FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2012, 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:

• 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) (9 subtopics);

In 2012, the operation time of the U400 and U400M FLNR cyclotrons amounts to 11300 h.

DRIBs-III
ACCELERATOR COMPLEX OF ION BEAMS OF STABLE AND RADIOACTIVE NUCLIDES

One of the principal projects of the 7-year plan for the development of JINR is the project DRIBs-III (Dubna Radioactive Ion Beams). Besides the essential modernization of the accelerators U400 and U400M, the project implies creation of the first in the world SHE-factory on the base of the new accelerator complex DC-280 and the new experimental hall. The project also implies essential modernization of operating separators and creation of new facilities, intended for experimental studies in the following fields: 1) physical properties of heavy and superheavy nuclei, synthesis of superheavy elements, the study of chemical properties of new elements, investigation of fusion–fission reactions and reactions of multinucleon transfer, mass-spectrometry and nuclear spectroscopy of superheavy nuclei; 2) the structure of light exotic nuclei far from stability line, exotic decays and reactions with exotic nuclei

Cyclotron DC-280. In 2012, within the plan of development of the FLNR accelerator base, a project of a new high-current cyclotron DC-280 was created. The new cyclotron will allow us to increase the intensity of beams of intermediate masses by a factor of 10 and thus to extend considerably experimental possibilities for the study of physical and chemical properties of new elements. The cyclotron is intended for production of accelerated beams of ions up to uranium with the energy 4–8 MeV/nucleon. The cyclotron will be equipped with two ion sources for production of intensive beams of light and heavy ions. At the present time a cyclotron magnet is at the stage of manufacturing. Besides, a construction of a cyclotron acceleration system is designed, as well as a beam extraction system using an electrostatic deflector and a magnetic channel.

A project of beam transportation using a beam line of 100 mm diameter is created. A beam size on a target makes 10 mm. A beam diagnostics system providing the measuring of the beam intensity, position, profile and local losses is designed for each part of a beam trajectory from the ion source to the target. The projects of the technical support systems including the water-cooling system, the power supply, and the control system are created.

ACCULINNA-2. In the frame of the DRIBs-III project, a design manufacturing of a new powerful fragment-separator ACCULINNA-2 intended for the production and transportation of secondary beams of radioactive ions is being constructed since 2011 within the Contract with the SigmaPhi company (France). The facility will be put into operation by the end of 2014. The first experiments are expected to start in 2015.

GALS. The detailed design of the project of a new setup intended for the extraction of reaction products by means of their stopping in gas and subsequent resonance laser ionization (GALS setup) have been finished. The final version of the project has been prepared and published. The project was approved by the PAC and accepted for realization. Technical documentation and actual positioning of the setup at the FLNR accelerators (U400M and U400R) are under development. Requirements for engineering systems and project of room reconstruction for the laser laboratory and the data acquisition system for the GALS setup have been prepared. The first stage orders of the equipment have been made.

VASSILISSA. Within the modernization of the VASSILISSA separator a final assembling of the facility was fulfilled. Besides, vacuum and high voltage tests have been completed as well as measuring of fields in the magnetic elements of the separator. The design and kitting-up of the focal plane detection array have been continued. The detection system includes a large clover detector, germanium detectors with anticompton shield, and silicon position sensitive double side detectors.

Ion Sources.

1. At the U400 cyclotron, an intense beams of ^{48}Ca, Ne, Ar, Kr, Xe, Bi ions were provided for physical experiments. With the intensity of injected beam of $^{48}Ca^{5+}$ up to 100 $e\mu$A the consumption of calcium constitutes of about 0.8 mg/h (without regeneration).

2. At the U400M cyclotron, the ion beams of ^{7}Li, ^{11}B, ^{15}N, ^{18}O, ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{132}Xe, ^{209}Bi were provided for physical experiments.

3. At the CI-100 cyclotron, the ion beams of Ar, Kr, Xe were provided for production of nuclear filters and for physical experiments.

4. The ECR4M ion source was modernized and tested. The experiments on production of Ti and Gd ion beams were performed.

5. The test of the DECRIS-5 ECR ion source and the axial injection system for the DC-110 cyclotron complex was performed.

6. The development of the multiply charged ion injector project for the DC-280 cyclotron complex is in progress.

A scientific staff took part in a number of conferences: XX International Workshop on ECR Ion Sources, ECRIS 2012 (Sydney, Australia); XXIII Russian Particle Accelerator Conference, RuPAC-2012 (S. Petersburg, Russia); XIX International Conference on Electrostatic Accelerators and Beam Technologies, ESACCEL 2012 (Obninsk, Russia).

SYNTHESIS AND PROPERTIES OF NUCLEI AT THE STABILITY LIMITS

Synthesis of New Elements. A series of experiments carried out in 2012 was aimed at the study of radioactive properties of the isotopes of element 117, their α-decay products and also at measuring the excitation function of the complete fusion reaction $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$. The experiments were carried out with the use of the gas-filled recoil separator at FLNR JINR in collaboration with the laboratories of Oak Ridge (ORNL), Livermore (LLNL), Knoxville (UT), Nashville (VU) and Dimitrovgrad (RIAR). The target material was produced in Oak Ridge and the 0.33 mg/cm^2 thick target was manufactured in Dimitrovgrad.

Experiments were performed at five different energies of the ^{48}Ca ions ranging from 244 to 260 MeV with a total dose of $4.56 \cdot 10^{19}$. In two runs at the excitation energy of the compound nucleus $^{297}117$ $E^* = 30.4{-}37.5$ MeV, three decay chains of $^{294}117$ were detected (Fig. 1, *a*). At the three higher energies ($E^* = 37.0{-}48.3$ MeV) 11 nuclei of $^{293}117$ were synthesized. Decay properties of all the nuclei in the decay chains of $^{294}117$ and $^{293}117$, as well as of $^{289}115$ measured in the reactions of ^{48}Ca with ^{249}Bk and ^{243}Am targets in the previous and present experiments agree in full. The decay chains observed are shown in Fig. 1, *a* including four decays of the isotopes $^{289}115$ produced in the reaction $^{243}\mathrm{Am}\,(^{48}\mathrm{Ca}, 2n)$. The measured excitation function proves that the observed isotopes are the products of the $3n$ and $4n$ channels of the reaction $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$ (Fig. 2). In addition, in the reaction with ^{249}Cf, that is the β-decay product of ^{249}Bk, we registered a single decay of $^{294}118$ (Fig. 1, *b*) that was produced earlier in 2002 and 2005. The data obtained are published in [1, 2].

Chemistry of Transactinides. In 2012, a preparation for experiments on the study of chemical properties of the elements 113 and 114 in the reactions $^{243}\mathrm{Am}\,(^{48}\mathrm{Ca}, 2n)$, $^{249}\mathrm{Bk}\,(^{48}\mathrm{Ca}, 4n)$, and $^{242,244}\mathrm{Pu}\,(^{48}\mathrm{Ca}, 3n)$ has been continued. A number of new technologies of actinide targets production were developed. In particular, the targets of enhanced resistance based on oxides and intermetallic compounds were manufactured. A new cryogenic detector intended for measuring an adsorption heat of elements studied on a gold surface was created and tested. In December 2012, a first cycle of experiments using the reaction $^{243}\mathrm{Am}\,(^{48}\mathrm{Ca}, 2n)$ was started.

Separator VASSILISSA. Analysis of the ^{253}No, ^{244,246}Fm decay data obtained in 2009–2010 was continued in 2012. The main results are presented in works [3, 4] as well as in proceedings of 5 international conferences.

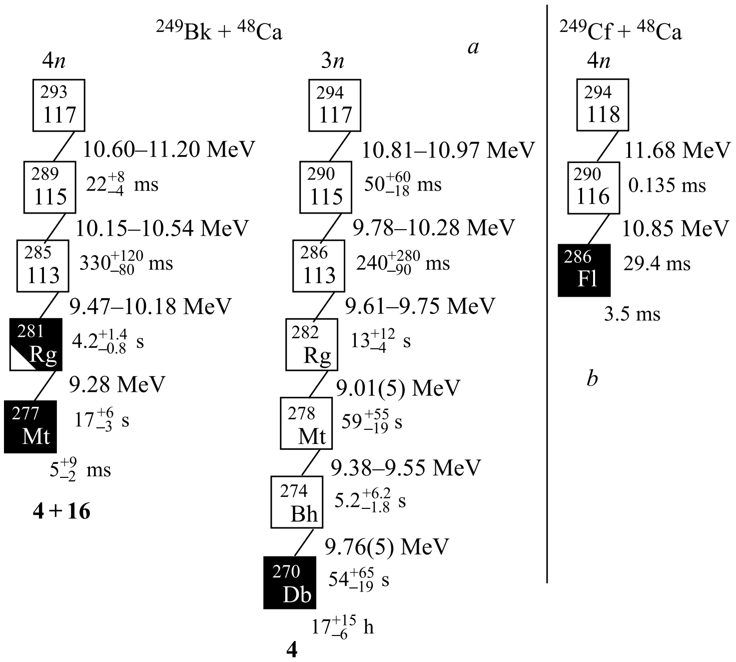

Fig. 1. (*a*) Radioactive properties of ^{293,294}117 and their daughter nuclei. Energies of α particles and half-lives are given in the figure. The spontaneously fissioning isotopes are shown as black squares. (*b*) Decay chain of ^{294}118 (with α-particle energies and decay times)

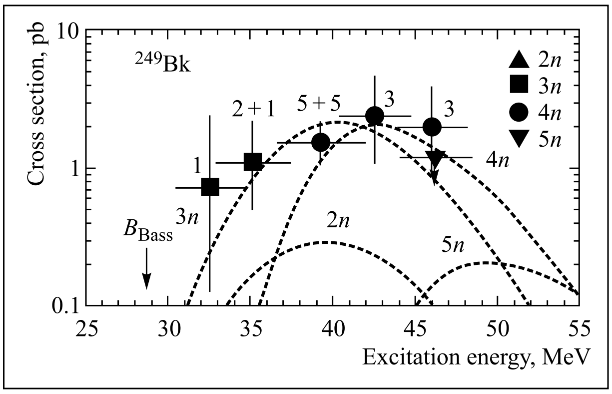

Fig. 2. Production cross sections of ^{294}117 and ^{293}117 vs. excitation energy of the compound nucleus. Figure specifies the number of nuclei synthesized in the present experiment and in 2010

The works on modernization of the separator VASSILISSA are being continued (see the section DRIBs-III). First experiments at the modernized separator are planned for the middle of 2013.

Mass-Spectrometer MASHA. In 2012, the time response of the ISOL separation system consisting of a hot catcher and an ECR ion source was measured in the test experiments at the U400M cyclotron [5]. Mercury short-lived isotopes produced in the complete fusion reaction ^{40}Ar + ^{144}Sm were detected at the separator focal plane. Total separation time was 1.9 s. The mercury separation efficiency measured in these experiments makes about $\sim 6\%$.

Measurement of the mass of the ^{283}Cn nucleus synthesized in the ^{48}Ca + ^{238}U reaction was performed at the cyclotron U400M. There was used the uranium carbide target used also as a hot catcher for stopping products of the complete fusion reactions. The flux of ^{48}Ca ions passed through the target was $1.3 \cdot 10^{18}$.

At the present time a software for a hybrid silicon pixel detector MEDIPIX is being developed in collaboration with the Institute of Experimental and Applied Physics of the Prague University (Czech Republic).

Laser Spectroscopy. In collaboration with universities of Leuven, Mainz, and GANIL, the experiments on determining the efficiency of laser ionization of stable and radioactive Cu, produced in the gas cell on the LISOL setup at the CYCLON cyclotron, have been finished. Different laser systems, based on eximer lasers with dye lasers and TiSa lasers with pumping by YAG laser have been used. The comparable ionization efficiency under higher repetition rate of solid state lasers with the best resolution has been demonstrated [6].

The common experiments with the Catholic University of Leuven (Belgium) and CERN with the use of the in-source laser spectroscopy method in the ion source RILIS are continued. Detailed analysis of experimental data for the determining of nuclear charge radii and moments of neutron-deficient Po isotopes and isomers has been performed [7].

Dynamics of Heavy Ion Interaction, Fission of Heavy and Superheavy Nuclei. The analysis of experimental data on mass-energy and angular distributions of binary fragments formed in the reaction ^{136}Xe + ^{208}Pb at energies 700, 870, and 1020 MeV (near the Coulomb barrier) measured with the CORSET setup at the U400-M cyclotron was finished. It was found that the yield of the fragments with masses greater than 210 aμ is one order of magnitude larger than that predicted by theory. The direct measurement of production cross section for ^{224}Ra, ^{222}Rn, ^{210}Po was carried out [8].

The analysis of the data on pre- and post-scission neutron multiplicities for fission-like fragments formed in the reactions $^{36}\mathrm{S}+{}^{238}\mathrm{U}$, $^{26}\mathrm{Mg}+{}^{248}\mathrm{Cm}$, $^{58}\mathrm{Fe}+{}^{208}\mathrm{Pb}$ in order to clarify the origin of these fragments has been finished [9].

Experiment devoted to the search for fission channel of $^{260}\mathrm{No} \to {}^{208}\mathrm{Pb}+{}^{48}\mathrm{Ca}+4n$, formed in the reaction ^{12}C (5.7–8 MeV/u) + ^{248}Cm at the energy of the ^{12}C extracted beam of 135 MeV, was carried out at the U400M cyclotron. Fission fragments were detected in coincidence by the two-arm time-of-flight spectrometer CORSET. The increase of fragment yield in the mass region around 52/208 u, that corresponds to the formation of a fissioning pair of two magic nuclei Ca/Pb, was observed.

In the framework of the collaboration between the Accelerator Laboratory of the University of Jyväskylä, the Department of Physics of the University of Naples (INFN, Italy), and FLNR, at the JYFL accelerator K-130, we performed a test experiment on the production of volatile products of Osmium isotopes and their cross section measurements in the reaction $^{136}\mathrm{Xe}+{}^{208}\mathrm{Pb}$ at the energy $E_{\mathrm{lab}} = 820$ MeV. The experiment was performed with the use of the CORSAR setup (FLNR) installed into the HENDES scattering chamber (JYFL, Finland). As a result of preliminary analysis of experimental data on beta–gamma coincidence the decay chains of ^{195}Os and ^{196}Os were identified.

In the framework of the collaboration between JINR–GSI (Germany), the experiment devoted to the investigation of the shell effects and clusterization in superheavy dinuclear system formed in the reaction $^{238}\mathrm{U}+{}^{238}\mathrm{U}$ was performed. The obtained experimental data are in processing.

Exotic Decays. Linear structures revealed in the mass correlation plot M_1–M_2 for the fragments from ^{252}Cf (sf) were analyzed for the first time. The data were obtained at the COMETA setup in the FLNR of the JINR. The linear dot structure comprising the lines $\mathrm{M}_{1,2} = \mathrm{const}$ is seen in Figure 3 below the locus of the conventional binary fission. The lines are marked by the arrows and correspond to the magnetic fragments of ^{128}Sn (1), ^{68}Ni (2), and ^{72}Ni (3). Two tilted diagonals corresponding to $\mathrm{M_s} = \mathrm{M}_1 + \mathrm{M}_2 = 196$ aμ and $\mathrm{M_s} = 202$ aμ (marked by number 4) start from the partitions 68/128 and 68/134, respectively. Both partitions are also based on the magic constituents. The structures lie in the region of big missing mass and are linked with at least ternary decay of the mother nucleus. We came to conclusion that quaternary decay on ions heavier than alpha particles is likely to be the most probable channel standing behind the rectangular structures under analysis. At the same time another structures which look like tilted ridges can be a result of ternary decay.

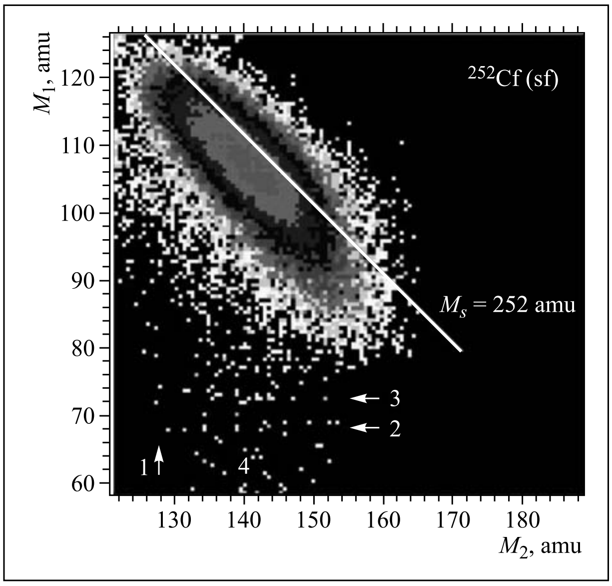

Fig. 3. Mass–mass distribution for the fragments from ^{252}Cf (sf) around the «Ni bump»

Structure of Exotic Nuclei. The 0^+ ground state of the ^{10}He nucleus produced in the $^3\mathrm{H}\,(^8\mathrm{He},p)\,^{10}\mathrm{He}$ reaction was found at about 2 MeV ($\Gamma \sim 2$ MeV) above the three-body $^8\mathrm{He}+n+n$ breakup threshold. Angular correlations observed for ^{10}He decay products show prominent interference patterns allowing one to conclude about the structure of low-energy excited states. Observed correlations were interpreted as a coherent superposition of a broad 1^- state having a maximum at energy 4–6 MeV and a 2^+ state above 6 MeV, setting both on top of the 0^+ state «tail». This anomalous level ordering indicates that the breakdown of the $N = 8$ shell known in ^{12}Be thus extends also to the ^{10}He system [11].

Investigations of rare beta-decay branches of ^{8}He, ^{14}Be, and ^{31}Ar were carried out with the use of the optical time-projection chamber at the ACCULINNA and FRS separators in 2012. High statistics and better quality data were obtained in the ^{8}He case. It was demonstrated that the beta-delayed neutron emission events in the decay of ^{8}He can be observed by the detection of tracks of recoiling ^{7}Li nuclei.

Reactions with Beams of Light Stable and Radioactive Nuclei. In 2012, an experiment at the fragment-separator COMBAS with the use of the detection system MULTI was carried out. As a result of fragmentation of the ^{40}Ar ($35A$ MeV) primary beam accelerated at the cyclotron U400M, the secondary beams of the isotopes ^{39}Cl and ^{38}S were produced. The beam intensity made about 10^4 s^{-1}. The experiment will be continued in the beginning of 2013 with the ^{48}Ca beam.

Experimental results obtained in 2011 were published. In the paper we discuss an energy dependence of the total cross section obtained in the reaction ^{6}He + Au. The measurements were done at the fragment-separator ACCULINNA.

A number of experiments on the study of interactions of light cluster nuclei (d, ^{6}Li) were carried out in Bucharest (Romania) and Řež (Czech Republic). The results obtained show that a cluster structure of weakly bound nuclei enhances sub-barrier reactions. This conclusion is of importance both for fundamental nuclear physics and for astrophysics.

Obtained results are published in [12–14] and reported at the various International Conferences: «NN Collision» (San-Antonio, USA), «Nuclei 2012» (Voronezh, Russia) and «EXON-2012» (Vladivostok, Russia).

Theory and Computational Physics. New possibilities for the synthesis of superheavy elements in fusion reactions, in multinucleon transfer processes and by multiple neutron capture have been studied. For the first time a possible method has been proposed for the production of long-lived superheavy nuclei located just in the middle of the island of stability [15], inaccessible by conventional fusion reactions because of insufficient total amount of neutrons. New method relies on a possibility for successive beta(+) decays of neutron enriched isotopes ^{287,291}115 and ^{287,291}114 leading directly to the long-lived superheavy elements ^{287}110 and ^{291}112 having half-lives of several years or longer [16].

Most promising nuclear reactions have been found for the synthesis of new superheavy nuclei located between those produced in the «cold» fusion reactions at GSI and those produced in the «hot» fusion reactions in Dubna [15]. Cross sections of these reactions are predicted to be quite large to perform the corresponding experiments at available facilities.

It was shown that not-yet-studied neutron enriched superheavy elements might be synthesized also in the successive processes of multiple neutron capture and beta(−) decays [17]. High neutron fluense needed for that could be provided by multiple (rather «soft») nuclear explosions, pulsed nuclear reactors of the next generation, and in astrophysical r-process of nucleosynthesis. Natural abundance of long-lived superheavy nuclei formed in astrophysical r-process is predicted to be about 10^{-12} relative to lead [17].

Within the framework of the JINR–ARE cooperation programme a role of neutron transfer in fusion processes of stable nuclei near and below the Coulomb barrier has been investigated [18]. Large enhancement of fusion cross sections owing to neutron transfer has been predicted for several nuclear reactions available for experimental studies.

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

1. Experiments on the development and optimization of track membranes with improved productivity and additional arrays of pores were performed. As a result, a patent on a new kind of track membranes (RF Patent No. 2440840) was obtained.

2. Systematic studies of diode properties of asymmetric nanopores filled with electrolyte solution were performed. The conditions under which the rectification coefficient of the ion current reaches its maximum value were determined [19].

3. Effect of irradiation by Xe (167 MeV) and Bi (700 MeV) ions on the properties of oxide nanoparticles in the alloys Fe–16Cr–3W–0.3Y (Cr16) and Fe–15Cr–4Al–2W–0.35Y_2O_3 (KP4) was studied. It is shown that irradiation by high-energy ions leads to the formation of latent tracks in oxide nanoclusters. Overlapping track regions lead to complete amorphization of nanoclusters [20].

4. The study of hydrogen blisters in silicon re-irradiated with Bi (710 MeV) ions was performed. It is shown that the process of isochronous annealing at 250–800 °C stimulates the growth of hydrogen pores (article submitted to JETP).

5. The study of the element composition of the samples of palladium irradited with bremsstrahlung gamma–quanta with an energy threshold of 8 MeV in dense deuterium gas was performed. The significant anomalies in the structure and element composition of the irradiated samples were revealed [21].

6. New methods of separation and concentration of isotopes ^{178m}Hf, ^{88,89}Zr, ^{176,177}Ta, ^{91m,92m}Nb were developed.

7. The cross sections and yields of reactions ^{118}Sn$(\gamma,n)^{117}$Sn and ^{196}Pt$(\gamma,n)^{195m}$Pt were measured.

8. In 2012, the cyclotron DC-110 created at the Flerov Laboratory for the scientific industrial complex BETA (Dubna) was assembled and put into operation. The accelerator will be used for production of track membranes of medical application. The Ar, Kr, and Xe ion beams with the energy $2.5A$ MeV were accelerated. First irradiation of a polymeric foils was carried out.

9. Microelectronic chips for space industry were tested at the accelerator U400M within the contract between JINR and Federal space agency ROSKOCMOS. For this purpose two beam lines for the transportation of beams with energies 5 and 30–50A MeV were constructed.

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