ABSTRACT FOR THE THEME 03-5-1130
"SYNTHESIS AND PROPERTIES OF SUPERHEAVY ELEMENTS,
STUCTURE OF NUCLEI AT THE LIMITS OF NUCLEON STABILITY"
to be prolonged for 2022–2023

Leaders: M.G. Itkis, S.I. Sidorchuk
Scientific Leader: Yu.Ts. Oganessian

The primary objectives under the theme are the following:

1. Synthesis and study of the properties of superheavy elements with Z = 110-120 at the Factory of Superheavy Elements.
2. Study of chemical properties of superheavy elements.
3. α-, β-, γ-spectroscopy of heavy and superheavy nuclei;
4. Production of new heavy and superheavy nuclei in reactions of multinucleon transfers and quasifission.
5. Investigation of nuclear reactions with stable and radioactive nuclei.
6. Study of structure of nuclei near the drip lines.
7. Theoretical studies of the structure of nuclei and nuclear reactions involving stable and radioactive nuclei.
8. Development of the web knowledge base on low-energy nuclear physics.
9. Development of physical facilities for the study of nuclei at the boundaries of stability.

Theme funding in 2022-2023

(USD, in thousands)

NN	**Budget item**	**2022**	**2023**
1	Wages	2 933.3	2 933.3
2	International cooperation on research and development	400.0	400.0
3	Materials, equipment	2 600.0	2 200.0
4	Electric energy, water		
5	Operational costs	47.4	52.2
6	Basic facility	2 197.9	2 254.5
7	General and administrative costs	966.6	1 047.2
	TOTAL:	**9 145.2**	**8 887.1**

HEAVY AND SUPERHEAVY NUCLEI

Synthesis and study of nuclear properties of isotopes of superheavy elements

The launch of the cyclotron DC280 and the separator DGFRS-II at the SHE Factory allows considerable increase of efficiency of experiments on studies superheavy elements.

Experiments on the synthesis of Mc isotopes in the reaction ^{243}Am(^{48}Ca,2-4n)$^{287–289}$Mc will be continued. This reaction allows studying rare channels of formation, as well as more deep study the properties of nuclei. For example, cross-section of pxn channels, probability of an electron capture branch of ^{288}Mc, α–decay of ^{281}Rg and fission of the daughter isotope ^{277}Mt may be mentioned. In the very first experiments α decay of ^{268}Db leading to the unknown isotope ^{264}Lr has been observed.

This reaction, as well as the reaction ^{242}Pu(^{48}Ca,3-4n)^{286,287}Fl, will be used to study the chemical properties of the elements Nh, Mc, Cn and Fl. The relevance of these studies is associated with the possibility to compare the properties of these elements with the properties of their homologues. Thus, it is possible to determine experimentally the influence of relativistic effects on the chemical properties of the heaviest elements, to get information concerning the compliance of the chemical behavior of superheavy elements with the law of periodicity of properties, which is extremely important for understanding the structure of the Periodic Table of elements. The DGFRS-3 separators will be used as a preseparator in front of the chemical facility. In the same experiments, the decay properties of the synthesized nuclei will also be studied.

One of the important experiments is the synthesis of yet unknown heaviest isotopes $^{293,295–297}$Og in the $^{249–251}$Cf+^{48}Ca reactions (Fig. 1). These nuclei are located most close to N=184, that strongly influences their decay properties and production cross sections. The measurement of the α-particle energies of $^{293–296}$Og and the dependence of Q_α on N as well as their production cross sections could clarify the problem of the proton magic number for superheavy nuclei.

The most important task of studying the domain of superheavy nuclei remains the synthesis of new elements 119 and 120. These elements can be synthesized in the reactions with ^{50}Ti, specifically in ^{249}Bk(^{50}Ti,3-4n)^{295,296}119 and $^{249–251}$Cf(^{50}Ti,3-4n)$^{295–298}$120. Increased mass and proton numbers of the projectile can lead to a considerable decrease in the probability of formation of the compound nucleus. For a more accurate evaluation of this factor, investigation of the reaction induced by ^{50}Ti and ^{48}Ca, leading to the same compound nucleus, is crucial. The reaction ^{244}Pu(^{50}Ti,3-4n)^{290,291}Lv makes it possible to estimate the production cross section of Lv nuclei in comparison with data obtained in the reaction ^{48}Ca+^{245,248}Cm.

Alternatively, as shown in the previous experiments the fusion cross sections the reactions with ^{54}Cr and ^{50}Ti leading to the production of elements 119 and 120 are quite close. Therefore, the reactions ^{243}Am(^{54}Cr,3-4n)^{293,294}119 and ^{248}Cm(^{54}Cr,3-4n)^{298,299}120 may be even more promising.

To estimate the degree of cross-section drop in the transition from ^{48}Ca to ^{54}Cr, it is necessary to perform an experiment on the synthesis of the isotopes of Lv in the reaction ^{238}U(^{54}Cr,3-4n)^{288,289}Lv. Identification of these new isotopes will be based on the fact that their decay chains include the known isotopes ^{284,285}Fl.

As can be seen in Fig. 1, all the listed reactions for the synthesis of new elements 119 and 120, except for ^{243}Am+^{54}Cr, lead after their decays to known isotopes, which will ensure their reliable identification by observing successive correlations. The decay properties of the daughter nuclei ^{293,294}119→^{289,290}Ts→^{285,286}Mc can be measured in the reaction ^{241}Am+^{48}Ca.

The reaction ^{241}Am(^{48}Ca,2-4n)$^{285–287}$Mc allows to study in detail the neutron-deficient nuclei with odd Z. Note, only three decay chains of ^{287}Mc and two of ^{282}Nh have been so far observed. The decay of ^{285}Mc can lead to the known nuclide ^{261}Lr (provided that ^{265}Db undergoes α-decay). This would allow us to observe for the first time a chain of successive decays from the region of superheavy nuclei to the region of known nuclides obtained not in reactions with ^{48}Ca.

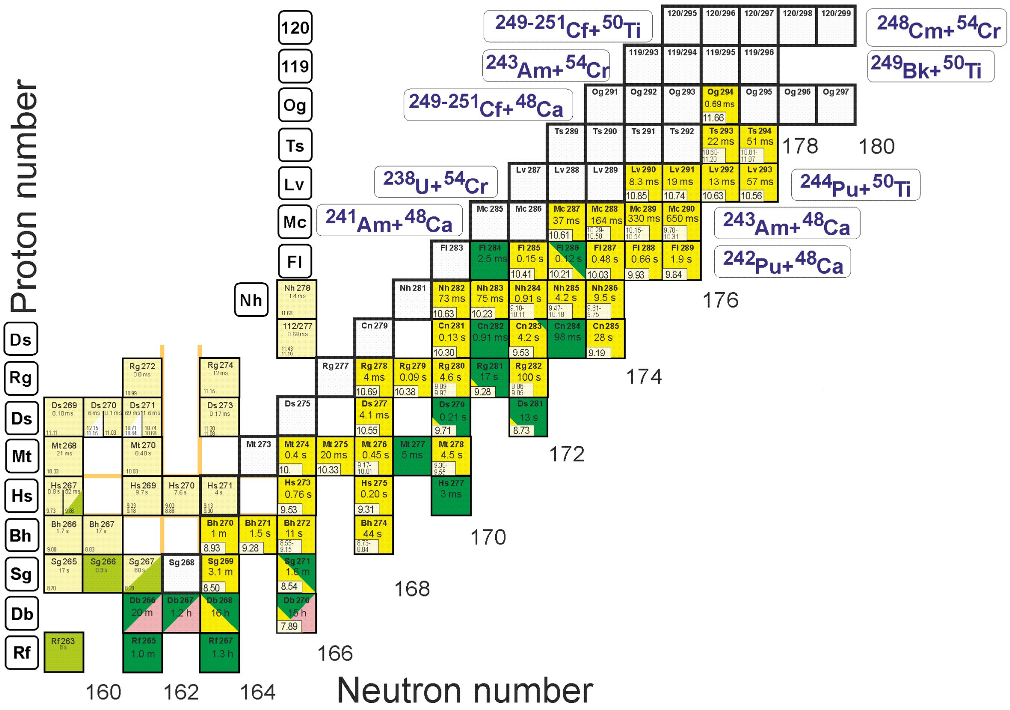

Fig. 1. The upper part of the Chart of Nuclides. New nuclides that can be synthesized are shown by blank squares.

These studies will be implemented in collaboration with the research centers of the USA in Oak Ridge (ORNL), Knoxville (UT), and Nashville (VU), as well as those of the Czech Republic, Olomouc (PUO), the People's Republic of China, Lanzhou (IMP, CAS) and the Russian centers, i.e., RIAR (Dimitrovgrad) and RIEPh (Sarov).

To be implemented by (FLNR staff): V.K. Utyonkov+15 persons.

Chemistry of superheavy elements

Today, the key issue requiring an in-depth study of the behavior of single SHE atoms is the identification of the influence of relativistic effects on their chemical properties and on the law of periodicity in the Periodic Table of D.I. Mendeleev. Such studies, requiring a significant increase in efficiency, became possible for the first time at the new experimental complex SHE Factory. Pioneering research on the chemical identification and study of the chemical properties of Cn, Nh and Fl (elements 112, 113 and 114) carried out in previous years is being prepared for continuation in 2022-2023 at a statistically new level. In 2006-2018, experiments were started on the chemical identification of elements 112 and 114 synthesized by irradiating a target from ^{242}Pu with accelerated ^{48}Ca ions at the U-400 accelerator. Decay chains of isotopes of elements 112 and 114 were registered and confirm results obtained earlier in a physical experiment. It was shown for the first time that the change in the chemical properties of element 112 (volatility, adsorption on the gold surface) occurs in accordance with the expected for analogs in the group of the periodic table of elements of D.I. Mendeleev (Zn, Cd, Hg), while element 114 showed properties closer to noble gases, and not to Pb. However, the small number of observed atoms and high background conditions did not allow an unambiguous determination of the chemical properties of the studied elements. These studies will be continued with the use of the method of gas adsorption thermochromatography at the DC-280 accelerator complex in the framework of cooperation between FLNR and PSI (Switzerland).

To study the conditions for the formation of volatile nihonium compounds and prepare for experiments with a higher efficiency at the SHE Factory, research will be continued at the SHELS separator. A new gas chamber for stopping and transport (RTC) recoil nuclei was developed. RTC will be mounted at the focal plane of SHELS and separated from vacuum by a thin mylar foil. A unique feature of this chamber is its speed and the ability to keep temperature up to 650°C. The isothermal chromatographic column installed behind the chamber can operate within the temperature range from the room temperature to 900°C. This will allow us to study the behavior of thallium, a light homologue of Nh, stopping of recoil nuclei in the gas phase, chemical reactions of hot atoms in pure conditions, kinetics of formation of chemical compounds, yield of chemical reaction products, and their transportation to a chemical detector depending on temperature, water vapor content and composition of gases. The formed volatile thallium compounds will be studied by isothermal adsorption chromatography in combination with γ- and α-spectrometry. The experiments will be carried out on-line under conditions strictly identical to those at the SHE factory, producing the short-lived thallium radionuclide ^{184}Tl ($T_{1/2}$ = 10.1 c) in the ^{141}Pr(^{46}Ti, 3n) nuclear reaction at the U-400 accelerator.

The planned experiments will require radiochemical research in the following areas: a theoretical study of the electronic structure and chemical properties of SHE; fabrication of accelerator targets from enriched isotopes of actinides that are stable in long irradiations with high-intensity beams of heavy ions; preparation of metallic ^{48}Ca and ^{50}Ti and ^{54}Cr compounds for ion sources; radiochemical analysis of the nuclear reactions products and methods for the isolation of radioisotopes from irradiated targets.

To conduct research on the chemical properties of SHE, a new setup will be installed at the separator GFS-3. It will consist of a gas chamber for collecting separated recoil nuclei, a system for fast gas transport of volatile elements and a detection module combined with gas adsorption chromatography - a cryodetector.

On-line separators for the Dubna Superheavy Element Factory

A new gas-filed separator, GFS-3, (Fig. 2) is being developed for a detailed spectroscopic study of heavy isotopes. This separator is manufactured, equipped and installed for testing at the beam of the DC280 cyclotron. High-beam intensities from the DC280 cyclotron and the increased detection efficiency of the modernized GABRIELA set-up for gamma and conversion electrons will allow us to plan spectroscopy experiments in 2022 aimed at study the nuclear structure of superheavy nuclei. In the complete fusion reaction ^{48}Ca+^{243}Am→ ^{291}Mc*, we can reach a relatively high yield of one decay chain per day with the beam intensity of 1.5-2 pμA. During the experiment, we plan to measure about 100 decay chains of isotopes of element 115 consisting of 5 subsequent alpha decays from Z=115 to 105. Coincidences with prompt and delayed gammas and conversion electrons will allow us to obtain information on the level structure of the populated isotopes.

Fig. 2. Separator GFS-3 (during assembly) at the experimental hall of the SHE Factory.

It is planned to use the GFS-3 setup for study chemical properties of SHE. For this purpose, the GFS-3 is supplemented with additional dipole magnet, before focal plane, which will allow to guide evaporation residues to a radiochemical setup. Besides, a new setup (pre-separator) aimed at the study of chemical properties of SHE has being worked out. For this purpose we consider a gas-filled superconducting solenoid.

To be implemented by (FLNR staff): A.V. Yeremin+15 persons.

α-, β-, γ-spectroscopy of heavy and superheavy nuclei with the SHELS setup

In the FLNR experiments, we use heavy-ion beams from the U400 cyclotron. Our main instrument for the separation of reaction products is the modernized separator SHELS. For detailed spectroscopy of the separated products, we use the GABRIELA array of different detectors for measuring alpha particles, conversion electrons, fission fragments, gamma rays, and *X*-rays. Fig. 3 shows available spectroscopy information (a number of known levels) in the upper part of the Nuclear Map. In this figure, the spectroscopically studied isotopes are depicted by red boxes, and those, which could potentially be studied in 2022–2023 using the SHELS + GABRIELA set-up are depicted by green boxes.

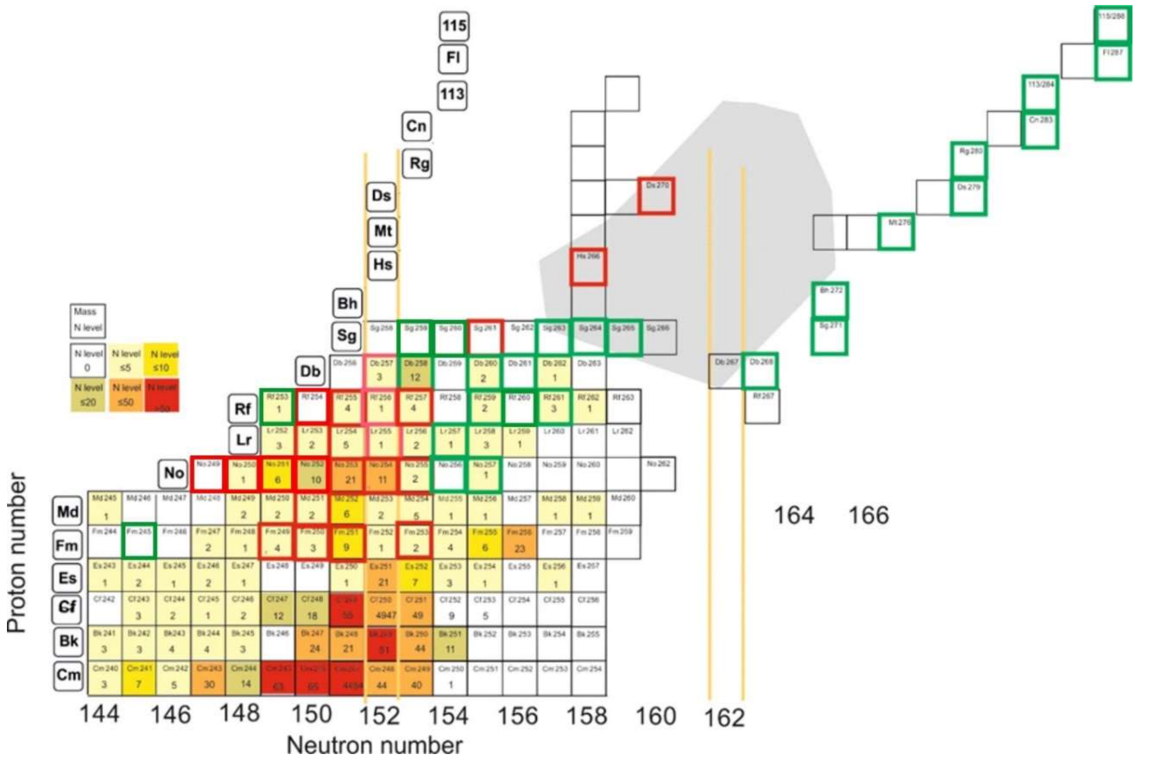

Fig. 3. The available spectroscopy information (number of the known levels).

By the end of 2021 we plan to modernize the SHELS separator. The first triplet of the quadrupole lenses will be replaced by a new one that will increase the separator acceptance (see Fig. 4). As expected, this will improve the suppression of background reaction products as well as increase the efficiency of transporting evaporation residues to the focal plane. The modernization will increase the separator transmission, especially for asymmetric complete fusion reactions e.g. ^{22}Ne + ^{238}U,$^{242,244}Pu$ that allows us to study the No-Rf isotopes in the vicinity of the deformed neutron shell N=162.

The upgraded detection system SFiNX includes (see Fig. 5) a combined detection system consisting of the 100x100 mm focal DSSSD detector and 116 neutron counters that will allow measuring the characteristics of spontaneous fission of short-lived nuclei in the region of SHE (Z > 104).

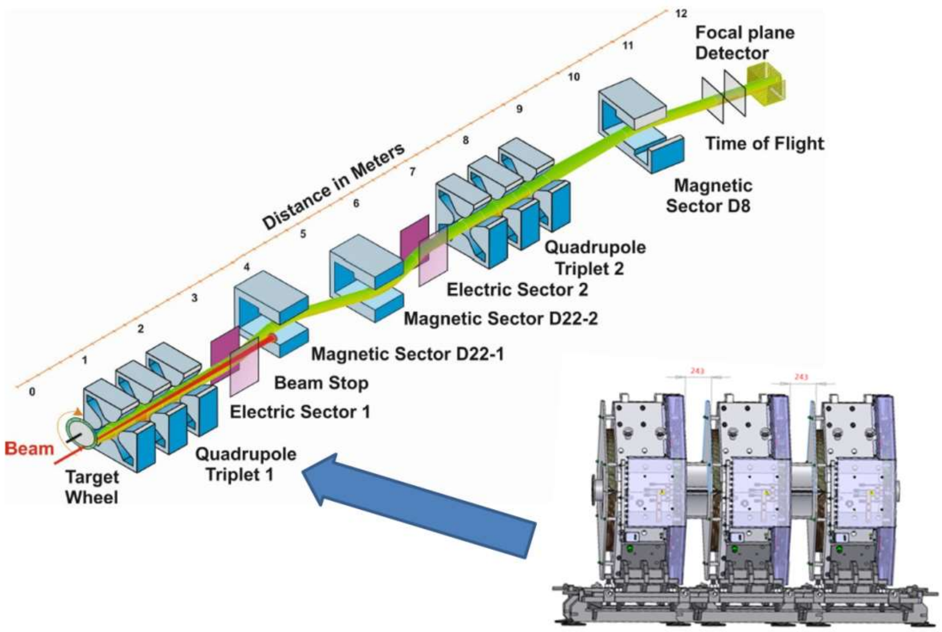

Fig. 4 SHELS separator. The expected increase in the entrance aperture is 30%.

Fig. 5. Combined detection system SFiNX (116 He-3 neutron counters, 128x128 strips Micron-DSSSD). Efficiency for the single neutrons – 57%.

Investigation of the mechanisms of heavy-ion induced reactions.

Multinucleon transfer process is one of the main reaction channels in collisions of heavy nuclei as well as fusion-fission, quasifission, and fast-fission. Now multinucleon transfer is widely discussed as a method for the production of neutron-enriched isotopes of heavy elements hardly achievable by other methods. The least studied regions of heavy neutron-enriched nuclei are those near the neutron shell closure N=126 and heavier than uranium. Therefore, special interest can be paid to combinations of colliding nuclei that can lead to the production of nuclei in these two regions.

Combinations of colliding nuclei spherical in the ground state are of great interest not only for the synthesis of new nuclei but also for studying mechanisms of nuclear reactions since the mutual orientation of colliding nuclei doesn't influence nuclear dynamics. The matter of fact is that it simplifies corresponding theoretical analysis of such reactions. In particular, promising combinations of colliding nuclei for production of heavy neutron-enriched nuclei near *N*=126 comprise nearly spherical nuclei like ^{198}Pt and ^{208}Pb as targets and ^{136}Xe as a beam.

Systematical study of multinucleon transfer in several combinations of colliding nuclei with such heavy spherical targets as ^{208}Pb should be continued. The reaction ^{136}Xe + ^{208}Pb had been already investigated at CORSET and showed intensive nucleon transfer in this system. Spherical projectiles like ^{48}Ca, ^{86}Kr, ^{136}Xe, ^{208}Pb can be used to study multinucleon transfer in the absence of orientation effects and help to answer the question on the optimum choice of the projectile for the production of neutron-enriched target-like fragments (near *N*=126). In particular, a dynamic model based on Langevin equations predict broadening of mass and charge distributions of reaction products as the total system mass increases.

To understand the role of orientation effects in collisions of statically deformed nuclei, similar systems can be studied: one consisting of spherical colliding nuclei and another one contained nuclei deformed in the ground state. There are only a few systematical studies of deep inelastic collisions of such kind: ^{144}Sm + ^{144}Sm, ^{154}Sm + ^{154}Sm, ^{208}Pb + ^{208}Pb, ^{238}U. Corresponding experimental data are of great value for testing theoretical models of heavy-ion reactions. The impact of closed nucleon shells can also be studied in these experiments.

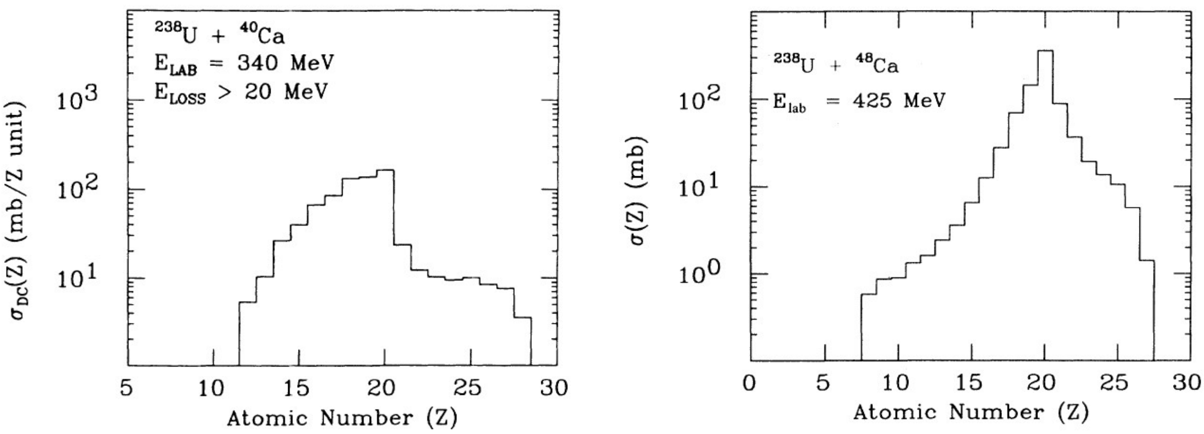

Fig. 8. Experimental cross section of the projectile-like products are shown in units of mb/Z unit versus atomic number (Z) for E_{loss} > 20 MeV [R. T. de Souza et al., Phys. Rev. C 37, 1901 (1988); ibid 39, 114 (1989)].

Different theoretical approaches predict quite large production cross sections of neutron-enriched isotopes of transuranium elements as target-like fragments in the multinucleon transfer reactions. Therefore, special attention should be paid to multinucleon transfer processes in systems with heavy actinide targets in order to investigate this prediction.

Choice of a projectile in combination with an actinide target is also an important issue. Using even different isotopes of the same element as the projectile, the shape of charge (mass) distribution of multinucleon transfer products drastically changes. Corresponding observations for the ^{40,48}Ca + ^{238}U systems are shown in Fig. 8. Similar behavior was also found for the ^{58,64}Ni + ^{238}U system. So, the ^{40}Ca, ^{58}Ni + ^{238}U reactions can be studied in addition to available data on ^{48}Ca, ^{64}Ni + ^{238}U systems in order to investigate this issue in more detail.

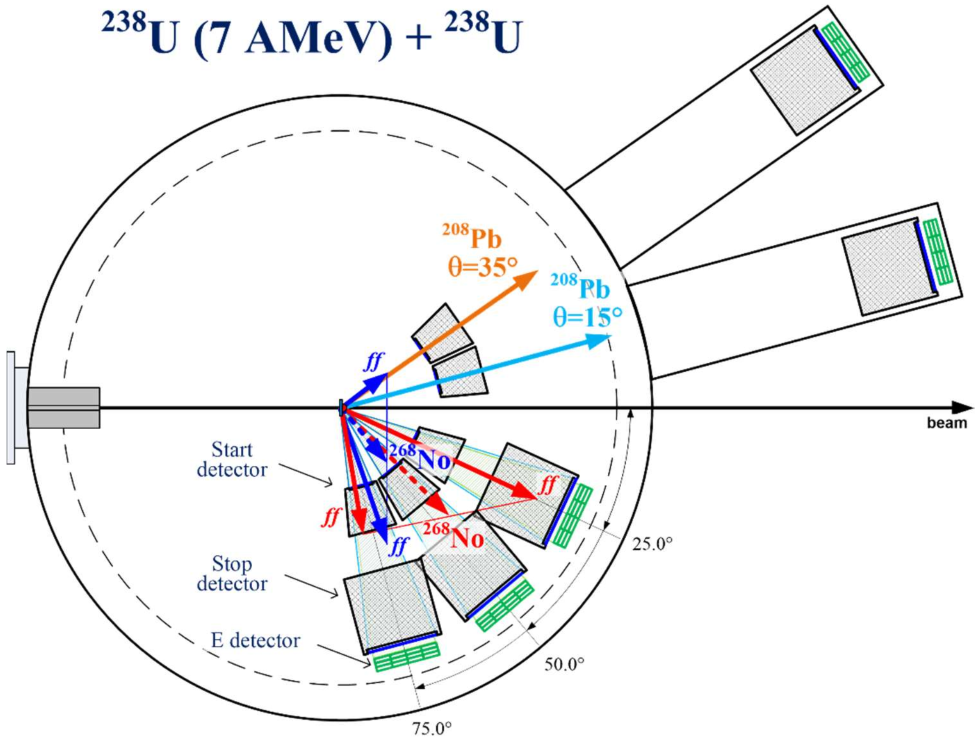

Fig. 9. Scheme of the CORSET setup to measure the formation of ^{208}Pb + ^{268}No fragments in multinucleon transfer process in the reaction ^{238}U + ^{238}U at the interaction energy of 7 AMeV. The orange and red arrows show the velocity vectors for the formation of Pb + No pair at an angle of 35° for Pb fragment, the light blue and blue arrows correspond to the case of an angle of 15° for Pb fragment.

In the nearest future, we plan to study the multinucleon transfer in the ^{238}U + ^{238}U reaction at the energy above the barrier. At the first step of the investigations, the probability of the ^{208}Pb + ^{268}No pair formation will be studied. According to our calculations, the fragments of ^{268}No are expected to have excitation energy from 40 up to 150 MeV and undergo fission during the de-excitation process. In order to detect the binary channel ^{238}U + ^{238}U → ^{208}Pb*+ ^{268}No* as well as

$^{208}Pb^{*}$+ fragments from the sequential fission of $^{268}No^{*}$ we installed five ToF-E arms inside the CORSET chamber. Such geometry allows reconstructing the full kinematics of formed fragment pairs even in the case of the sequential fission of No fragments. The scheme of the experiment is shown in Fig. 9.

Rare decay modes

In 2022-2023 it is planned to continue the study of clusterization in heavy nuclei in order to obtain experimental estimates of the lifetime of isomeric states in fission fragments in the $^{235}U(\gamma, f)$ reaction and to carry out a kinematically complete experiment with the measurement of the masses, energies, and velocity vectors of all nuclei involved in the process in the spontaneous fission of ^{252}Cf.

Recently new VEGA (V-E Guide based Array) setup was installed at the MT-25 microtrone in FLNR. Fission fragments (FFs) from the ^{235}U (γ, f) reaction are captured by the electrostatic guide system (EGS) consisted of the tube and the central wire forming a cylindrical capacitor. FF masses are measured using the time-of-flight spectrometer located at the exit of the EGS. The EGS allows increasing a counting rate at the detector placed few meters away from the target. A spectrometer with an extremely long flight path is a unique instrument for estimating the shape isomers' lifetime lying even in the microsecond range.

It is planned to complete by the end of 2022, the upgrade of the spectrometer aimed at essential increasing of its efficiency due to using the EGS voltage up to 12kV, reconstruction of the radiation shield of the beam channel used, testing of the second spectrometer arm.

For this purpose, joint work with a group from the Czech Republic has begun on the use of their Timepix3 two-coordinate pixel detector with 55μ spatial resolution in studies of multibody decays. A new experimental setup based on Timepix3 pixel device, mosaics of PIN diodes and microchannel plates-based timing detectors will be constructed and put into operation in nearest two years.

Study of the structure of exotic nuclei near and beyond the drip-lines

Analysis of the experimental data obtained early in 2018-2020 at the ACCULINNA-2 fragment-separator together with related theoretical explanation will be continued. In particular, new information about the level schemes and characteristics of the decay modes of neutron-rich systems such as $^{6,7}H$, $^{7,9}He$, and $^{9,10}Li$ is expected.

Special attention will be given to the Monte-Carlo simulation of the future experiments, which will be made at ACCULINNA-2 with the use of a tritium target. High priority has the future study of the ^{7}H structure: the measurement of the width of its ground state with better energy resolution (σ~150 keV), the acquisition of new data on the ^{7}H energy spectrum resulting in the identification of ^{7}H resonant levels in the energy range $E_T < 12$ MeV, precise measurements of angular and energy correlations of the ^{7}H five-body decay products.

The neutron-rich systems ^{10}He, ^{11,13}Li, ^{16}Be, ^{18,19}C, and ^{26}O are also in the sphere of interest. For these systems as well as for the neutron-deficient systems ^{17}Ne, ^{23,24}Si, and ^{26,27}S, Monte-Carlo simulation will be done for the layouts of the planned experiments taking into account the characteristics of the newly implemented instrumentation, i.e., the RF-kicker and zero-angle spectrometer.

Experimental studies of the *β*-delayed charged particles spectroscopy with the OTPC (Optical Time Projection Target) will be continued. The OTPC technique is ideally suited for this measurement, given its almost 100% efficiency for low-energy charged-particle detection. The sphere of interest of these studies is focused mainly on neutron-deficient nuclei (e.g., ^{9}C, ^{23,24}Si, ^{27}S) and its exotic decays - *β*-2p, *β*-3p, *β*-^{3}He, *β*-2αp.

A new joint project between FLNR, JINR, and Faculty of Physics, UW, Warsaw, to equip the ACCULINNA-2 separator by universal instrumentation – AGT-TPC (Active Gaseous Target Time Projection Target) is foreseen. It should permit new studies of the structure and decays of the most exotic nuclei as well reactions with RIBs at low energies.

Another challenging task is measuring the cross sections for the RIB induced transfer reactions where the neutron-rich clusters (e.g., ^{6}He, ^{8}He) are relocated to nuclei with atomic numbers Z ≥ 92. Planned are experiments aimed at the cross-section measurements made (in inverse kinematics) for the reactions ^{238}U(^{10}Be,^{4}He)^{244}Pu and ^{238}U(^{12}Be,^{4}He)^{246}Pu performed at the RIB beam energies ~6 AMeV.

Development of new experimental methods and techniques with the use of different radioactive sources (alpha-neutron-gamma-fission) will be continued. In particular, a neutron array of 253 tightly composed plastic scintillators will be created and tested.

To be implemented by (FLNR staff): A.S. Fomichev +33 persons.

Reactions with exotic nuclei

In 2022-2023, studies of the mechanisms of reactions leading to formation of exotic nuclei will be continued with the use of high-resolution magnetic analyzer MAVR (U400 cyclotron).

Over the years to come, the implementation of the plan will be carried out as follows

2022 - Preparation of a method for the simultaneous measurement and identification of two products of nuclear reactions with emission of fast charged particles using magnetic analysis MAVR. Creation of detecting devices in the focal plane of the analyzer for registration of fast charged particles (with energies up to 120 MeV/A) and slow, heavy recoil nuclei (with energies up to 1-2 MeV/A). Performing test experiments on heavy ion beams of the U400 to study the sensitivity of the technique and the possibility of simultaneous (in coincidence) registration of two reaction products with emission of fast particles and a slow recoil nucleus.

2023 - Carrying out experiments to measure the yields of fast particles depending on the Z of a target and beam nuclei at different energies of the primary beam. Choosing of the optimal reactions for the synthesis of cold exotic nuclei. Carrying out test experiments on heavy ion beams of the U400 cyclotron to study the sensitivity of the technique and the possibility of simultaneous (in coincidence) registration of two reaction products with emission of fast particles and a slow recoil nucleus. Analysis of the obtained results based on the developed theoretical model of pre-equilibrium processes.

All research will be carried out in close cooperation with the scientific centers of the JINR member countries: Russia (Kurchatov Scientific Center, SINP MSU and Voronezh State University), Poland (Niewodniczański Institute in Krakow), Czech Republic (Nuclear Physics Institute in Řež), Kazakhstan (Cyclotron Laboratory DC-60, Institute of Nuclear Physics).

NRV knowledge base on low-energy nuclear physics.

The NRV web knowledge base on low-energy nuclear physics (http://nrv.jinr.ru/) has been developed in the Joint Institute for Nuclear Research. It integrates a large amount of experimental data with computational codes for modeling of nuclear properties and nuclear reactions. It also provides possibilities for planning experiments and analysis of experimental data. The knowledge base is available for any remote user via any web browser supporting the Java plugin. The main focus of the system is on modeling nuclear reactions: elastic and inelastic scattering, nucleon transfer, fusion with subsequent decay of the excited compound nucleus, etc. The NRV knowledge base may be used for both scientific and educational purposes.

Further use of the current version of the system is limited by the fact that there are trends of a gradual drop of support of the Java plugins (and, hence, Java applets) by the new versions of browsers. Thus, the further development of the NRV knowledge base is focused on the modernization of user interface, in particular, a transition from the use of Java applets to the use of new technologies, such as HTML5 and JavaScript. The current version of a new version of the system can be accessed via http://nrv2.jinr.ru. In parallel, we have developed a special browser supporting Java applets in order to preserve the possibility of using the current version of NRV. The browser is available for Windows and Linux OS and can be download from http://nrv.jinr.ru/.