STRATEGIC LONG RANGE PLAN FOR NUCLEAR PHYSICS

Executive Summary:

Since its foundation and up to now, the main direction of scientific research of the Laboratory of Nuclear Reactions (FLNR) of JINR has been and is the World-wide recognized 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 is planned based on the DC-280 heavy-ion cyclotron, the world's top accelerator among others of the same type. 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 separator (DGFRS-II) and other future set-ups installed at the SHE Factory will play an important role. The construction of a specialized building complex comprising radiochemical laboratories of Class 1 for the manufacture and regeneration of highly radioactive targets as well as a new 28 GHz ECR source is foreseen, completing the SHE-Factory.

FLNR's research program has been expanded into the region of neutron-rich isotopes of superheavy elements near the island of stability, since the neutron shell N=184 should have a stabilizing effect on the nuclear life-time. In addition, the hypothetical closed shell at Z = 114 should also be of maximum support for the synthesis of nuclei with the number of neutrons close to 184. We propose to reach the neutron excess not by using beams of neutron-rich radioactive nuclei, because of their low intensity, but rather by using more neutron rich target nuclei (e. g., ^{251}Cf). In target production, our international collaboration is of great importance and will be pursued further.

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 time-of-flight mass-spectrometer.

The FLNR JINR experimental programme in the field of SHE for 2024–2030 is aimed at studying the properties of the radioactive decay and the structure of isotopes of heavy and superheavy elements as well as chemical properties of SHE using the new DC-280 accelerator, the DGFRS-3 setup, and corresponding detections systems.

Multi-nucleon transfer reactions in near-barrier collisions of actinides are promising in synthesizing new neutron-rich isotopes of heavy and superheavy elements. These reactions can lead to the formation of neutron-rich superheavy nuclei, inaccessible via fusion reactions. This method allows the synthesis of a number of new isotopes of light superheavy elements, up to the beta-stability line. Unfortunately, no universal detector concept exits, however, our laboratory is looking into use our existing detectors like SHELS, MAVR, and CORSET as well as development new ones.

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-separators ACCULINNA-1 [Gri16] and COMBAS, installed on the primary beam line of the U400M cyclotron. Recently, the new generation separators, ACCULINNA-2 and MAVR, were 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 (2-nucleon virtual states, 2n- and 4n-radioactivity), two- proton radioactivity, search for new magic numbers and spectroscopy of exotic nuclei, reactions with halo nuclei. Further development of the RIBs research program is seen in extension of available primary beams.

In material research and technology, high energy heavy ion beams have been proven as powerful tools for material modification and are being widely used in radiation solid state physics. An important feature of heavy ions is the possibility of tailoring micro- and macroscopic properties of materials and creation of nano-dimensional structures. High damage production rates, typical for energetic heavy ions, open a way for rapid simulation of radiation damage produced by neutron irradiation in materials showing promise for nuclear applications. FLNR accelerators of heavy ions U-400 and IC-100 opened up unique opportunities for experimental researches in an energy range 1-20 MeV/A for ions from B to Bi.

Finally, all these research topics require a strong development of the experimental infrastructure, outlined further down. The first-priority project of the SHE Factory at FLNR will be a world-wide unique facility complementing those top nuclear physics facilities at GSI in Germany, RIKEN in Japan, BLNL in USA, and GANIL/SPIRAL 2 in France. Modernization and development of other FLNR's accelerator complexes (U400M and U400R) will allow realizing a highly demanding experimental program on the world-top level.

With this long-range program, FLNR intends to stay at the forefront of nuclear physics and wants to provide state of the art research in nuclear physics for the member-states of JINR and the international nuclear physics community.

A The main areas of nuclear research at FLNR

The research program of the Flerov Laboratory of Nuclear Reactions (FLNR) is - on one side-continuing on the successful Past, on the other side it takes on the challenge to stay at the forefront of nuclear physics research by strengthening its existing program and by opening up for great opportunities in nuclear physics research.

The main areas of nuclear research at FLNR are and will be the following:

- Synthesis of heavy and superheavy elements and study of their properties;
- Study of the properties of light exotic nuclei near the borders of nucleon stability
- Study of nuclear reaction mechanisms leading to the formation of heavy and superheavy elements and the analysis of reactions with radioactive nuclei

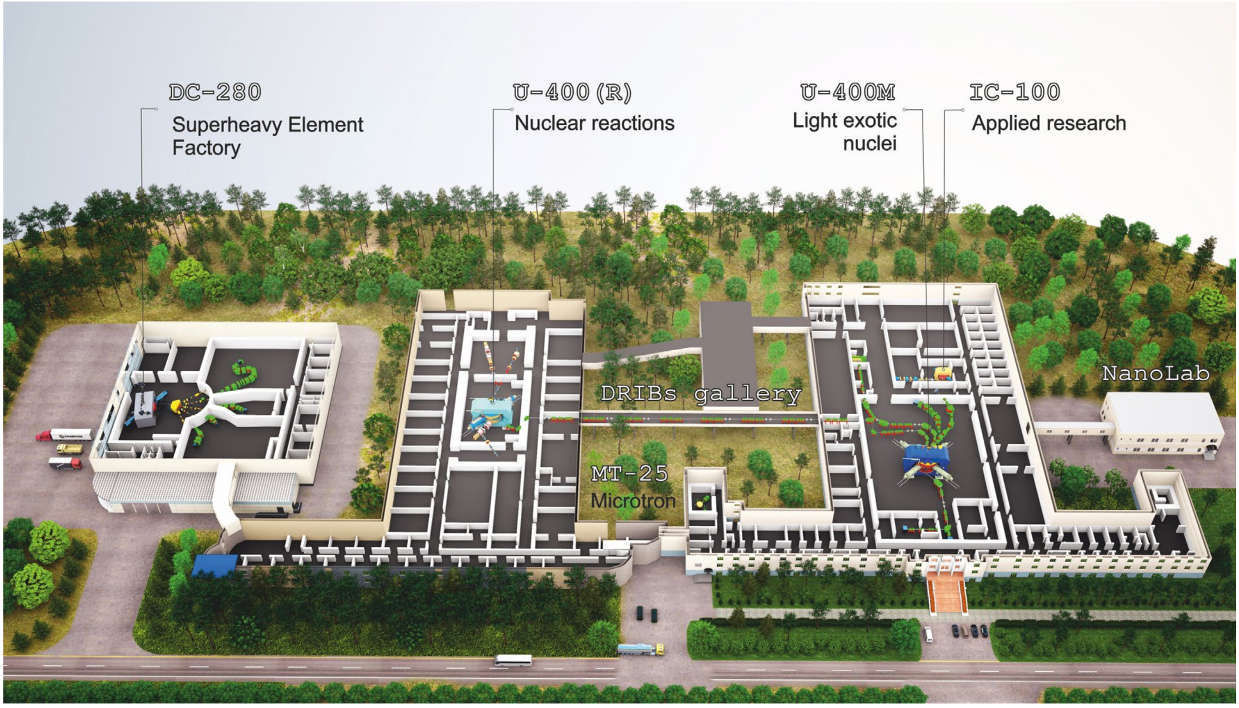

Fig. A.1:. The layout of the FLNR accelerator complexes.

The development of the FLNR experimental infrastructure under the Seven-Year Plan of 2017-2023 (see Fig.1. A.1) foresees the construction of three main accelerator complexes equipped with modern experimental set-ups meeting the goals of the FLNR research program. Each of the accelerator complexes will focus on the following physics tasks:

- Superheavy element **(SHE) Factory based on the DC280 accelerator**: synthesis of heavy and superheavy nuclei and the study of their properties:
- **U400M accelerator complex**: study of light exotic nuclei;
- **U400R accelerator complex**: study of nuclear reactions;

B. Synthesis of heavy and superheavy nuclei and study of their properties

The main direction of scientific research of FLNR since its foundation and up to now is the synthesis of new elements of the Mendeleev's Periodic table and the study of their properties. Particular attention was given to the synthesis of SuperHeavy Elements (SHE) as well as their search in nature. These studies are primarily interwoven with the question of the limits of the existence of nuclear matter as well with the determination of the boundaries of the *Island of stability of SHE*, a hypothetical region of the nuclear map where long-lived isotopes of SHE could be found.

One of the greatest JINR achievements of last years was the discovery of six heaviest elements of the Mendeleev's periodic table in hot fusion reactions using the ^{48}Ca beam and actinide targets (see review [Yu.Ts. Oganessian and V.K. Utyonkov // Rep. Prog. Phys. **78,** 036301(2015)] and references therein). The priority for the discoveries of five of them was assigned to an international collaboration of JINR with the Livermore and Oak Ridge National Laboratories (USA). These include 114-Flerovium, 115-Moscovium, 116-Livermorium, 117-Tennessine, and 118-Oganesson.

Substantial increase (dozen of times) in the efficiency of experiments is needed for the continuation of the research program in the field of SHE. This includes: synthesis of yet unknown elements with atomic numbers Z=119, 120, and heavier, synthesis of new isotopes of SHE, study of nuclear and chemical properties of already known elements, etc. A big step forward in this research will become possible through the construction of the world's first Factory of superheavy elements (SHE Factory) at JINR. The Factory will become a world base for future studies of superheavy nuclei and will reinforce the priority of all the JINR member states as leaders in the field of synthesis and study of superheavy elements.

A key element of the SHE Factory is the DC-280 heavy-ion cyclotron (Fig. 2), the world's top accelerator among others of the same type. The accelerator was designed at JINR and manufactured with the participation of many JINR member states. The design beam intensity of accelerated ^{48}Ca ions is 10–20 pμA, which is much higher than those attained at currently existing accelerators.

Fig. 2: DC-280 cyclotron of the SHE Factory.

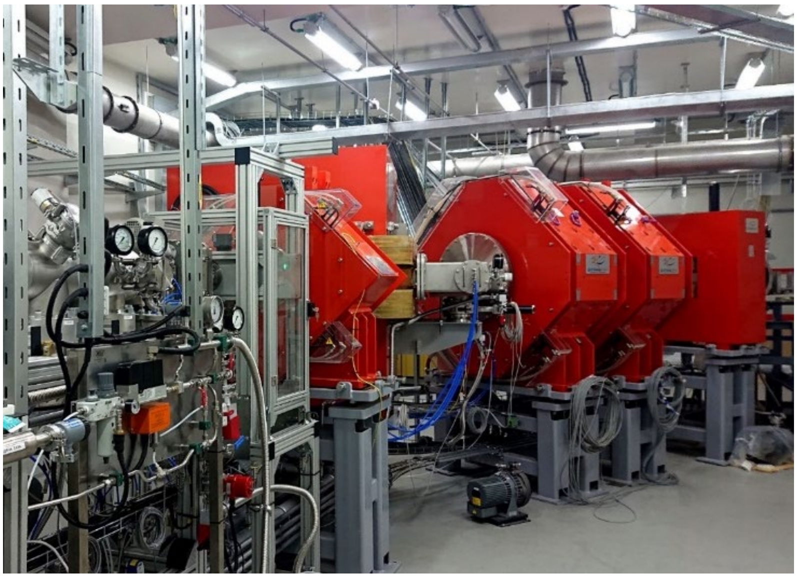

Fig. 3: DGFRS-II of the SHE Factory.

The first experimental set-up of the SHE Factory is a new gas-filled recoil separator, DGFRS-II (Fig. 3). A key feature of the set-up is the high efficiency of the collection of superheavy nuclei (over 60%), which is twice the one attained with the previous separator. Another set-up installed at SHE Factory will be a special gas-filled separator (DGFRS-III) equipped by two specialized channels for nuclear spectroscopy of SHE and for studying their chemical properties. Further development of the SHE Factory will expand the capacity of the acceleration complex to implement its experimental program.

Another important direction of our research in the field of SHE concerns investigation of mechanisms of nuclear reactions leading to formation of SHE, especially to their neutron-enriched isotopes, which are expected to be the most stable ones.

Promising studies in the synthesis and study of SHE were discussed at a number of conferences and workshops. The main tasks in SHE research were addressed during the those discussions:

- Elements beyond Z=118; expansion of the Periodic table
- Nuclides beyond ^{294}Og; expansion of the chart of the nuclides
- Connecting “hot-fusion” and “cold-fusion” regions
- Chemistry (well) beyond the standard Periodic table
- Excursion into the N=184 region of longer-lived superheavy elements
- Pinning down the presence of exotic topologies
- Delineating the role of superheavy nuclei in the Cosmos

The bulk of the open issues can is expected being successfully resolved at the SHE Factory in JINR.

B.1 Synthesis of New Elements

Among the above mentioned research directions, synthesis of new elements 119 and 120 is of highest importance and will certainly become the SHE Factory's top priority. According to theoretical predictions, the $^{249}Bk+^{50}Ti \rightarrow ^{299}119^*$, $^{249\text{-}251}Cf+^{50}Ti \rightarrow ^{299\text{-}301}120^*$, and $^{248}Cm+^{54}Cr \rightarrow ^{302}120^*$ reactions are most promising for the synthesis of elements 119 and 120 (Fig. 1.1).

The expected cross-sections are of several dozens of picobarns. The experimental programme

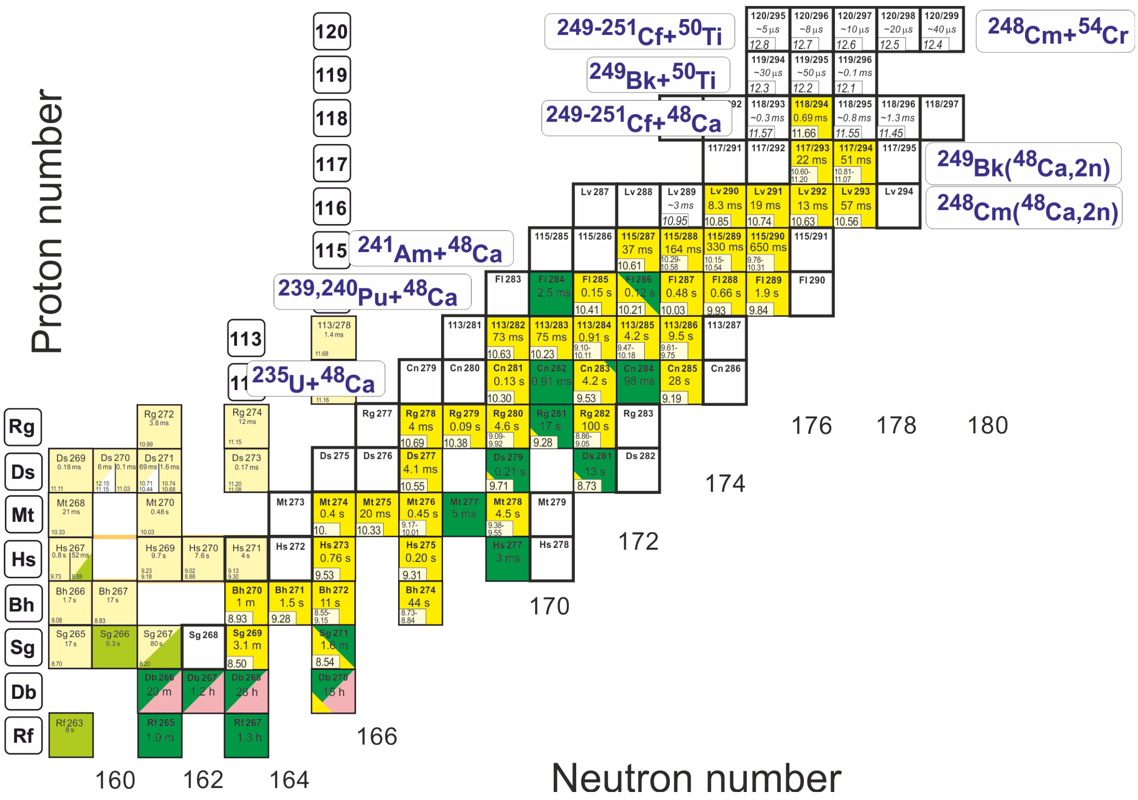

Fig.4: 1.1 Upper part of the nuclide chart. New nuclides that can be synthesized in the above reactions are marked with white squares. ^{283}Fl decay results in the known ^{71}Hs isotope.

aimed at synthesizing even heavier elements will be tailored to the results of experiments on the synthesis of elements 119 and 120 planned for the next seven years.

<u>Required experimental equipment:</u> The task can be fulfilled at the SHE Factory using Gas-filled recoil separator (DGFRS-II).

B.2 Synthesis of new isotopes of already known superheavy elements (Expansion of the chart of nuclides)

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 nuclide map chart (Fig. 4) is located among isotopes synthesized in "cold" and "hot" fusion reaction. This part of the nuclide chart nuclear map was shown [V. Zagrebaev, A. Karpov, W. Greiner // Phys. Rev. C**85**, 014608 (2012)] to be filled through "ordinary" fusion reactions with a ^{48}Ca beam and more neutron-deficient targets than those that have already been used (^{233,235}U, ^{239,240}Pu, ^{241}Am, ^{243}Cm, and others). Cross-sections are expected to be on the order of 1 pb, which is high enough for an experimental study.

Required experimental equipment: The task can be fulfilled at the SHE Factory using Gas-filled recoil separator (DGFRS-II).

B.3 Synthesis of neutron-rich isotopes of superheavy elements (Journey towards the region of longer-lived super heavies)

Experiments Expansion reaching into the region of neutron-rich isotopes of superheavy elements in the vicinity of the island of stability is are of great importance. The properties of neutron-rich nuclei are of particular interest as they should most strongly manifest the stabilizing effect of the neutron shell N=184. In addition, the effect of the hypothetical shell Z = 114 should also be at its maximum for nuclei with the number of neutrons close to 184. Studying systems with higher neutron excess can be achieved using beams of neutron-rich radioactive nuclei. As of today, however, the use of radioactive beams for these purposes seems not to be very promising due to their low intensity compared with the intensities of beams of stable nuclei, on one side, and because of the lack of the increase in the fusion-survival cross-section during the transition to radioactive beams, on the other side [1]. Thus, a more promising path to the synthesis, in our opinion, is via:

- ***Using 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, ^{251}Cf). The cross-sections for the formation of a new isotope ^{296}118 calculated in [2] in a 3n channel of the ^{48}Ca+^{251}Cf fusion reaction were of about 1 pb.

Required experimental equipment: The task can be fulfilled at the SHE Factory using Gas-filled recoil separator (DGFRS-II) and neutron rich targets.

- ***Focusing on the 2n channel of fusion-fission reactions***

Another way for possible shifting by 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. According to the calculations, this should lead to a several-fold (~2-4) reduction in the cross-section (compared to the one in the 3n-4n channel), which is however still within the capacities of the SHE Factory.

- ***Measuring Electron capture decay***

One of the main decay modes of the isotopes of superheavy elements located to the right from those synthesized earlier was predicted to be the electron capture [3]. This is due to the close proximity to the closed shell N=184 and, as a consequence, to a drastic increase in the half-lives of spontaneous fission and alpha-decay. Sequence of electron capture decays may allow to shift shifting towards the region of beta-stable SH nuclei, which are expected to be the most long-lived.

Obvious difficulties in the experimental identification of electron capture events impede the immediate implementation of this scheme in full. However, the possibility of producing neutron-rich superheavy nuclei (due to the decay of protons into neutrons) and even (!) approaching the centre of the island of stability—one of the most crucial objectives of SHE studies—makes experiments aimed at searching for not-yet-observed electron capture in this region of the nuclide chart nuclear map quite promising.

Required experimental equipment: The task can be fulfilled at the SHE Factory using Gas-filled recoil separator (DGFRS-II) and neutron rich targets.

- ***Studies of pxn and αxn channels of fission-fusion reactions***

One of the ways of advancing in the region of neutron-rich SHE can be based on the registration detection of evaporation residues produced during the emission of a charged particle (proton or alpha-particle) and several neutrons. First experiments on the registration detection of survival products in pxn channels conducted for the ^{50}Ti + ^{209}Bi reaction proved the efficiency of the method [4].

Thus, during the irradiation of the actinide target ^{248}Cm with ^{48}Ca in p2n and p3n channels, neutron-rich isotopes of Moscovium ($^{293,294}Mc$) can be produced.

In the region of excitation energies from 40 to 45 MeV, survival cross-sections for channels with proton evaporation are expected [5,6] to vary from 1 to 10% of the cross-section for the production of evaporation residues in xn channels, depending on the reaction. For αxn channels, the values vary from 0.3 to 10%. The corresponding cross-sections can be obtained experimentally using high-intensity beams of ^{48}Ca at the SHE Factory.

Required experimental equipment: The task can be fulfilled at the SHE Factory using Gas-filled recoil separator (DGFRS-II).

- ***Multi-nucleon transfer reactions***

The reactions of multi-nucleon transfers during deep inelastic collisions of heavy ions with energies near the Coulomb barrier were considered as a method for producing new nuclei since the discovery of this type of nuclear reaction in 1966 by Volkov et al. The interest in deep inelastic transfer processes that has grown in recent years is caused, first of all, by the widely discussed possibility of synthesizing unknown neutron-rich medium-mass nuclei, as well as heavy and superheavy nuclei. One of the main objectives of the study of such nuclei is a detailed understanding of the astrophysical r-process, which proceeds through neutron-rich nuclei far from the line of β-stability. Such nuclei located in the vicinity of closed neutron shells form the so-called waiting points of the r-process. Knowledge of the properties of these nuclides plays a key role in modelling the r-process.

One of the least studied regions of the nuclide map is located near the neutron spherical shell N = 126. This is due to the low values of the cross sections for fragmentation reactions, the only method for the synthesis of neutron-enriched nuclei in this area that has been used to date. Since the fragmentation cross sections rapidly decrease with each step in the direction of the neutron excess, the search and study of alternative effective methods for producing these nuclei is an urgent task.

Multi-nucleon transfer reactions in near-barrier collisions of actinides (^{238}U beam on the heaviest available actinide target) are predicted to be promising in synthesizing new neutron-rich isotopes of superheavy elements. In these collisions, the formation of compound nuclei is certainly impossible, but the time of contract can be long enough to cause transfer of a large number of nucleons. Cross-sections for the formation of cold nuclei [7] thus exceed a threshold value at 1 pb only in the region of light superheavy nuclei (*Z*=104–108). An important feature of multi-nucleon 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 superheavy elements, up to the beta-stability line.

It is of interest to study Llow-energy collisions of actinides are of interest because of the possibility to observe spontaneous electron-positron emissions when forming a nuclear molecule possessing an overcritical electric field. The fundamental process of quantum electrodynamics was predicted over thirty years ago [8] but has not yet been experimentally confirmed. Another interesting phenomenon expected for these reactions is triple quasi-fission forming two strongly coupled fragments in the lead region [9, 10].

The experimental study of multi-nuclear transfer reactions involves a fair number of difficulties owning to a great variety of reaction channels and special features of their kinematics (wide angular and energy distributions of products). Existing experimental setups worldwide used for the study of nuclear reactions with heavy ions have severe limitations. 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.

The complete picture of the process illustrated in a single experiment is hampered by lack of cutting-edge experimental setups. R&D programs should be started to develop and define a dedicated detector set-up for heavy-ion reactions at these low energies, covering most of the phase space of the reaction products. The following FLNR setups located at the U-400(R) experimental hall can be used at present and can be part of upgraded setups in the future for the programme of studying the multi-nucleon transfer reactions:

(1) SHELS for the measurement of reaction product yields and the their energy distributions at forward angles;
(2) MAVR for the measurement of yields of light reaction products in wide angular and energy ranges;
(3) GALS for the measurement of integral cross-sections for the production of fragments with lose of information on the reaction kinematics (emission angles and energies);
(4) CORSET for the study of the kinematics of reactions allowing the determination of the masses of primary fragments formed in reactions in wide angular and energy ranges. The main limitations of the setup: it cannot measure the charge of the fragment; uncertainty in mass measurements (about 4 a.m.u.), and the lack of information on survived reaction products.

In addition, new setups can be constructed, such as:

(1) Velocity filter on a turntable platform allowing working at different angles.
(2) Telescope for measuring time-of-flight, energy and angles of the products of binary reactions of heavy ions and for the identification of daughter nuclei after the beta-decay.

Discussion, designing, and manufacturing of these set-ups will require several years. It is expected that they can be ready by the end of 2023-2024 so that they may start to work at the modernized U400R cyclotron complex. The use of the multi-nucleon transfer reactions for synthesis and study of heavy actinides and light superheavies can be conducted at the SHE Factory when the uranium beam will be available there. This requires installation of an additional ECR ion source, which is planned for 28 GHz. This ion source is under development at FLNR and expected to be ready by 2024.

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C Nuclear SHE spectroscopy

Once superheavy elements are synthesised and detected, more detailed information on their properties, like mass, decay channels, 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.

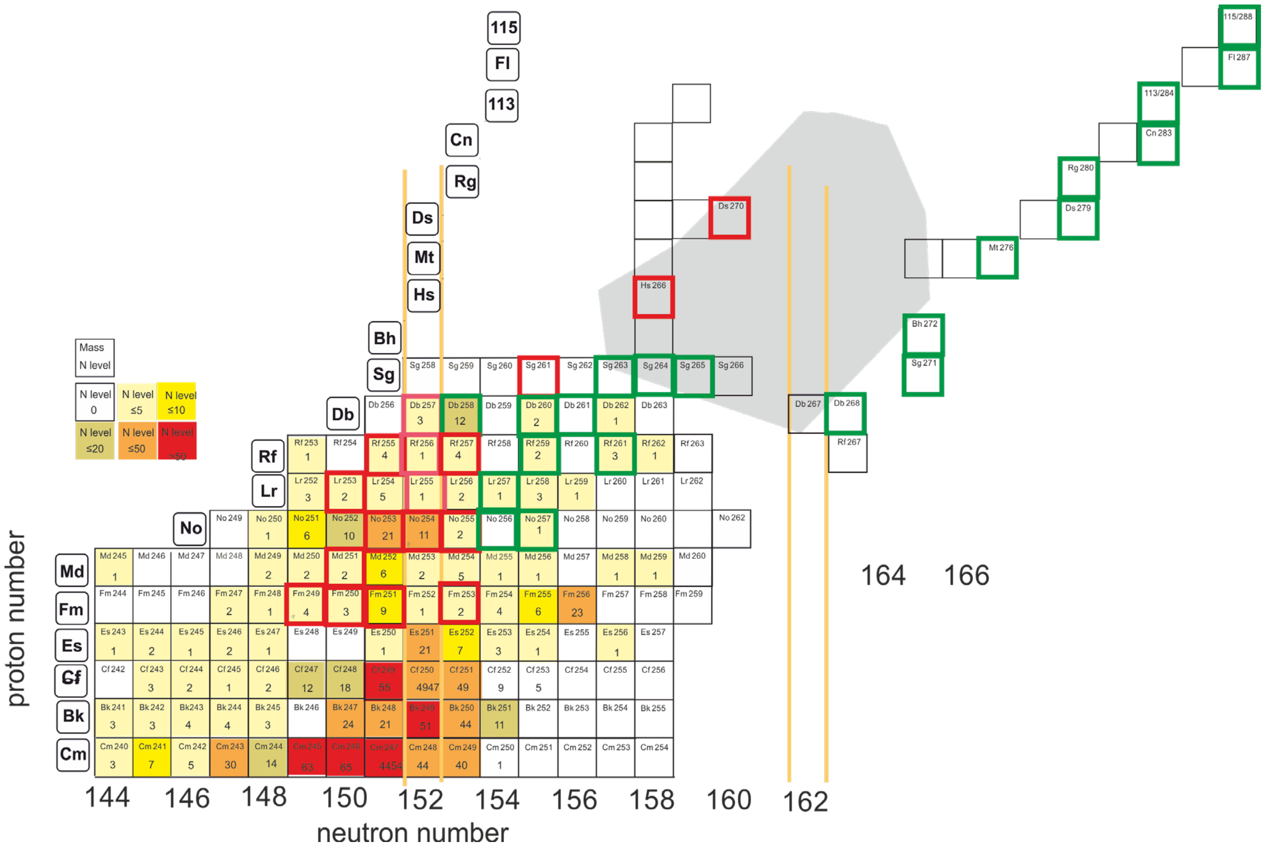

Fig. 5:. Spectroscopic data on isotopes of transuranium elements. The number of measured levels is shown by figures and is highlighted with colours. A small number of isotopes have been thoroughly studied to date (marked with red colour). Green colour is used to indicate isotopes whose spectroscopic properties are to be studied in scheduled experiments.

The spectroscopic data on isotopes of transuranium elements available at present is extremely limited (Fig. 5) and thus any new data especially in the SH mass region is of great interest and of great demand.

The spectroscopy of the isotopes of transuranium elements in the focal plane of the spectrometer (registration of alpha-particles, gamma- and 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.

To study the structure of heavy and superheavy elements, stopped in the focal plane, only one method for registration of nuclear radiation is applicable, which follows from the cross-sections for the formation of nuclei at the picobarn level. It assumes detection with high-energy resolution of alpha particles and gamma-quanta from the decays of ground and low-lying excited and isomeric states of both the recoil nuclei, implanted into the focal detectors of kinematic separators and their daughter products.

The main experiments for studying the properties of the radioactive decay and the structure of isotopes of heavy and superheavy elements under the FLNR JINR experimental programme for 2024–2030 will be conducted using the new DC-280 accelerator, the DGFRS-III setup, and the detecting system GABRIELA.

Using a cryogenic gas ion catcher is another promising approach to studying SHE properties. Such a catcher for separation of nuclei of SHE has its limits only in terms of separation time that is ~30 ms or longer. There are currently 31 isotopes of elements with Z≥110 with lifetimes of 30 ms or longer while the overall number of the known isotopes is 45.

All the isotopes of nuclei with Z≥110 synthesized and studied up till now are in the neutron-deficient region and thus can undergo β^{+}-decay and electron capture. Electron capture can be observed by registering characteristic X-rays emitted when outer-shell electrons fill a vacancy (essentially a *K*-shell). As noted above, electron capture can both help synthesize unknown nuclei and advance into the region of a larger number of neutrons in these nuclei.

D Study of the chemical properties of superheavy elements

Relatively high stability of new superheavy nuclei opens up new avenues of enquiry in the study of the chemical behaviour of superheavy elements (SHE). 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.

First results on the chemical identification and study of the properties of SHE with Z = 112 – 114 in the elementary state obtained at the FLNR U-400 accelerator complex revealed their high volatility and low chemical activity affecting the search for superheavy elements in nature. Detailed studies with higher statistical significance will continue at the SHE Factory.

The construction of a new experimental base at the SHE Factory within the current seven-year period (2017-2023) will become key to further work on the study of the chemical properties of SHE. The new infrastructure will comprise:

- New target assemblies for experiments at the DC-280 accelerator with the ion beam intensity up to 10 pμA;
- A pre-separator of nuclear reaction products for selective separation of isotopes of elements under investigation, which will considerably improve background conditions and the reliability of results;
- A gas ion catcher with speedy transport (30–40 ms) of reaction products, which will open up many new and exciting possibilities for exploiting the chemical properties of more short-lived isotopes of new elements.

New setups will allow investigations that today are out of reach of experimental techniques and will push existing technologies beyond current limits – one atom during one week of irradiation. Besides conventional experiments on the study of SHE properties in elementary states, new experiments on the study of the chemical compounds of the heaviest nuclei with Z=115–118 and with ultra-short lifetimes (0.1–0.5 s) will be conducted.

Synthesis of SHE and the study of their properties require the construction of a specialized complex comprising radiochemical laboratories of class 1 certification for the manufacture and regeneration of highly radioactive targets. Such a complex will add a "finishing touch" to the SHE Factory project and will become the JINR key infrastructure for its further development and the application of radioactive isotopes in other fields.

E Measurement of masses of superheavy atoms

The determination of the masses of superheavy nuclei (atoms) 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 SHE masses is the alpha-decay (Q_α) 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, Q_α 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.

One of the most efficient and rapid techniques for measuring nuclei masses is based on the use of multiple-reflection time-of-flight spectrometers. The main parameters of the modern spectrometer are the following:

- mass resolution $M/\Delta M \leq 600000$;
- precision of mass determination $\sim 10^{-7}$;
- measurement duration (time for multiple time-of-flight between the mirrors) ~10 ms;
- sensitivity of statistically significant data is ~10 ions;
- measurement frequency up to 400 hz;

- transmission efficiency up to 70%.

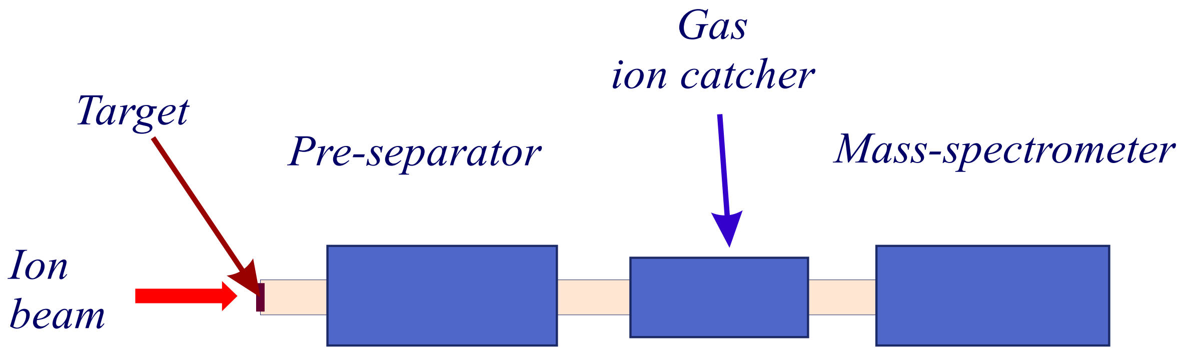

Fig. 6: The block diagram of the setup for measuring the masses of SHE nuclei.

Fig. 6 depicts a block diagram of the experimental setup. The setup comprises the following main elements: a target unit, a pre-separator for recoil nuclei (DGFRS-3), an ion gas catcher, and a mass-spectrometer with a registration system complex in the focal plane. The elements currently lacking at FLNR are the gas ion catcher and time-of-flight mass-spectrometer.

The gas ion catcher is under development at FLNR. We follow the design of one of the most efficient gas ion catchers, which was designed in GSI [1]. The working gas in the setup is cooled down to 40 K, without the necessity of ultra-deep gas purification. The extraction time of such a gas cell is ~30 ms with the efficiency up to 70% [2,3]. Having these parameters, the MR-ToF MS is able to successfully compete with Penning traps for the atomic mass measurements with lifetimes at the level of a few seconds or shorter.

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F Properties of nuclei far from the β-stability line

Radioactive ion beam (RIB) factories are well suited for the study of exotic nuclear systems remote from the β-stability line. The principal scientific goal of these facilities is the study of nuclei oversaturated with neutrons or protons, situated near or beyond the nuclear drip-lines.

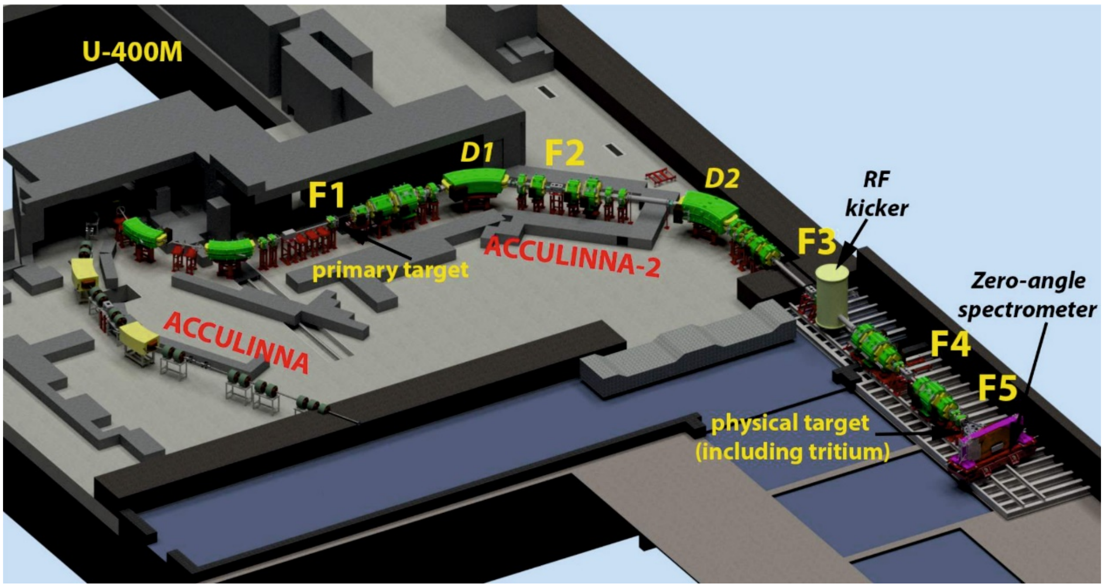

Fig. 7:. Layout of the fragment-separators ACCULINNA and ACCULINNA-2 at the U400M cyclotron.

The experimental program on the study of relatively light exotic nuclear systems of the current and previous 7-year periods at FLNR has been carried out at the fragment-separators ACCULINNA and COMBAS installed on the primary beam line of the U400M cyclotron. Recently, the new generation separators, ACCULINNA-2 (Fig. 7) and the high resolution analyser MAVR, have been 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. Fragment-separator ACCULINNA-2 is equipped with a number of supplementary tools to be fully put into operation by 2023. This includes:

- A vertically deflecting radio-frequency kicker (RF-kicker) is installed just after the achromatic focal plane F3, providing additional purification of a secondary beam. For separation of charged reaction products a zero-degree spectrometer is placed downstream of the physical target in the F5 focal plane. This will improve considerably the cumulative energy resolution of experiments with observation of beam-like products.
- By 2023 we expect to have put into operation a unique complex of a cryogenic gas target that will provide safe operation with gases (helium and hydrogen isotopes including tritium in gaseous or liquid states). The lowest temperature at the target cell should reach 11 K.
- Rare modes of decay of nuclei far from the stability line (two-proton radioactivity, β-delayed decays) are to be explored with a unique Optical Time-Projection Chamber (OTPC), allowing to get 3D reconstruction of the decay of an exotic nucleus to charged particles.

The development of new detector systems and mastering modern digital technologies include:

- New generation of micro-strip silicon detectors dedicated for tracking/spectroscopy experiments.
- Radiation-hard and extremely fast silicon detectors providing a very good time resolution σ~50 ps) for TOF measurements and beam diagnostics.

- A multi-module array of neutron detectors on the base of stilbene crystals, scintillation fibres and conventional multi-layer plastic scintillator arrays for experiments on the study of decay correlations of neutron-rich nuclear systems.
- Arrays of CsI, $LaBr_3$ etc. crystals for the charged-particle and gamma-ray detection.
- New 4π detection system DEMAS-MULTI comprising 90 ^{3}He neutron counters, CeBr3 scintillators and γ-clovers.

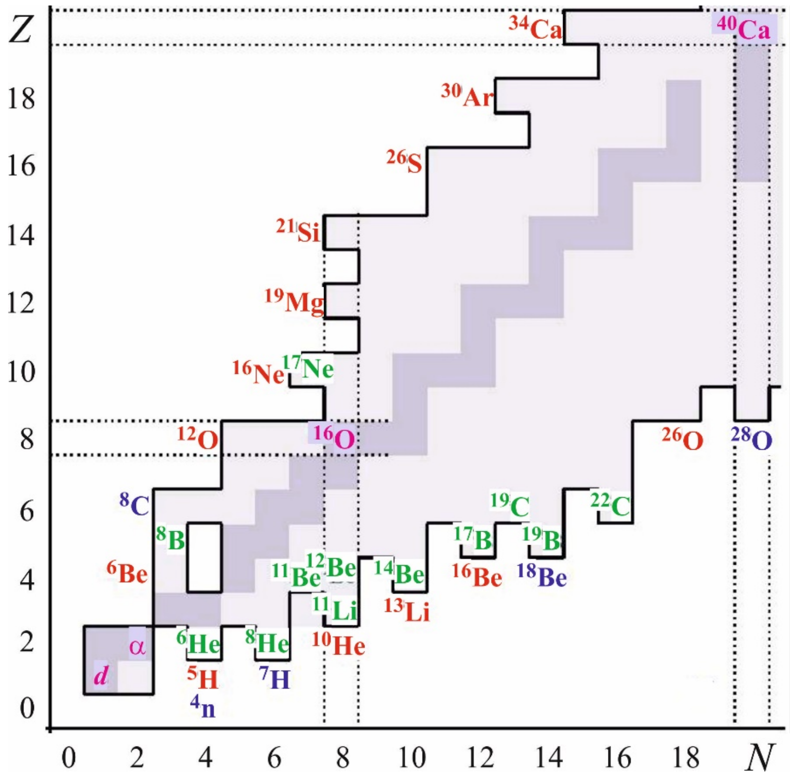

Fig. 8: The lightest nuclei on the nuclide map. The well established nucleon drip lines are presented with thick solid lines. The stability valley is shown in bluish tone.

The ACCULINNA-2 separator yields RIB with intensities 20-30 times larger than the ACCULINNA separator launched more than 20 years ago. The performance of ACCULINNA-2 is analogous to that inherent to the RIPS (RIKEN) or LISE (GANIL) fragment separators, which were the landmark facilities of the previous generation of RIB arrangements. Modernization of the U-400M driver cyclotron (planned for 2020-2022) will give solid basis to the scientific program at ACCULINNA-2, meaning more stable delivery of a broader variety of primary beams of somewhat larger energy than today.

The domain of drip-line nuclei shown in Fig. 2 8 is accessible at the Flerov Laboratory today and in near future. It embraces a region of light nuclei where transfer reactions make an effective tool allowing reaching the neutron/proton drip lines.

F.1 Nucleon haloes, neutron skins

Weakly bound few-body exotic systems show properties very different from the nuclei, which are not too far from the valley of stability. The halo phenomenon is important for a better understanding of nuclear structure close to the drip lines.

Along the neutron drip line, the relatively small enhancement of the total binding occurring for paired neutrons has important impact. Experiments giving new knowledge about the properties of the interleaving neutron-unbound nuclei should be put into the agenda of the research aimed at understanding the character of neutron-nucleus interaction far from stability, the coupling to the continuum in neutron-rich systems, and delicate structures inherent to the multi-neutron haloes or skins. Studies of the adjacent neutron-unbound odd-N nuclei could yield information on the nucleon orbitals important for the description of the heavier bound nuclei. Concerning the drip-line, nuclei of beryllium, boron and carbon, the spectra of ^{13}Be, ^{16}B, ^{18}B, and ^{21}C are of special interest.

Nucleon knockout and the more conventional transfer reactions are complementary methods. While knockout reactions mainly probe hole strengths, the nucleon transfer reactions like (d,p), (t,d), (t,p) and (^{3}He,d) populate particle orbitals. Adding to the arsenal of methods the nucleon pickup reactions from the RIB projectile nuclei, e.g. reactions of the (d,^{3}He), (p,d), and (p,t) types, one can populate nucleon-hole states in exotic nuclei. The orbital angular momentum quantum numbers, the relative location of single-particle states, and spectroscopic factors are accessible in experiments employing direct reactions. Transfer reactions access many excited states simultaneously, and their strong kinematic matching allows the optimum choice of reactions populating the nuclear states with orbital angular momentum of the interest.

F.2 Exotic multi-neutron decays (2-nucleon virtual states, 2n- and 4n-radioactivity)

Beyond the drip lines, we get at the regions of strong nuclear instability. Here, in the region of light neutron-rich nuclear systems, the experimental observations could be especially confusing. In the absence of strong potential barriers the observables becoming typical for the neutron decays, are often sensitive to the reaction mechanism. Also, the appearance of novel dynamics forms is not impossible here. These include the possible existence of hypothetical two-neutron virtual states [Gri08] and two/four-neutron radioactivity [Phu12]. The search for the few-neutron radioactive decays is inspired by the discovery of the two-proton radioactivity [Phu02, Gio02]. In contrast with the situation coming across near the proton drip line, the long-lived one-neutron emitters are practically impossible, while the 2n- and 4n-emitters may have quite long lifetimes, even falling in the radioactivity timescale. The discovery of such a novel type of radioactive decay is a challenging task requiring elaborate experimental approaches. At present time, the studies of nuclear systems with large neutron excess are active in different centres having intermediate-energy RIBs. Different authors published the results of their experiments devoted to the studies of the true two-neutron emitters ^{10}He [Sid12, Joh10], ^{13}Li [Koh13a], ^{16}Be [Tho13], and ^{26}O [Lun12, Kon16].

The excitation spectra of ^{7}H, $^{11\text{-}13}$Li, $^{13\text{-}16}$Be, $^{16\text{-}19}$B etc. will be a first-priority task for the group of the ACCULINNA-2 separator. The study will include precise determinations of ground-state masses made for these nuclei. It is worth noting that currently none of the neutron separation energies are known to better than 10 % for these nuclei. Transfer reactions of the (t,p) and (d,p) type, studied in inverse kinematical conditions, are the most suitable ones for the precise mass measurements.

F.3 New magic numbers and intruder states

There are basic problems in the field of exotic nuclei where ACCULINNA-2 operates. One example is the ascertainment of the patterns associated with the closed-shell breakdown at the magic neutron number N=8 and the manifestation of s-d intruder states in the neutron-rich nuclei ^{9,10}He, ^{10,11}Li, ^{11,12}Be. Clarification of filling sequences arising in the s-d neutron shell in a number of neutron-excess nuclei (e.g. ^{15}Be, ^{16,18}B, ^{17,19}C) and the interplay of s- and d- wave states in their even-N neighbours is another basic problem, which calls for thorough investigation. On the proton-excess side, similar phenomena call for the study of the possible two-proton halo structure, with a ^{15}O core, predicted by theory for ^{17}Ne. Of special interest is the termination of the s-d shell occurring in the C, N, O, F and Ne nuclei in the vicinity of neutron number N=16. The 20-30A MeV beams of ^{24}O, ^{26,27}F, ^{28,29,30}Ne provided at ACCULINNA-2 are well suited for studying resonant states of nuclei (e.g. $^{24\text{-}26}$O) lying near and beyond the drip line.

F.4 Two-proton radioactivity

The upgrade of the U-400M cyclotron planned for the period 2020-2022 will open ways to the whole series of proton-rich nuclei with $Z \leq 36$, lying close and beyond the proton drip-line. These include a number of nuclei predicted to exhibit 2p-radioactivity. Furthermore, great interest is in the dynamics of the 2p decay of resonant states, e.g., of ^{6}Be, ^{12}O, ^{16}Ne, ^{26}S, ^{30}Ar, ^{48}Ni etc. The detection of the 2p-decay branch for the first excited state of ^{17}Ne will clarify the issues related to the Z=8 waiting point affecting the rp-process in the sites of hot stellar burning.

The properties of nuclei ^{21}Si, ^{30}Ar and ^{34}Ca with half-lives shorter than 100 ps can be ascertained well due to the excellent choice of RIBs provided by the ACCULINNA-2/U-400M complex. In particular, the rare phenomenon of the β-delayed 3p-decay of ^{31}Ar [Lis15] could be investigated in great details. The quest for ^{21}Si and ^{26}S is challenging because it is very probable that the two-proton emission is the main decay mode of these nuclei. Quite detailed studies of the 2p decay mode will be feasible for the nuclei having lifetime $T_{1/2}$>50 ps. This becomes realistic because one can produce these nuclei in transfer reactions induced by RIBs. The (p,d) and (p,t) type reactions are favourable to cope with this task. For the ^{21}Si and ^{26}S nuclei, their formation and decay, occurring in-flight, should be verified by the detection of the daughter nucleus and the two emitted protons.

F.5 Spectroscopy of exotic nuclei

At ACCULINNA, a notable experiment series of transfer reactions via correlation techniques have been performed, and excitation spectra in exotic nuclei have been measured. Such technique has been applied before to identify the spin-parity of excited states displaying the emission of spinless particles. In the experiments performed at ACCULINNA, the method was further developed [Gol04a, Gol05]. As is well known, highly aligned states are produced in direct reactions. In the rest frame of the exotic nucleus, formed as the reaction product, the highest degree of spin alignment is obtained in respect to the axis parallel to the transferred momentum vector. The decay of the aligned configuration may produce sharp correlation patterns. The interpretation of the observed correlations may appear to be unique, this was the case, for example, with the spectrum of ^{9}He populated in the (d,p) reaction [Gol07].

Typically, the resonance states of light drip-line nuclei (especially on the neutron-excess side) are broad and overlapping, and their correlation patterns are affected by interference. Therefore, even weakly populated states may become apparent due to the contribution made into the interference patterns. The addition of amplitudes acts in this situation as a kind of "quantum amplifier" giving access to the details of the spectrum which otherwise would be too complicated for their revelation.

F.6 Cluster states

Many nuclei up to the sd-shell are known to have cluster structures in the ground state and at excited states. Rotational bands with a well-expressed molecular structure, characterized by large deformation have been observed. Good candidates for such studies are the heavy isotopes of He, B, C, O, Ne, etc.

The correlation measurements and the complete kinematics studies, discussed above, form the most common way for elucidating clustering aspect of nuclear dynamics. The importance of the Optical Time-Projection Chamber [Mie07, Lis15] should be specially emphasized here. It gives opportunity to make complete kinematics measurements in experiments where the "useful" counting rates are just units and tens of events. This is important for the studies of exotic nuclear systems attainable with low production rates.

F.7 Reactions with halo nuclei

Fusion reactions detected with the beams of halo nuclei have been of increased interest from experimental and theoretical points of view. In particular, much effort has been devoted to the subject of near-barrier fusion of light, weakly bound projectile nuclei. Unusual effects are expected here both from the halo structure of these nuclei and from the specific tunnelling mechanism of the composed weakly bound system which is of general interest for quantum theory. One example of this type of effects represents the recent study of the fusion reaction ^{6}He+^{206}Pb carried out at DRIBs-3 [Pen07]. Another example is the study of complete and incomplete fusion reactions of ^{6}He and ^{6}Li projectiles with ^{165}Ho and ^{116}Er target nuclei [Fom12]. The upgraded DRIBs-3 complex will give higher intensity and higher quality beams of ^{6}He nuclei and also a variety of other exotic beams (^{8}He, ^{9}Li, ^{12}Be, etc.) thus offering prospects for new insights into the process of low-energy fusion and multi-nucleon-transfer reactions of light exotic nuclei hitting against heavy targets.

F.8 Astrophysical applications

Nowadays, the nuclear astrophysics research is an integral part of the novel forms of nuclear dynamics study. Finite nuclear matter is the only directly accessible "testing ground" for theoretical models that are meant to look into the states of the infinite stellar matter.

Nuclear reactions in stars involve short-lived proton-rich and neutron-rich nuclei that can be studied only with radioactive beams. The cross sections of interest have to be obtained indirectly by the study of resonance reactions made via inverse kinematics on hydrogen and helium target nuclei. Transfer reactions allow determining level schemes and spectroscopic properties of nuclear states. Peripheral transfer reactions are suitable for measuring the quantities called Asymptotic Normalization Coefficients (ANCs), determining stellar capture rates. Transfer reactions performed with the RIBs delivered by DRIBs-3, such as (d,n), (d,p), (t,d), (p,d), or (^{3}He,d) can be used to extract the proton spectroscopic factors, ANCs, or neutron spectroscopic factors in mirror nuclei.

Two-proton radiative capture along the rp-process path is poorly understood so far. This process is directly related to two-proton radioactive decay. Of great importance will be experiments around the critical waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr. The ^{15}O waiting point is also important for the passage of the rp-process. The two-proton capture is a possible alternative to the (α,p) reaction as a pathway for the rp-process allowing the search for a weak 2p decay branch of the first excited $3/2^-$ state in ^{17}Ne. Decay of this state via emission of γ-quanta, yet the two proton decay was also predicted theoretically at the level $\Gamma_{2p}/\Gamma_\gamma \sim 10^{-5}$ - 10^{-6} [Gri07]. This assumption is still not confirmed experimentally [Chr97, Sha17] but might be feasible with the use of intense Z = 8-10 radioactive beams provided by DRIBs-3.

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G Material Science studies with heavy ion beams

High energy heavy ion beams have been proven as powerful tools for material modification and are being widely used in radiation solid state physics. An important feature of heavy ions is the possibility of tailoring micro- and macroscopic properties of materials and creation of nano-dimensional structures. High damage production rates, typical for energetic heavy ions, open a way for rapid simulation of radiation damage produced by neutron irradiation in materials showing promise for nuclear applications.

FLNR accelerators of heavy ions U-400 and IC-100 opened up unique opportunities for experimental researches in an energy range 1-20 MeV/A for ions from B to Bi. Main directions of ongoing and planned investigations are:

- Simulation of fission product impact in nuclear reactor materials and inert matrix fuel hosts with heavy ion beams of fission fragments energy.
- Study of surface modification and nanoscale damage formation on the surface of materials enhanced by single swift heavy ions in electronic stopping regime.
- Study of structural effects of dense ionization produced by swift heavy ions in radiation-resistant insulators.
- Elaboration of the basic principles of high energy ion implantation technology – the study of gettering effects, modification of electrically active dopant profiles and defect structure evolution in semiconductive materials, induced by high energy ions.

Human Resources

Development of the Laboratory projects will require increase of personnel from the existing staff of 450 persons to about 480 -500 persons in the next 10 years, focusing mainly on increasing the engineering and technical staff. Therefore, close collaboration with leading technical universities and institutes is necessary for sustainable development of FLNR. In this respect, a recently signed agreement between JINR, Bauman Moscow State Technical University and Government of

Moscow region on establishment of a higher engineering school in Dubna based on the Dubna State University is of great importance. Furthermore, improving our user-friendly environment for national and international collaborators requires additional resources.

Other proven and also new methods of training and recruiting of personnel include:

- Supervision of practical, bachelor, master, and PhD works prepared by students studied at scientific and technical departments of universities from the JINR Member.
- Excursions to the facilities and lectures about activity of the Flerov Laboratory for students.
- Planning various supplement schools for students of local universities during scientific conferences organized by FLNR.
- Investing into development of the human capital and training of the employees in the world leading educational centers.

General summary

Finally, during the next 7-year period 2024-2030 we plan the following:

1. The first priority of the long-term development of FLNR is synthesis of SHE and their isotopes as well as study of their chemical and nuclear properties at the SHE Factory, including:

– Development of experimental facilities of the SHE Factory.
– Implementation of an experimental program in the field of SHE.
– Construction of a specialized complex comprising radiochemical laboratories of class 1 certification for the manufacturing and regeneration of highly radioactive targets used, first of all, for the SHE research.
– Develop a new 28 GHz ion source in order to, first of all, extend the list of ions available at the SHE Factory up to uranium.

The SHE Factory will become a world base for future studies of superheavy nuclei and will reinforce the priority of all the JINR member states as leaders in the field of synthesis and study of Superheavy Elements.

2. Other priorities of FLNR until 2030 are:

– Reconstruction of the U-400 accelerator complex, including the construction of a new experimental building, the modernization of the cyclotron to U-400R and the creation of new facilities for studying nuclear reactions with heavy ions. Implementation of the experimental program of the U-400R complex.
– Continuation of experimental research in the field of light exotic nuclei located at the borders of nuclear stability on the modernized U-400M cyclotron, using the ACCULINNA-2 fragment separator and the DRIBs complex to produce post-accelerated beams of radioactive nuclei.

Modernization and development of these FLNR's accelerator complexes, construction, in particular, a unique cryogenic system for tritium and other gaseous target materials, will allow realization of a highly demanding experimental program on the world-top level.

3. Continue discussion of long-term plans for the development of the complex of FLNR scientific and technical facilities.

The majority of experiments carried currently out at FLNR are performed in a broad international collaboration with leading institutions from the JINR member states and beyond. This practice will be continued in future. The total available beam time of three FLNR's cyclotrons (DC-280, U-400R, and U-400M) is expected to be of about 15 000 hours annually. This will allow us to formulate a user policy and open the FLNR facilities for external users.

The FLNR budget necessary for implementation of the development and research program in the period 2024-2030 should be in line with the Laboratory budget for the current 7-year period.