**APPROVED**

**JINR Vice-Director**

**/**

**" " \_\_\_ 2023**

**SCIENTIFIC AND TECHNICAL REASONING FOR THE**

**RENEWAL OF THEME**

**IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH**

**1. General information on the theme**

**1.1. Theme code** 03-5-1130-2017

**1.2. Flerov Laboratory of Nuclear Reactions**

**1.3. Scientific field:** Physics of heavy ions

**1.4.** **The name of the Theme:** Synthesis and Properties of Superheavy Elements, the Structure of Nuclei at the Limits of Nucleon Stability

**1.5. Theme Leader:** S.I. Sidorchuk

**Theme Scientific Leader:** Yu.Ts. Oganessian

**1.6. Theme Deputy Leader:** A.V. Karpov

**2. Scientific rationale and organisational structure**

**2.1. Annotation**

The main directions of JINR scientific research in the field of modern nuclear physics concerns heaviest nuclei and atoms as well as light nuclei far from the line of -stability. In the field of heaviest nuclei we will focus on the synthesis of new elements of the Periodic Table and their isotopes, the study of decay properties by nuclear spectroscopy methods (α-, β-, γ-spectroscopy), as well as their chemical properties, the study of the mechanisms of various nuclear reactions leading to the formation of new, yet unknown nuclei. Scientific program also includes the study of structure of the lightest nuclei at the borders of nucleon stability and mechanisms of their production.

**2.2. Projects in the Theme**

* **Investigation of heavy and superheavy elements**
* **Structure of the lightest nuclei at the borders of nucleon stability**

**2.3. Scientific justification**

# The main direction of scientific research of the Flerov Laboratory of Nuclear Reactions (FLNR) of JINR is the synthesis of new elements of the Mendeleev's Periodic table, the study of their properties, via nuclear spectroscopy (α-, β-, γ-spectroscopy) and via chemical analysis.

The pursuit of this research will be also the main part of FLNR’s program for the next decade: Looking for the limits of the existence of nuclear matter by focusing on the boundaries of the island of stability of superheavy elements (SHE). For that endeavour, a SHE-Factory based on the DC-280 heavy-ion cyclotron will be used. Substantial increase (dozen times higher) in the efficiency of experiments is needed for the synthesis of the heaviest elements 119 and 120 and for the study of nuclear and chemical properties of already known elements. On the detection side, the new Gas-filled recoil separators (DGFRS-II and GRAND) and other future set-ups installed at the SHE Factory will play an important role.

Multinucleon transfer reactions in near-barrier collisions of heavy ions are promising in synthesizing new neutron-rich isotopes of heavy and superheavy elements. In particular, these reactions can lead to the formation of yet-unknown neutron-rich superheavy nuclei up to the beta-stability line, inaccessible via fusion reaction. The direct use of multinucleon transfer for the purpose of synthesis of new nuclei is significantly restricted by experimental difficulties of detecting products of these reactions and extremely limited information of the reaction mechanism. Thus, among our purposes is studying the reactions them self.

Another ambitious scientific goal is measuring the masses of SHE and this laboratory is planning for a special mass detection system, consisting right after the target of a pre-separator, followed by a cryogenic gas ion catcher and a multireflection time-of-flight mass-spectrometer.

Radioactive ion beam (RIB) facilities allow the study of exotic nuclear systems remote from the β-stability line. At low energies, the FLNR is pursuing an experimental program on relatively light exotic nuclear systems at the fragment-separator ACCULINNA-2 was put into operation. ACCULINNA-2 is a fragment-separator, installed at the U400M cyclotron to produce in the “in-flight” mode secondary beams of radioactive exotic nuclei. This allows studies of nuclear haloes, neutron skins, cluster states, of exotic multi-neutron decays, two- proton radioactivity, search for new magic numbers and spectroscopy of exotic nuclei.

The theme comprise of two projects: “Investigation of heavy and superheavy elements” and “Light exotic nuclei at the borders of nuclear stability”.

# Project “Investigation of heavy and superheavy elements” will include the following directions of research:

# Synthesis of new elements

Among the above-mentioned research directions, synthesis of new elements 119 and 120 is a task of the highest importance and will certainly become the SHE Factory's top priority. The 249Bk+50Ti→299119\*, 249-251Cf+50Ti→299-301120\*, and 248Cm+54Cr→302120\* reactions are most promising for the synthesis of elements 119 and 120. According to theoretical predictions, the expected cross-sections are of several dozens of femtobarns.

**Synthesis of new isotopes of already known SHE**

The expansion of the region of known nuclei towards both neutron excess and neutron deficiency is extremely promising and crucial to understanding the properties of superheavy nuclei located near the island of stability. An interesting region of the nuclei map is located among isotopes synthesized in "cold" and "hot" fusion reaction. This part of the nuclear map can be filled through fusion reactions with 48Ca beam and more neutron-deficient targets than those that have already been used (233*,*235U, 241Am and others). Expected cross-sections are sufficient for an experimental study.

Systematic experimental studies of nuclei in this region are certain to contribute substantially to our knowledge of their properties and to improve accuracy of further predictions.

Expansion into the region of neutron-rich isotopes of SHE towards the island of stability is of great importance. Studying systems with higher neutron excess can be achieved through:

1. Use of more neutron-rich targets

The shift of 1-2 neutrons to the right is still possible in fusion reactions with the use of more neutron-rich targets (for example, 251Cf).

1. 2n channel of fusion-fission reactions

Another way for possible shifting of 1 neutron to the right is the synthesis of superheavy nuclei in projectile-target combinations employed earlier, but focussing onto the 2n evaporation channel instead. Expected several-fold reduction in the cross-section (compared to the one in the 3n-4n channel), should be however still within the capacities of the experimental infrastructure.

1. Alternative methods

The possibility of producing neutron-rich superheavy nuclei will be considered based on predicted (but not yet observed) electron capture in the vicinity of the island of stability as well as based on the registration of evaporation residues produced during the emission of a proton and several neutrons. Thus, during the irradiation of actinide targets 244Pu and 248Cm with 48Ca in p1n- p3n channels, neutron-enriched isotopes of moscovium and nihonium can be produced.

Such experiments will allow the determination of the boundaries of the island of stability. These experiments will also demand a substantial increase in the experiment sensitivity.

1. Multinucleon transfer reactions

Multinucleon transfer reactions in near-barrier collisions of heavy ions are promising in synthesizing new neutron-rich nuclei in the heavy and superheavy mass region. In particular, low-energy collisions of actinides can be of special interest. An important feature of multinucleon transfer reactions is that they lead to the formation of neutron-rich superheavy nuclei inaccessible via fusion reactions, which allows the synthesis of a number of new isotopes of light SHE, up to the beta-stability line.

The experimental study of multinuclear transfer reactions involves a fair number of difficulties owning to a great variety of reaction channels and peculiarities of their kinematics (wide angular and energy distributions of products). A complete study of multi-nucleon transfer reactions should comprise: the determination of the energies of reaction products, their charges, masses, and angles of scattering. The register of corresponding particles (neutron, gamma) is also desired.

**Nuclear SHE spectroscopy**

Once SHE are synthesised and detected, more detailed information on their properties, like mass, decay channels, low-laying level structure, etc. are to be gathered. This will be possible by detailed studies of their decay properties (α-, β-, γ-spectroscopy) and by accurate mass measurements.

The spectroscopy of the isotopes of transuranium elements in the focal plane of the spectrometer (registration of alpha-particles, gamma-quanta, X-ray quanta, and conversion electrons) allows us to determine transitions from mother nucleus (ground state) to daughter nucleus (ground, excited and isomeric states), and transitions of isomeric states to ground and excited states in the mother nucleus.

The main experiments for studying the properties of the radioactive decay and the structure of isotopes of heavy and superheavy elements at the FLNR will be conducted at the SHE Factory, with the use of the GRAND setup, and the detecting system GABRIELA. The first experiments will be on the properties of flerovium and moscovium isotopes produced with several picobarn cross sections in the 48Ca+242Pu,243Am reactions.

After modernization of U400R accelerator complex, experiments of spectroscopy of transfermium nuclides will be also continued at the velocity filter SHELS.

# Study of the chemical properties of SHE

Relatively high stability of SHE opens up new avenues of enquiry in the study of their chemical behaviour. It is interesting to compare the properties of SHE with the properties of their light analogues from the Mendeleev's Periodic table, thus evaluating a hypothesis about the influence of relativistic effects on the law of periodicity of chemical properties in the SHE region. The answer to this fundamental question is extremely important for the chemical identification of synthesized elements.

Chemical identification and study of the properties of SHE with Z = 112 – 114 (having known isotopes living longer than 1 sec) in the elementary state with higher statistical significance will continue at the SHE Factory with the use of the GRAND separator.

The construction of a new experimental setups at the SHE Factory within the seven-year period will become key to further work on the study of the chemical properties of SHE. That is first of all a new separator GASSOL based on a superconducting solenoid aimed at studying chemistry of SHE including those living shorter than 1 sec.

# Measurement of masses of superheavy atoms

The determination of the masses of SHE is very important both for further experimental studies in the field and for the development of theoretical models, including those defining the masses of as-yet-undiscovered nuclei. At present the only source of reliable experimental evidence on SHN masses is the alpha-decay) measured with an accuracy of about 30 keV. In the case of decay from the ground state of the mother nucleus into the ground state of the daughter nucleus,  allows us to determine the difference between the masses of these nuclei. Therefore, mass measurement of any of the nuclei in the alpha-decay chain with a precision of about 30 keV will give the masses of all the nuclei in the chain.

In 2020–2022 a preliminary design of the multireflection time-of-flight mass spectrometer, meeting the requirements with respect to the mass measurement precision, was elaborated in collaboration with the Institute for Analytical Instrumentation RAS in Saint-Petersburg. The construction of the instrument is planned in the upcoming seven-year period at FLNR JINR. The spectrometer will be installed at the SHE Factory, following the GRAND separator and the cryogenic gas catcher. First experiments using the novel mass spectrometer are planned under the Project in 2027–2028.

**The project “Light exotic nuclei at the borders of nuclear stability” will include the following directions of research:**

**Properties of nuclei far from the β-stability line**

Radioactive ion beam (RIB) facilities are well suited for the study of exotic nuclear systems far and beyond from the β-stability line. The principal scientific goal of these facilities is exploring nuclei with neutron or proton excess, situated near or beyond the nuclear drip-lines. We note that exploration of the structure of light exotic nuclei and the boundaries of stability is still a hot topic of researches at many worldwide facilities and they are actively contributing in the production and studies of these nuclei. The limits of nuclear stability have been reached only for the lightest nuclei, and the properties of these nuclei (5,6,7H, 9,10He, 11,13Li, 16,18Be, 17,19B, etc.) are intensively studied.

The current and near-future goals of the research program at the FLNR are focused in studying the structure of light nuclei and nuclear systems near and beyond the borders of nuclear stability through the utilization of transfer reactions, investigation of rare decay modes, and the assessment of the reaction mechanisms’ influence on the observed characteristics of the studied nuclei. The successive application of transfer reactions to study the structure of isotopes near the borders of nuclear stability can lead to obtaining the most reliable information and revising existing knowledge.

The experimental program of study of light exotic nuclei is proposed to be carried out at the ACCULINNA-2 separator, installed on the U400M cyclotron primary beam line. The separator was designed to produce in the “in-flight” mode secondary beams of radioactive exotic nuclei. The energy of these secondary beams, ⁓20-50 MeV/nucleon, is very prominent for study of nuclear structure in a (few-)nucleon transfer reactions. It allows one to populate states of light nuclei with rather high cross sections from few μb/sr to 1 mb/sr. The experiments that have been already performed at the FLNR experimental complex were intended for the study of the structure of neutron-rich 4-7H, 6-10He, 10,11Li, proton-rich 6Be, 17Ne, and 26S nuclei.

In realization of our experimental goals, we will take advantage of increased operability of upgraded the U-400M cyclotron complex: increased energy, intensity, and quality of heavy ion beams as well as the separator key equipment (RF-kicker, zero-degree spectrometer, cryogenic target complex, an array of neutron detectors and telescopes for detection of charged particles). The ACCULINNA-1 facility will be used for tests measurements, detectors testing and applied studies that do not require a high intensity and purity of the secondary beam.

The main advantages of ACCULINNA-2 complex compared to world analogues of in-flight separators are relatively low range of ion energies (from ~5 MeV/nucleon to 50 MeV/nucleon), the ability to work as a physical target with all helium and hydrogen isotopes (including tritium) in a wide range of thicknesses (from 1019 to 1021 atoms/cm2), achieved by choosing the phase state of the substance - gas or liquid. Availability of cryogenic targets of hydrogen and helium isotopes offers an opportunity to move toward more exotic, more neutron rich nuclei via one- and two-neutron transfer Moreover, this energy range is optimal for studying direct transfer reactions, which, in turn, could deliver the most reliable information about the nuclear structure.

**Research program on exploring borders of nuclear stability.**

The scientific program aims to study the properties of isotopes at the boundaries of stability. One of the main directions is investigation of hard-to-access neutron-rich nuclei along with their mirror nuclei or isobar analogs, which are important for studying the properties of atomic nuclei and for testing of nuclear models. By comparing the properties of isobar analogues, one can gain insights into the underlying nuclear forces and interactions that govern the behavior of atomic nuclei. Studies of mirror nuclei have been used to test the symmetry properties of the nuclear forces, and to investigate the role of isospin symmetry in nuclear structure.

Proposed studies are:

5He-5H: This topic takes advantage of using the same combination of beam+target for conducting of the 6He(d,3He)5H and 6He(d,3H)5He reactions in inverse kinematics. Both isotopes are characterized by a two-neutron decay, which is essential for understanding the interactions between neutrons in such systems. By investigating the behavior of the *t*+*n*+*n* and 3He+*n*+*n* correlations, we can gain insights into the structure of 5H,5He, the dynamics of the two-neutron decay process, and on the interactions between neutrons in neutron-rich nuclei, respectively.

7H-7He-7B: The available combinations of beams and targets provide us with the possibility to populate low-lying states through different reaction mechanisms and investigate their impact on the structure of these states. Neutron-rich isotopes, such as 7H and 7He, can be populated in reactions with the 6He and 8He beams. Low-lying states of 7B can be populated through neutron transfer or charge-exchange reaction. Investigating the 7B nucleus, a mirror nucleus for 7He, will offer improved experimental access to 7He properties.

10He-10Li-10N: These isotopes represent some of the most complex and hardly accessible isobars with a mass number A=10. They can be populated through transfer reactions with 8He, 9Li, and 9C beams. Measuring all reaction products for both mirror nuclei, 10Li and 10N, will facilitate comparative analyses of their nuclear structure properties. This comparison will provide valuable insights into the behavior of these exotic isotopes and their interactions, helping to refine theoretical models that describe their properties and decay mechanisms.

Availability of a cryogenic tritium target complex offers a unique possibility to explore borders of nuclear stability and nuclear matter beyond them by means of 2*n*-transfer reactions. 3H is seen as a prominent source of 2*n* to be transferred. The structure of a group of light neutron dripline nuclei could be probed. The use of 3H as a target is an effective way (due to relatively large cross sections of the (*t*,*p*) reactions) to probe low-lying states at nuclear resonances such as 7H, 10He, 13Li,16Be.

**Structure of drip line isotopes in (*d*,*p*) and (*d*,*n*) reactions**

Single nucleon transfer reactions have played a major role in developing our understanding of the structure of nuclei. Reactions such as (*d*,*p*) have served as fundamental tools for studying the properties of single particle states in nuclei throughout the periodic table. The kinematics selectivity and high cross-section of one-neutron transfer of the (*d*,*p*) reaction in particular have made it one of the most heavily used reactions for the experimental determination of spin-parity, and for probing the wave functions of single-particle states in nuclei. Interest in direct transfer reactions such as (*d*,*p*) has been rejuvenated and bolstered with the possibility to test new, powerful theoretical methods for calculating nuclear structure, as well as the ability to address new questions in nuclear astrophysics. Such a tool is particularly important while there is abundance of contradictory data on the same nuclear systems which need to be clarified. A detailed study of the spectrum of low-lying 7,9He, 10Li levels populated in (*d*,*p*) reactions, using the zero degree spectrometer and an upgraded neutron detection wall, is planned.

**Exotic radioactivity - search for 2*p* radioactivity**

Commissioning of the RF filter will pave way for series of experimental studies of proton-rich nuclei with *Z*≤36, situated near the proton drip-line. These include several nuclei predicted to exhibit 2*p*-radioactivity. Moreover, there is a significant interest in the dynamics of the 2*p* decay of resonant states, such as 6Be, 12O, 16Ne, 26S, 30Ar, etc. The study of the 2*p* decay mode in 17Ne, 26S should be feasible in transfer reactions (*p*,*d*), (*p*,*t*) induced by RIBs and will be included in the research program.

Study of 26S low-lying states and the search for the 2*p* decay channel from the 26S ground state in the (*p*,*d*), (*t*,*n*) and (*p*,*n*) reactions with 27S, 24Si and 26P beams, respectively. It represents a novel approach that has not been used before. Moreover, the operation of the RF-kicker will significantly enhance the purity of the desired secondary beam 27S/26P/24Si by a factor of ~50 comparing to such beam produced at the ACCULINNA-1.

The research agenda involves investigation of the 2*p*-decay channel of the first excited state of 17Ne (Jπ=3/2¯) to refine the data obtained in previous work at ACCULINNA-1, namely, to significantly lower (by a factor of 50) the limit of the ratio of partial widths Γ2*p*/Γγ of this excited state. Such information plays a crucial role in astrophysics, particularly in the theoretical description of stellar combustion. At ACCULINNA-2, the 17Ne isotope may be populated in (*p*,*d*) and (3He,*n*) reactions with the 18Ne and 15O beams, respectively. A new experimental setup with the RF kicker and the zero-degree spectrometer will benefit in a significant improvement in beam purification and a background reduction interference from the projectile-like fragments, allowing for the acquisition of high-quality data.

**2.4. Participating JINR laboratories**

FLNR

**2.5. Participating countries, scientific and educational organizations:**

|  |  |  |
| --- | --- | --- |
| **Organisation** | **Country** | **City** |
| IMP CAS | China | Lanzhou |
| PKU | China | Beijing |
| GSI | Germany | Darmstadt |
| MPIK | Germany | Heidelberg |
| VECC | India | Kolkata |
| IIT Roorkee | India | Roorkee |
| IIT Ropar | India | Rupnagar |
| MU | India | Manipal |
| IUAC | India | New Delhi |
| Unina | Italy | Naples |
| INP | Kazakhstan | Almaty |
| CGL | Mongolia | Ulaanbaatar |
| IFIN-HH | Romania | Bucharest |
| SSC RIAR | Russia | Dimitrovgrad |
| IPTP | Russia | Dubna |
| INEOS RAS | Russia | Moscow |
| MSU | Russia | Moscow |
| NRC KI | Russia | Moscow |
| SINP MSU | Russia | Moscow |
| VNIIEF | Russia | Sarov |
| IAI RAS | Russia | St. Petersburg |
| Ioffe Institute | Russia | St. Petersburg |
| KRI | Russia | St. Petersburg |
| SPbSU | Russia | St. Petersburg |
| INR RAS | Russia | Moscow, Troitsk |
| CU | Slovakia | Bratislava |
| iThemba LABS | South Africa | Somerset West |
| UNISA | South Africa | Pretoria |
| KU | South Korea | Sejong |
| PSI | Switzerland | Villigen |
| HCMUS | Vietnam | Ho Chi Minh |
| IOP VAST | Vietnam | Hanoi |

**2.6. Co-executing organisations** *(those collaborating organisations/partners without whose financial, infrastructural participation the implementation of the research programme on the theme is impossible. Example - JINR participation in the LHC experiments at CERN).*

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category**  **employee** | **Core staff,**  **Amount of FTE** | **Associated**  **Personnel**  **Amount of FTE** |
| 1. | scientific staff | 72 |  |
| 2. | engineers | 33.45 |  |
| 3. | professionals | - |  |
| 4. | employees | ~~-~~ |  |
| 5. | workers | ~~-~~ |  |
|  | **Total:** | **105.45** |  |

**3.2. Human resources available**

**3.2.1. JINR core staff** (total number of participants)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№№**  **n/a** | **Category of employees** | **Division** | **Position** | **Amount**  **FTE** |
| 1. | Scientific staff |  |  |  |
|  |  | JINR Directorate | Vice-director | 1 |
|  |  | FLNR | Deputy scientific leader | 1 |
|  |  | FLNR | Deputy director | 2 |
|  |  | FLNR | Scientific secretary | 1 |
|  |  | FLNR | Head of sector | 5.4 |
|  |  | FLNR | Head of group | 9 |
|  |  | FLNR | Chief researcher | 1.5 |
|  |  | FLNR | Leading researcher | 4.5 |
|  |  | FLNR | Senior researcher | 12.4 |
|  |  | FLNR | Researcher | 15 |
|  |  | FLNR | Junior researcher | 18.7 |
|  |  | FLNR | Intern-follower | 1 |
| 2. | engineers |  |  |  |
|  |  | FLNR | Leading engineer | 6.4 |
|  |  | FLNR | Senior engineer | 5.2 |
|  |  | FLNR | Engineer | 19.6 |
|  |  | FLNR | Laboratory assistant | 2.25 |
|  | **Total:** |  |  | **105.45** |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category of employees** | **Partner organisation** | **Amount of FTE** |
| 1. | Scientific employees | - | - |
| 2. | engineers | - | - |
|  | **Total:** | **-** | **-** |

**4. Financial support**

**4.1.** **The full estimated cost of the Theme**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Items of expenditure** | **Cost** | **Expenditure per year**  **(thousands of the US dollars)** | | | | | | |
| 1st  year | 2nd  year | 3rd  year | 4th  year | 5th  year | 6th  year | 7th  year |
| 1. | International cooperation | 2 380 | 340 | 340 | 340 | 340 | 340 | 340 | 340 |
| 2. | Materials | 7 000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| 3. | Equipment, Third-party company services | 13 870 | 1950 | 1950 | 1970 | 2000 | 2000 | 2000 | 2000 |
| 4. | Commissioning | 80 | 30 | 30 | 20 | - | - | - | - |
| 5. | R&D contracts with other research  organisations |  |  |  |  |  |  |  |  |
| 6. | Software purchasing | 490 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| 7. | Design/construction | 50 | 20 | 20 | 10 | - | - | - | - |
| 8. | Service costs (*planned in case of direct project affiliation)* |  |  |  |  |  |  |  |  |
| **TOTAL:** | | **23 870** | **3 410** | **3 410** | **3 410** | **3 410** | **3 410** | **3 410** | **3 410** |  |

**4.2. Extrabudgetary funding sources**

Co-financing from co-executors/customers is foreseen under the theme

to the following extent (specify cumulatively by project).

**AGREED:**

**Chief Scientific Secretary Laboratory Director**

**/S.N. Nedelko/ /S.I. Sidorchuk/**

**" " 2023 " " 2023**

**Head of BERO Scientific Secretary of the Laboratory**

**/\_ Kalinin N.V. / /A.V. Karpov/**

**" " 2023 " " 2023**

**Head of DSOA Laboratory Economist**

**/\_\_\_\_\_\_\_ / /T.V. Mamonova/**

**" " \_\_\_\_\_\_ 2023 " " 2023**

**Head of HRRMD Theme leader**

**/\_\_\_ Kolganova E.A. / /S.I. Sidorchuk/**

**" " \_\_\_\_\_\_ 2023 " " \_\_\_\_\_\_ 2023**

**Project leader (\_\_\_\_\_\_\_\_\_\_\_\_\_\_)**

**/M.G. Itkis/**

**“ “ 2023**

**Project leader (\_\_\_\_\_\_\_\_\_\_\_\_\_\_)**

**/A.V. Karpov/**

**“ “ 2023**

**Project leader (\_\_\_\_\_\_\_\_\_\_\_\_\_\_)**

**/G. Kaminski/**

**“ “ 2023**

**Project leader (\_\_\_\_\_\_\_\_\_\_\_\_\_\_)**

**/S.I. Sidorchuk/**

**“ “ 2023**