FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2011, the FLNR scientific programme on heavy ion physics included experiments on the synthesis and study of properties of heavy and exotic nuclei using ion beams of stable and radioactive isotopes, studies of nuclear reaction mechanisms, heavy ion interaction with matter, applied research and development of acceleration technology. These research fields were represented in three laboratory topics and one all-institute project:

- Synthesis and properties of nuclei at the stability limits (9 subtopics);
- Radiation effects and physical bases of nanotechnology, radioanalytical and radioisotope investigations on the FLNR accelerators (5 subtopisc);
- Accelerator complex of ion beams of stable and radioactive nuclides (DRIBs-III) (5 subtopics);

In 2011, the operation time of the U400 and U400M FLNR cyclotrons amounts to ~ 11500 hours.

SYNTHESIS OF NEW ELEMENTS

In 2011, a series of experiments has been carried out being aimed at measuring excitation function of complete fusion reaction ^{243}Am(^{48}Ca, xn)$^{291-x}$115 and study of radioactive properties of the isotopes of element 115. The work was performed employing the gas-filled separator of FLNR (JINR) in collaboration with the laboratories of Oak Ridge (ORNL), Livermore (LLNL), and Nashville (VU) [1, 2].

Experiments were carried out at three energies of ^{48}Ca ions, 240, 243, and 248 MeV, accelerated at the U400 cyclotron with the corresponding beam doses of $16.5 \cdot 10^{18}$, $3.3 \cdot 10^{19}$ and $3.7 \cdot 10^{19}$. In the three experimental runs there were detected 21 decay chains of the isotope ^{288}115; three such nuclei were synthesized for the first time in 2003 at the energy of 248 MeV (see Fig. 1). Decay properties of all the six nuclei, ^{288}115, ^{284}113, ^{280}Rg, ^{276}Mt, ^{272}Bh, and ^{268}Db, produced in 2003 and in the present experiments coincide in full. The measured excitation function confirms that the observed isotope is ^{288}115 — the product of the $3n$ channel of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ (see Fig. 2).

At the energy of ^{48}Ca ions of 240 MeV, a heavier isotope ^{289}115 was synthesized, its α decay leads to the isotopes ^{285}113 (α decay) and ^{281}Rg (spontaneous fission). These nuclei were produced for the first time in the reaction $^{249}\mathrm{Bk}(^{48}\mathrm{Ca}, 4n)^{293}$117 after the decay of the mother nucleus. Radioactive properties of ^{289}115 and its daughter nuclei measured in this experiment agree with those that were determined for them from the five-decay chains of ^{293}117 in the reaction $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$. Thus, the isotope ^{289}115 was produced in two cross bombardments that convincingly proves the discovery of the superheavy elements 113, 115, and 117.

The complete fusion reactions ^{243}Am+^{48}Ca and ^{244}Pu+^{48}Ca leading to elements 115 and 114 have the highest cross sections compared with other reactions in which superheavy nuclei with higher or lower proton number were synthesized.

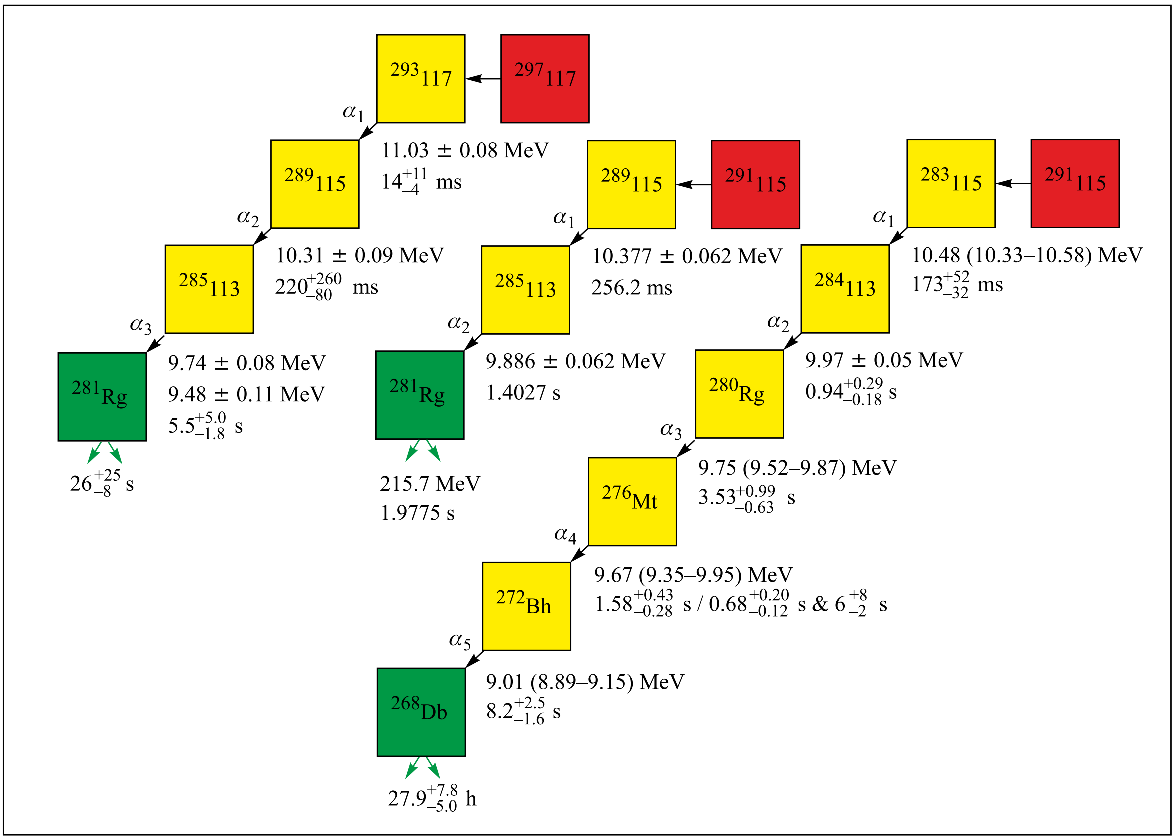

Fig. 1. Energies of α particles and half-lives of the nuclei in the decay chains of the isotopes $^{293}117$, $^{289}115$, and $^{288}115$. For $^{293}117$, $^{288}115$ and their daughter nuclei, the mean values, determined from 5 and 24 chains, respectively, are given

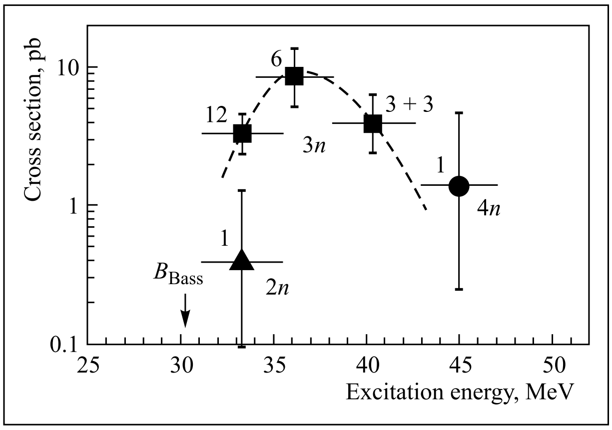

Fig. 2. Production cross sections of the nuclei $^{289}115$, $^{288}115$, and $^{287}115$ vs. excitation energy of the compound nucleus. Figures show the number of the nuclei synthesized in the present experiment and in 2003

CHEMISTRY OF TRANSACTINIDES

In 2011, a series of experiments on chemical identification of ^{268}Db as a final product of the $^{288}115$ decay was carried out. That study was aimed at the independent confirmation of the 115 synthesis in the reaction ^{48}Ca + ^{243}Am. In the experiments at U400 accelerator, the target composed of a thin titanium foil covered with ^{243}Am (99.9%) oxide at 0.5 mg/cm^2 thickness was irradiated by ^{48}Ca ions at the energy of 247 MeV. Integral beam dose makes $8.9 \cdot 10^{18}$. After preseparation at the gas-filled recoil separator (the separation coefficient makes 10^4–10^5) recoil nuclei were collected upon the copper foil located after the magnetic separation system. Irradiation time in each study was from 24 up to 48 hours. After the irradiation session the copper foil was transported to the radiochemical laboratory for chemical treatment. A set of semiconductor detectors were used for α-particles and nuclear fission fragments registration. Efficiency of Db fraction isolation according to spectroscopic measurements data was found to be within the range of 60–80%. A separation factor for group 5 elements from actinides was estimated to be $\geqslant 10^6$. Eight fission events were detected in 19 sessions ($T_{1/2} = 23^{+13}_{-6}$ h). Cross section of the reaction of interest was found to be $6.0^{+3.6}_{-2.4}$. The results acquired in the experiment are in good agreement with previous results. The most important results obtained in 2011 are published in [3, 4].

SEPARATOR VASSILISSA

In 2011, we continued the analysis of the data obtained at the separator VASSILISSA in experiments on the study of properties of the ^{253}No decay and spontaneous fission characteristics of neutron deficient Fm [5, 6].

In August 2011, the old VASSILISSA separator and the beam line were dismounted and the upgrade of the VASSILISSA separator was started. New vacuum section and two dipole magnets are being tested in the present time. The new focal plane detection array is being designed. Two new 10×10 cm position sensitive Si detectors were purchased, the special test chamber was manufactured. Design and efficiency simulations for Si and Ge detectors in the VASSILISSA focal plane are now in progress [7].

In 2011, researches of the VASSILISSA group took part in the GSI SHIP experiments on the synthesis of the 120 element in the reaction $^{54}\mathrm{Cr} + {}^{248}\mathrm{Cm} \rightarrow {}^{302}120^*$.

MASS-SPECTROMETER MASHA

In 2011, the time-of-light channel on the base of microchannel plates intended for the beam energy measurement was put into operation at the mass-spectrometer MASHA [8]. The control system of the hot catcher was upgraded. The measuring of the atoms transportation time from the hot catcher to the ECR source was carried out with using the inert gases gauge flows. The results of the measuring confirmed the preliminary estimates and allowed one to impose restrictions on the time response of the technique used.

Test measurements with using a hybrid silicon pixel detector MEDIPIX were performed in collaboration with the Institute of Experimental and Applied Physics of the Prague University (Czech Republic). These test measurements showed the perspective of applying this kind of detectors on the MASHA mass spectrometer for detection and identification of the nuclei beyond the region of stability. One plans to make use of the MIDIPIX detector in the experiments on measuring the efficiency of the MASHA facility by detecting the mercury isotopes synthesized in the reaction $^{40}\mathrm{Ar} + {}^{144}\mathrm{Sm}$.

LASER SPECTROSCOPY

The series of experiments dedicated to the study of hyperfine splitting and isomer shift measurement of ^{229}Th isomer was carried out at the FLNR laser spectrometer with the use of recoil nuclei ^{229}Th originating from the α decay of ^{233}U. It was shown that the low-lying isomer state with the energy ~ 5 eV is populated with the branching ratio of about 2%.

Further detailed development of the project of a new setup dedicated to extraction of reaction products by means of their stopping in gas and subsequent resonance laser ionization have been performed. The actual realization schemes of this setup and requirements for its different parts have been developed. Technical documentation and actual positioning of the setup at the FLNR accelerators (U400, U400M) is under development. The Workshop on Resonance Laser Separation of Nuclear Reaction Products with participation of leading specialists from Leuven, Jyvaskyla, GANIL, CERN, Darmstadt, Mainz, and iThemba LABS was organized in FLNR.

Modernization of the setup intended for laser spectroscopy of transuranium elements included a development of a high temperature atomizer on the base of electron bombardment heating. Vacuum and thermotesting were carried out. The atomizer was equipped with a new stabilized high-voltage power source allowing us to increase the atomizer temperature and the beam stability.

DYNAMICS OF HEAVY-ION INTERACTION, FISSION OF HEAVY AND SUPERHEAVY NUCLEI

The main task of the group is searching for new ways of production of neutron-rich isotopes near the stability island with the use of processes of multinucleon transfer and quasi-fission in reactions with heavy ions near the Coulomb barrier. Within the framework of this problematics, the mass, kinetic energy, and angular distributions of reaction products from the $^{136}Xe + ^{208}Pb$ reaction near the Coulomb barrier have been measured. The experiments were carried out at the Flerov Laboratory of Nuclear Reactions using the beam of ^{136}Xe ions extracted from the U400M cyclotron at the energies of 700, 870, and 1020 MeV. Besides, to get information about production cross sections of new neutron-rich isotopes of Os in the reaction $^{136}Xe + ^{208}Pb$, the experiment was carried out at the K-130 cyclotron of the Jyvaskyla University (Finland) at the energy of 820 MeV. The obtained data are very useful for further experiments on the production and investigation of properties of neutron-rich isotopes of ^{197}Os, ^{198}Os, ^{199}Os, and ^{200}Os.

Approaches used for the study of nuclei with $N = 126$ can be applied for the synthesis of superheavy elements in low-energy transfer reactions. If the cross sections are large enough for the production of the intensive beam, the synthesis of new isotopes located much closer to stability island with $Z = 114$, $N = 184$ will appear to be possible [9, 10].

EXOTIC DECAYS

Investigations of a new type of the multibody decay called by us a collinear cluster tri-partition (CCT) were continued at the new COMETA spectrometer [11]. It is a double arm time-of-flight spectrometer including a microchannel plate based "start" detector with the ^{252}Cf source inside. Two mosaics of eight PIN diodes each and a «neutron belt» consisting of 28 ^{3}He-filled neutron counters are used. Each PIN diode provides both energy and timing signals.

The fission fragments mass–mass distribution for the events, corresponding to three neutrons detected in coincidence and getting to the locus of conventional binary fission in the V_1–E_1 (velocity–energy) distribution, is shown in Fig. 3. A rectangular structure similar to that observed earlier in the data obtained at the modified FOBOS spectrometer is seen, however, for a different mass range. The additional gates let us to reveal new CCT decay modes with very light fragments. The rectangular structure is limited by masses close to those of known magic nuclei. These masses (except for ^{132}Sn) were calculated basing on the unchanged charge density hypothesis for the ^{252}Cf nucleus. It is known that at least three neutrons were emitted in each fission event presented in Fig. 3. Change in the mother system leads to the shift of masses of magic nuclei if neutrons were emitted just from the decaying system (prescission neutrons). Prescission neutrons emitted from the decaying system have preference in the registration efficiency due to geometry of the neutron counters array. This is a reason of revealing the structure under discussion if the neutron multiplicity selection is applied.

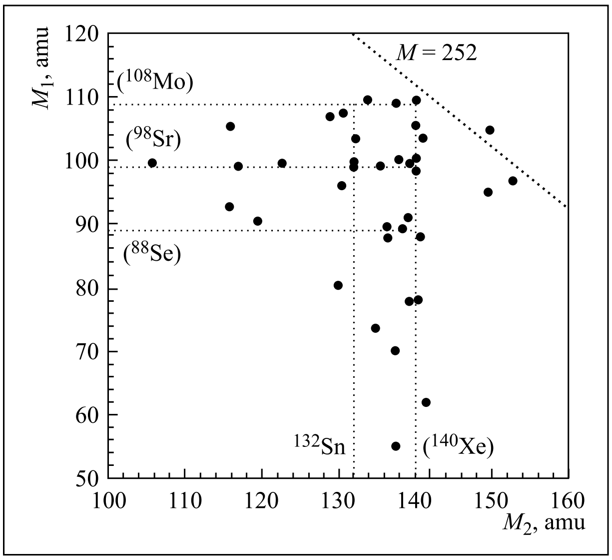

Fig. 3. Results obtained at the COMETA setup: mass–mass distribution of the FFs from ^{252}Cf (sf) when three neutrons ($n = 3$) were detected in coincidence and an additional selection with the gate in the (V_1–E_1) distribution

STRUCTURE OF EXOTIC NUCLEI

The low-lying spectrum of ^{10}He was studied in the $^{3}H(^{8}He, p)^{10}He$ transfer reaction at the fragment-separator ACCULINNA. The 0^+ground state energy and width are found to be 2.1 ± 0.2 and ~ 2 MeV. The spin-parity assignment for low-lying states of ^{10}He is made for the first time: the correct analysis allowed us to define the ^{10}He spectrum as a mixture of the 0^+, 1^- (at the energy above the decay threshold $E_T > 4$ MeV) and 2^+ ($E_T > 6$ MeV). The established level sequence shows that ^{10}He is one more dripline system demonstrating the breakdown of the shell structure [12].

In 2010, the structure of ^{6}Be was studied experimentally in the charge–exchange reaction ^{1}H(^{6}Li, ^{6}Be)n performed with 25 and 32A MeV ^{6}Li beams. Complete analysis of these data was continued in 2011. It was shown that the ^{6}Be spectrum up to 16 MeV of energy E_T (energy referred to three-body decay threshold) is completely described by the population of the three main structures in ^{6}Be: 0^+ at 1.37 MeV, 2^+ at 3.05 MeV, and the $\{0^-; 1^-; 2^-\}$ continuum state mixture at $\sim 4-16$ MeV. The negative parity continuum was interpreted as a novel phenomenon — the isovector soft dipole mode [13]

REACTIONS WITH BEAMS OF LIGHT STABLE AND RADIOACTIVE NUCLEI

The study of the energy dependence of the total reaction cross section was performed for the reaction Au + ^{6}He at the fragment-separator ACCULINNA with the use of 4π γ-spectrometer. In the experiment we measured excitation functions of the fusion reaction ^{196}Au + ^{6}He, charge particle emission, neutron transfer channels and isomeric states populations for the energies above the Coulomb barrier. Activation method based on the use of the high efficiency γ-spectrometer was applied.

Scientific collaboration with other institutes has been extensively developed in 2011. Experiments dedicated to the study of peculiarities of the interaction induced by weakly-bound nuclei with a cluster structure (d, ^{6}Li) were carried out at the U120 cyclotron NPI (Rez, Czech Republic) and the Tandem IFIN-HH (Bucharest, Romania) at the energies around the Coulomb barrier. The experimental data give evidences of the influence of a cluster structure of interacting nuclei on enhancement of particular channels at the energies around the Coulomb barrier as compared with model-dependent calculations [14]. One should mention, that the transfer of a d-cluster from the ^{6}Li projectile has a large cross section in this energy region and a maximum exactly at the Coulomb barrier (see Fig. 4). The obtained results are very important both for fundamental nuclear physics and astrophysics.

The series of experiments was performed at the microtron MT-25 to study a possibility for alternative production of the secondary ^{6}He beam in the reaction using the bremsstrahlung γ-rays ^{7}Li(γ, p)^{6}He. Atoms of ^{6}He, produced in the reaction, get to the ECR source and were ionized there (that gives a possibility for their subsequent delivery to an accelerator). Output intensity of $4 \cdot 10^5$ s^{-1} ions of ^{6}He was obtained at 1 μA current of electron beam.

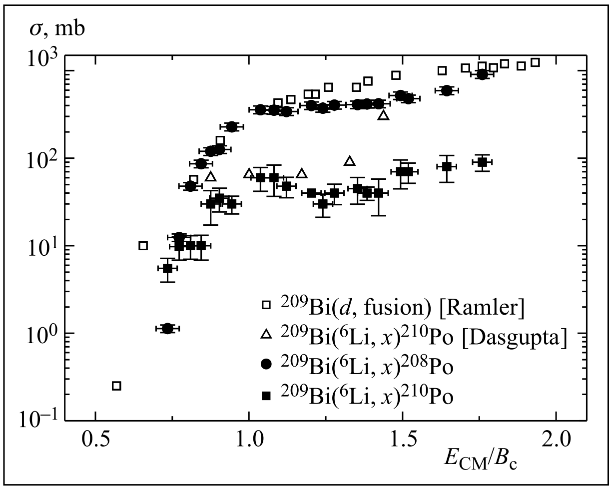

Fig. 4. Production cross sections for ^{209}Po (●) and ^{208}Po (■, △) vs. $E_{\rm CM}/B_{\rm c}$ obtained in the reaction ^{6}Li+^{209}Bi. Cross section for ^{210}Po (□) from the reaction ^{209}Bi(d, n)^{210}Po is given for comparison

THEORY AND COMPUTATIONAL PHYSICS

The problem of production and study of heavy neutron-rich nuclei has been discussed [15]. Multinucleon transfer processes in near barrier collisions of heavy (and very heavy, U-like) ions seem to be the only reaction mechanism allowing us to produce and explore neutron-rich heavy nuclei. Several transfer reactions for different projectile–target combinations are studied in detail. Besides the predictions for the cross sections of such processes, we also analyze the angular and energy distributions of primary and survived reaction products in the laboratory frame. These results, as well as predicted excitation functions for the yields of neutron-rich superheavy isotopes, might be useful for the design of appropriate experimental equipment and for carrying out experiments of such a kind.

The neutron capture process is considered as an alternative method for production of superheavy (SH) nuclei. Strong neutron fluxes might be provided by nuclear reactors, nuclear explosions and supernova explosions in nature. Two gaps of short-lived nuclei (the so-called «fermium gap» and the one located at $Z = 106-108$ and $N \sim 170$) impede the formation of SH nuclei by rather weak neutron fluxes realized at available nuclear reactors. We found [16] that in the course of multiple (rather «soft») nuclear explosions these gaps may be easily bypassed, and thus, a measurable amount of the neutron-rich long-living SH nuclei located at the island of stability may be synthesized. We formulate requirements for the pulsed reactors of the next generation that could be used for production of long-living SH nuclei. Natural formation of SH nuclei (in supernova explosions) leads to the yield of SH nuclei relative to lead of about 10^{-12}, which is not beyond the experimental sensitivity for a search for SH elements in cosmic rays.

The knowledge base on low-energy nuclear physics (NRV), allocated at the Web-site http://nrv.jinr.ru/nrv, was extended [17] with the partial support from the JINR-SAR cooperation programme. i) Computational code for a calculation of the few nucleon transfer cross sections within the distorted wave approximation was included into the knowledge base. ii) The possibility of taking into account of neutron transfer channels in the course of nuclear fusion processes was added to the system within the empirical model.

In the framework of the JINR-ARE cooperation programme the problem of the enhancement of subbarrier fusion reactions by the neutron transfer was studied. Large effect of the neutron transfer was predicted for several reactions available for experimental studies.

RADIATION EFFECTS AND PHYSICAL BASES OF NANOTECHNOLOGY, RADIOANALYTICAL AND RADIOISOTOPE INVESTIGATIONS ON FLNR ACCELERATORS

Track Membranes

1. Properties of a «nanofluidic» diode based on the asymmetric track-etch nanopore are investigated in detail. The relationship between the rectification coefficient and the nanopore geometry (its profile and dimensions) is studied. The dependence of the rectification ratio on the electrolyte concentration is analyzed. These results are essential for understanding of the processes in biological channels and for the development of biomolecular sensors.

2. A novel process of a porous carbon material production including irradiation with swift ions of polyimide and subsequent chemical etching and thermal carbonization has been suggested and implemented. The structural characteristics of the obtained material are studied.

3. A structure and charge transport properties of the poly(ethylene terephthalate) track membrane on one side of which thin layers of aluminum were deposited by vacuum thermal evaporation have been studied. It has been found that the deposition of the aluminum layer on the surface of a track membrane results in the creation of composite metal-polymer membranes that possess a conductivity asymmetry in electrolyte solutions — a rectification effect similar to that of a p–n junction in semiconductors.

Nanostructures in Materials

1. The studies of high-energy heavy-ion irradiation effects on radiation stability of yttrium oxide nanoparticles have been started in in collaboration with BSU, Minsk and Nelson Mandela Metropolitan University, Port Elizabeth. The first results have evidenced that high level of ionizing energy loss may induce partial amorphization of Y_2O_3 clusters.

2. New results on low-dosage radiation-enhanced ion-implanted formation of nanowinnings of the iron in molybdenum with preliminary generated ordered helium porosity have been received.

Radioanalytical Investigations

1. The new methods of separation and concentration of radioisotopes (selective radiochemical separation, collection of recoil nuclei) are developed.

2. The reactions $^{118}\mathrm{Sn}\,(\gamma,n)\,^{117m}\mathrm{Sn}$ and $^{100}\mathrm{Mo}\,(\gamma,n)\,^{99}\mathrm{Mo}$ were investigated with the purpose of radioisotope production for biomedical researches.

The most important results obtained in 2011 are published in [18–20].

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