in these areas will depend on further development of the accelerator complex and continued international collaboration.

Conclusion

Over the past seven decades, the Flerov Laboratory of Nuclear Reactions has developed from the first heavy-ion experiments into a modern accelerator complex for studies of nuclei at the limits of stability. This development illustrates the close connection between advances in accelerator technology and progress in nuclear-reaction studies. The transition from the first cyclotrons to the U-400 and U-400M, and subsequently to the DC-280 and the Superheavy Element Factory, provided progressively higher beam intensities and more efficient separation and detection systems, making it possible to investigate nuclear processes with increasingly small production cross sections.

One of the major outcomes of this development has been the synthesis and investigation of superheavy nuclei in ^{48}Ca -induced reactions. The present experimental program is now entering a new stage, in which the emphasis is shifting from the successful ^{48}Ca -based approach toward reactions with heavier projectiles, particularly ^{50}Ti and ^{54}Cr . Recent experiments demonstrate both the potential and the experimental difficulty of this transition. Further progress toward elements 119 and 120 will depend not only on beam intensity, but on the combined performance of

the accelerator, target systems, recoil separators, and detection methods.

At the same time, the scientific program of FLNR extends beyond the synthesis of superheavy elements. Experiments with radioactive beams at ACCULINNA and ACCULINNA-2, together with studies of multinucleon-transfer reactions, provide complementary approaches to neutron-rich and weakly bound nuclei that cannot be efficiently accessed through complete-fusion reactions. The development of the accelerator facilities has also expanded the applied-research program in radiation materials science, ion-track studies, membrane technologies, and radiobiology.

The future program therefore combines several complementary routes toward unexplored regions of the nuclear chart: searches for elements beyond $Z = 118$, detailed studies of known superheavy isotopes, production of neutron-rich nuclei in transfer reactions, and investigations of light exotic systems near the limits of nucleon stability. Together with the continuing development of the FLNR accelerator complex and international collaboration, these directions provide the basis for the next stage of heavy-ion research at JINR.

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