In 2016, a wide range of scientific and applied research in heavy ion physics was conducted at the existing cyclotrons of the Flerov Laboratory of Nuclear Reactions – U-400, U-400M, and IC-100. In 2016, the total time of the cyclotrons operation has amounted to 15,724 hours. In the reporting year, the main research areas were: development of the Laboratory accelerator complex, including the construction of the "Factory of Superheavy Elements"; synthesis and study of the properties of nuclei at the drip-lines; study of the interaction of heavy ions with condensed matter; applied research. These fields of research are presented in three Laboratory themes that were completed in the reporting year.

DRIBs-III

ACCELERATOR COMPLEX OF ION BEAMS OF STABLE AND RADIOACTIVE NUCLIDES

Construction of the accelerator complex "Factory of Superheavy Elements" based on the DC-280 cyclotron

The new experimental building of the SHE Factory was prepared for the accelerator equipment installation works (see Fig. 1). In accordance with the schedule of installation and commissioning works, on September 15, 2016 the assembly of the DC-280 cyclotron was started. In December, the assembling of the cyclotron magnet was completed and the adjustment of the magnetic structure was carried out. The works on the preparation of the system of magnetic measurements scheduled for early 2017 were performed. The engineering equipment of the cyclotron was prepared for installation in the new building. The installation of the water cooling system was almost fully completed. The ion source was fully bench-tested. The complex commissioning works are scheduled to be started at the end of 2017 [1].


Building of the Superheavy elements factory

Assembling of the main magnet of DC-280 cyclotron

Installation of the water cooling system

Blocks of electronics of the DC-280 control system

Development of the existing FLNR accelerator complex

Most of the time of the cyclotron U-400 operation was used to implement the research program on the synthesis and studies of the properties of a number of new isotopes of superheavy elements using ^{48}Ca beams. The studies on obtaining ^{50}Ti ion beams from the ion source by MIVOC (**M**etal **I**ons from the **VO**latile **C**ompounds) were carried out. The developed method has allowed obtaining a stable accelerated $^{50}Ti^{5+}$ beam at the U-400 cyclotron with an energy of 5.3 MeV/nucleon, an intensity of approximately 10 eμA (Fig. 2), as well as conducting two long-run physics experiments using a ^{50}Ti ion beam. The same method was used to obtain an intense Cr beam from the ion source (Fig. 3).

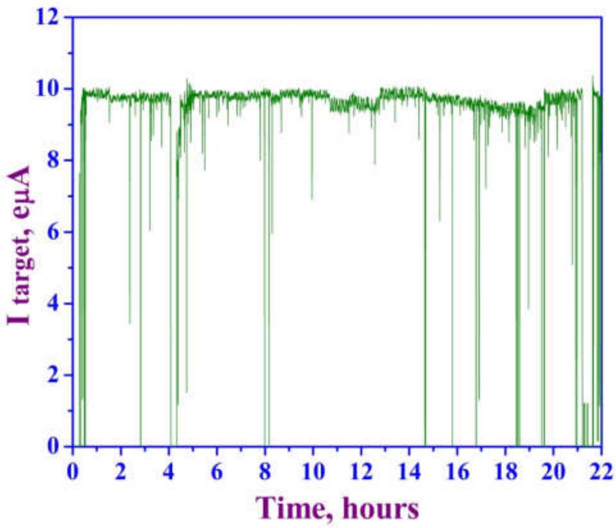

Fig. 2. Intensity of the beam of accelerated ^{50}Ti ions extracted from the U-400 cyclotron

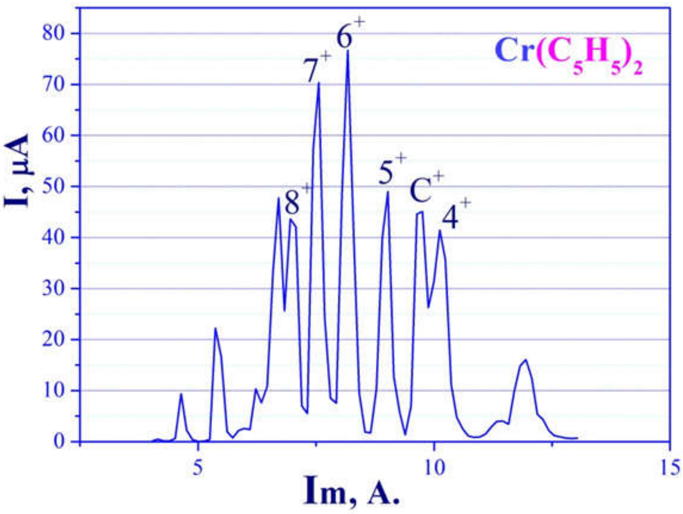

Fig. 3. Charge spectrum of chromium ions produced by the ECR4M source at cyclotron U-400

A second electron-cyclotron resonance ion source with superconducting coils, which operates at a frequency of 18 GHz, was installed at the U-400M cyclotron. It allowed obtaining Fe^{17+}, Xe^{30+}, Bi^{37+} ions with an energy of 15-30 MeV/nucleon. Accelerated beams were used to implement the program of physics experiments, and in particular, to test radiation resistance of the electronic components.

The modernized cyclic implanter IC-100 was used to implement the program of applied research using intensive ions from C to W with an energy of 1.0-1.2 MeV/nucleon. The ions accelerated in the IC-100 were also used for the calibration of detectors in the preparation of experiments at the U-400 and U-400M of FLNR, as well as for experimental setups of the other laboratories.

Designing of experimental setups for the complex “Factory of Superheavy Elements”:

A new gas-filled recoil separator (DGFRS-II) is being manufactured. The contract with SigmaPhi for the manufacturing of the separator was signed in 2015. The contract stipulates the delivery of the separator in the middle of 2017.

The works on the designing of a pre-separator intended for the studies of chemical properties of superheavy elements with lifetimes longer than 1 second were started. The possibility of designing a separator using superconducting magnets is being investigated.

Fragment separator ACCULINNA-2

The works on the construction of a new fragment separator ACCULINNA-2 were continued. Earlier in 2015, the separator was fully assembled, vacuum tests and magnetic measurements were run. In December 2015, a test run of the setup with the primary ^{32}S beam was conducted. In 2016, the construction of an experimental cabin in the focal plane of the separator was completed. Works on the preparation for the construction of a biological shield in the area of the production target of the setup were performed. The necessary concrete blocks were purchased and delivered to FLNR.

Construction of a separator based on resonance laser ionization (GaLS setup):

Works on the construction of the GaLS setup designed for the separation of transfer reaction products by selective laser ionization were continued [2]. In 2016, the assembly of the GaLS setup laser subsystem was completed. Its installation is expected to be finished at the beginning of 2017. The necessary vacuum equipment was purchased and delivered to FLNR. The designing of the mass separator was completed. The manufacturing of the separator magnet was started. The vacuum chamber of the separator was manufactured, tested and delivered to FLNR. The first version of the arrangement of the GaLS setup gas cell was designed and manufactured at the pilot plant of FLNR. In collaboration with iThemba Labs (RSA) the transport system for reaction products was designed and the manufacturing of its prototype was started.

Mass-spectrometer MASHA. The designing of a new version of the ECR ion source and the “Hot Catcher” was started. The upgrade was done to increase the total separation efficiency of mercury-like elements. The main feature of this version is the possibility to work at a temperature of up to 300°C. The inner surfaces will be covered with a chemically inert glass-enamel layer. The technical requirements specification for the new version was prepared and a model of the new chamber of the ECR ion source was manufactured.

A setup for measuring the absolute cross sections of fusion reactions with heavy ion beams was designed. The model calculations were carried out, the necessary equipment was purchased and the drawings were prepared. The main results obtained by the MASHA separator team are published in [3,4].

SYNTHESIS AND PROPERTIES OF NUCLEI AT THE DRIP-LINES

Synthesis of new elements. On November 28, 2016, the International Union of Pure and Applied Chemistry (IUPAC) formally approved [5] the names and symbols for the new elements of D.I. Mendeleev's Periodic Table with atomic numbers 115, 117, and 118. At the end of 2015, the priority for these discoveries was assigned to JINR in collaboration with the USA scientific centers. The following names were approved:

Moscovium and symbol Mc for element 115;

Tennessine and symbol Ts for element 117;

Oganesson and symbol Og for element 118.

Thus, all the five chemical elements discovered in recent years completing the seventh periods of D.I. Mendeleev's Periodic Table received their final names (Fig. 4).

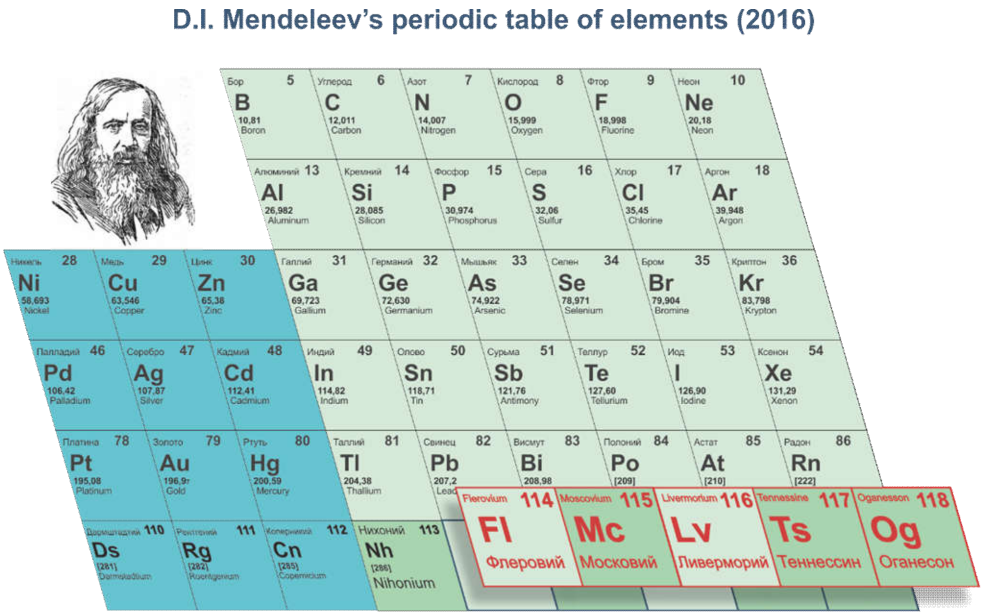

Fig. 4. Part of D.I. Mendeleev's Periodic Table highlighting the elements synthesized at JINR over the past 16 years.

In 2016, we resumed and went further with the experiments aimed at the synthesis of the isotopes of Og with mass numbers 293-296 and study of their radioactive properties. The experiments were carried out using the Dubna Gas-filled Recoil Separator of FLNR, JINR, in collaboration with the laboratories of Oak Ridge (ORNL), Knoxville (UT), Livermore (LLNL), and Nashville (VU). The target with a thickness of 0.35 mg/cm^2 was produced at ORNL and consists of a mix of Cf isotopes: ^{249}Cf (50.7%), ^{250}Cf (12.9%), and ^{251}Cf (36.4%). The energy of ^{48}Ca ions in the middle of the target layer was increased by 6 MeV compared to the experiment of 2015 and came up to 258 MeV, which corresponds to the expected cross section maximum of the complete-fusion reactions $^{249–251}$Cf+^{48}Ca with evaporation of four neutrons.

The total beam dose of ^{48}Ca ions accumulated at this energy value was 1.1×10^{18}. The experiment was stopped, as the target surface got covered with ballast admixture used in the process of target manufacturing. In the experiment, at the 252-MeV energy of ^{48}Ca we detected one decay chain of ^{294}Og – a product of the 3*n* channel of the ^{249}Cf+^{48}Ca reaction [6]. In the same reaction we synthesized four nuclei of this isotope in 2002, 2005, and 2012 [7]. The decay properties of all the nuclei of ^{294}Og, ^{290}Lv, and ^{286}Fl are in good agreement with the results obtained both in the reaction with ^{249}Cf and in the cross reactions ^{245}Cm(^{48}Ca,3*n*)^{290}Lv and ^{242}Pu(^{48}Ca,4*n*)^{286}Fl [6,7].

The experiments will be resumed in 2017, as soon as a new target was manufactured.

Chemistry of transactinoides. The influence of the relativistic effects on the chemical properties of superheavy elements Cn and Fl using gas thermochromatography on the surface of selenium was investigated. Thermochemical calculations and tests on a ^{48}Ca beam were conducted. The results showed formation of stable selenides of light homologues of Cn and Fl in groups 12 and 14 of D.I. Mendeleev’s Periodic Table with the opposite stability trends. It will allow separating the deposition zones of these elements in the thermochromatographic column for the first time [8]. In October 2016, in the framework of cooperation between FLNR and PSI (Switzerland) a joint experiment at the U-400 of FLNR was carried out to study the adsorption of Cn and Fl on the surfaces of selenium and gold. To synthesize Cn and Fl isotopes, the reaction ^{48}Ca + ^{242}Pu was used, which made it possible to investigate the adsorption of these elements in a single experiment. The reaction products were retained in the recoil nuclei collecting chamber filled with argon and helium. Further on, using a gas jet, they were transported through the capillary to the thermochromatographic column. The column consisted of an isothermal part including 16 Si-PIN detectors coated with selenium and 16 Si-PIN detectors coated with gold at a temperature gradient from +20 to -165 degrees Celsius. The analysis of the accumulated data is in progress.

Spectroscopy of heavy and superheavy nuclei. The experiment aimed at the spectroscopy studies of the ^{255}Lr isotope synthesized in the complete-fusion reaction ^{48}Ca(^{209}Bi,2n)^{255}Lr was performed using the modernized recoil separator SHELS and a new detector chamber including a Clover-type detector and four single-crystal Ge gamma detectors. The experiment showed that the modernization of the ion-optical system of the separator together with the increase in the gamma detection efficiency for the new design of the detector system (at least by a factor of 3) resulted in a

10-fold increase of statistics on the detected decays collected for the same integral flux of incident ions.

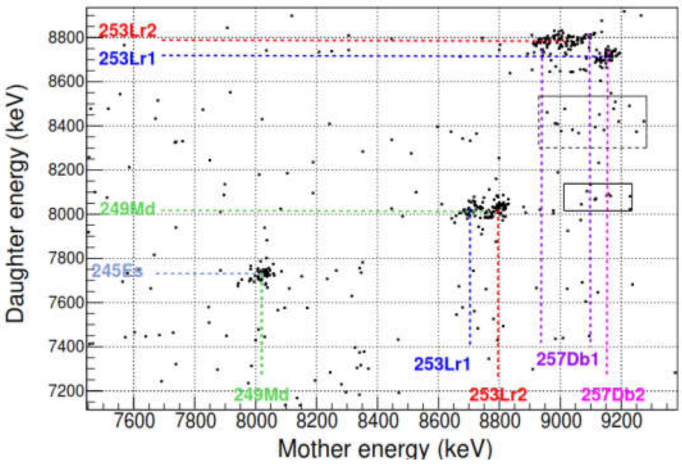

Fig. 5. Alpha-alpha correlations for ^{257}Db decay.

The experiments aimed at the study of the decay properties of ^{255}Lr and ^{257}Db isotopes synthesized at the complete-fusion reactions ^{48}Ca(^{209}Bi,2n)^{255}Lr and ^{50}Ti(^{209}Bi,2n)^{257}Db were carried out. More than 1000 events of the ^{257}Db isotope decay were detected (see Fig. 5). The experimental data are under analysis.

Using ^{50}Ti, rare reaction channels with evaporation of a proton and several neutrons in the complete-fusion reaction ^{209}Bi (^{50}Ti,pxn)$^{258-x}$Rf were investigated. A number of decay events were detected at two beam energies. These events can be attributed to the p0n channel. A cross section limit for the p1n channel was obtained. In October-November 2016, the experiment was continued at a higher ^{50}Ti beam energy corresponding to a theoretically estimated maximum of the p2n evaporation channel. Several spontaneous fission events of ^{256}Rf were detected.

The current status of the SHELS separator and certain results of the experimental campaigns are presented in [9, 10].

Dynamics of heavy-ion interaction, fission of heavy and superheavy nuclei. In 2016, a series of experiments was carried out at the CORSET setup (U-400 accelerator). The experiments were aimed at the estimation of contribution of quasifission, which hinders the complete fusion channel, when one uses heavy-ion beams of Ti, Cr, etc. instead of Ca. These investigations are particularly important for the planning of experiments on the synthesis of new superheavy nuclei with Z > 118. In 2016, the mass and energy distributions of binary fragments produced in the ^{52}Cr+^{232}Th, ^{248}Cm reactions at energies near the Coulomb barrier were measured. The analysis of the mass-energy distributions of ssion and quasifission fragments produced in the reaction ^{48}Ti+^{238}U was completed [11,12]. It was found that at energies below the Coulomb barrier the contributions of the symmetric fragments are virtually the same within the error bars for the $^{48}Ca+^{244}Pu$, $^{48}Ti+^{238}U$, and $^{52}Cr+^{232}Th$ reactions leading to formation of a composite system with $Z = 114$. However, at energies above the barrier, the contribution of the symmetric fragments increases monotonously in the case of the Ca-ions-induced reaction, whereas for the reactions with ^{48}Ti and ^{52}Cr ions it does not change and constitutes about 8-9%. It may indicate a considerable increase of the quasifission contribution at the transition from Ca to Ti and Cr ions. In addition, in 2016 the mass-energy and angular distributions of binary products formed in the $^{86}Kr+^{198}Pt$ reaction, also leading to the $Z = 114$ composite system, were measured at the U-400M cyclotron of FLNR. For this reaction, a deep inelastic process is the main exit channel.

In June 2016, in the framework of the collaboration between JINR (Dubna) and IN2P3 (France) a joint experiment to study the $^{32}S+^{197}Au$ reaction dynamics was performed in ORSAY. The measurements were carried out at the ALTO facility of IPN (Orsay, France) at the energy of incident ions of 5.2 Mev/u [13]. The energies and the multiplicities of γ-rays were measured using the γ-ray spectrometers ORGAM and PARIS. The binary reaction fragments were measured by the double-arm time-of-flight spectrometer CORSET. The multiplicities and the energies of the prompt γ-rays are related to the angular momentum and the excitation energy of fragments, respectively, while the shape of the giant dipole resonance spectrum depends on the deformation of the composite system. All these properties play an important role in the evolution of the dinuclear system. The analysis of the obtained experimental data is in progress.

The yields of radon isotopes in multinucleon transfer reactions $^{48}Ca+^{242}Pu$ and $^{48}Ca+^{208}Pb$ were measured at the MASHA separator. The results were presented at the EXON-2016 conference.

Structure of exotic nuclei. In 2016, an experiment aimed at searching for a 2*p* decay branch of the first excited $3/2^{-}$ state of ^{17}Ne populated in the $p(^{18}Ne,d)^{17}Ne$ transfer reaction was conducted [14]. The population of the low-energy states up to 3 MeV of excitation in the ^{17}Ne nucleus was studied. As a result, a new upper limit $\Gamma_{2p} / \Gamma_{\gamma} \leq 2.5\times10^{-4}$ was established for the ratio of partial widths of the first excited $3/2^{-}$ state of ^{17}Ne in respect to the *2p* and gamma decay. This significantly (about a factor of 30) reduces the value of the limit defined in the previous work [M.J. Chromik, et al. Phys. Rev. C 66 024313 (2002)]. Such a strong improvement of the $\Gamma_{2p} / \Gamma_{\gamma}$ limit over the previous data was achieved due to the choice of reaction and due to the novel “combined mass” method applied in the reconstruction of the ^{17}Ne excitation spectrum. The latter allowed us to significantly increase the instrumental resolution in the measurements done with a thick target. Such improvements open a way to a direct experimental observation of the true radioactive 2*p*-decay of the ^{17}Ne $3/2^{-}$ state. The theoretically predicted value is $\Gamma_{2p} / \Gamma_{\gamma} \sim 2.5\times10^{-6}$. A possibility of direct observation of such weak partial decay branches in one experiment makes this approach prospective for solving the problems of nuclear astrophysics.

The data analysis of the experiment aimed at the study of beta-delayed proton emission from ^{26}P and ^{27}S isotopes was completed [15]. The study was carried out at the ACCULINNA setup, together with the team from Warsaw University. The crucial feature of this experiment based on the use of the Optical Time Projection Chamber was direct observation of decay events in the absence of background. The results obtained for the decay of ^{26}P were found to be consistent with the previous study [J.-C. Thomas et al., Eur. Phys. J. A21, 419 (2004)]. The measured half-life of ^{27}S agrees with the value determined in the previous work [G. Canchel et al., Eur. Phys. J. A 12, 377 (2001)], where a stack of silicon detectors was used to perform proton measurements only with $E_p >$ 1.5 MeV. In contrast, the OTPC detector provided low-background results for energies E_p>0.15 MeV, and in this region the strongest emissions at 320 and 710 keV were detected. As a result, the new values of the branching ratios for βp and $\beta 2p$ channels were found to be much greater than the previous ones (by a factor 3 or more). The studies showed that the technique based on the optical time projection chamber is preferable for the identi cation of decay channels and precise determination of their absolute branching ratios.

Reactions with beams of light stable and radioactive nuclei. At the cyclotron U-400M, using the ACCULINNA separator, a series of experiments was conducted to measure the energy dependence of the cross sections for the nuclei ^{6}He, ^{6,9}Li in a wide range of energies (10-50 MeV/nucleon). In these experiments, the so-called transmission method supplemented by registration of gamma rays was applied. A significant increase of the cross section in the form of a broad peak in the energy range 10-30 MeV/nucleon was noticed (Fig. 6). This effect was not observed in the excitation functions of the reactions with the beams of ^{3}He, ^{4}He, ^{7,8}Li [16]. This was explained by the influence of cluster degrees of freedom, including the neutron ones, on the enhancement of the cross sections in this energy range [17].

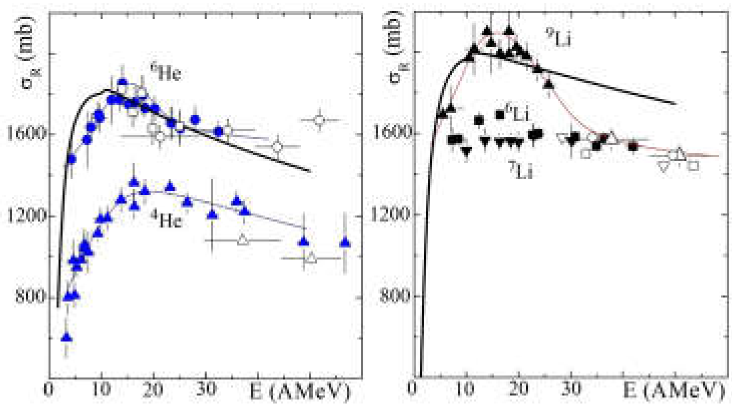

Fig.6. Excitation functions of the total cross sections of nuclear reactions ^{4,6}He+Si and ^{6,7,9}Li+Si

A set of experiments was conducted at the fragment separator COMBAS to study the cross sections of light neutron-rich nuclei interaction (isotopes of helium ^{6,8}He and lithium ^{8,9,11}Li). Optimal reactions for the synthesis of these nuclei were selected and their beams were obtained in the focal plane of the separator. Experiments have shown that in the interaction of these nuclei at high energies certain peculiarities in the characteristics of the reactions associated with their cluster structure may also be manifested. Information on the cluster structure of ^{9}Be nucleus was obtained. For example, the values of the form factors were identified for two configurations of ^{9}Be: ^{8}Be+n and ^{5}He+α. The experiments were carried out at the cyclotron at the University of Jyväskylä (Finland). Angular distributions of the reaction products were measured for the channels ^{9}Be(^{3}He,^{4}He)^{8}Be and ^{9}Be(^{3}He,^{7}Be)^{5}He. It follows from the analysis that the contribution of the cluster configurations n+^{8}Be and α+^{5}He constitutes 69% and 25% of the total cross section, respectively. Experiments were conducted to study the possible existence of the ^{5}He cluster. For this purpose, the angular distribution of inelastic scattering d on ^{9}Be nuclei was measured for the α + ^{7}Li exit channel. The studied reaction may proceed in two different ways: with the transfer of d or of ^{5}He from the target to the projectile. Calculations of the transfer cross sections made within the DWBA method yielded a sufficiently large value of the spectroscopic factor for the system ^{9}Be = α + ^{5}He. It confirms the α+^{5}He cluster structure of the ^{9}Be nucleus and a high probability of transfer of ^{5}He as a cluster [18].

Theoretical and computational physics. A three-center shell model, which allows calculating the potential energy of the deformed nucleus both for binary and ternary fission, was proposed [19]. The features of the potential energy landscape in the ternary fission of the ^{252}Cf nucleus were studied. It was shown that the macroscopic properties of the potential energy suppress the process of ternary fission. At the same time, the suppression factor increases with an increasing mass of the third (middle) fragment. True ternary fission of heavy nuclei with the formation of fragments of comparable masses is possible only due to the shell effects lowering the ternary fission barrier for certain combinations of fragment masses. Well-defined potential valleys, which make possible the ^{252}Cf ternary fission with the formation of a magic tin-like cluster as one of the fragments, were observed (Fig. 7).

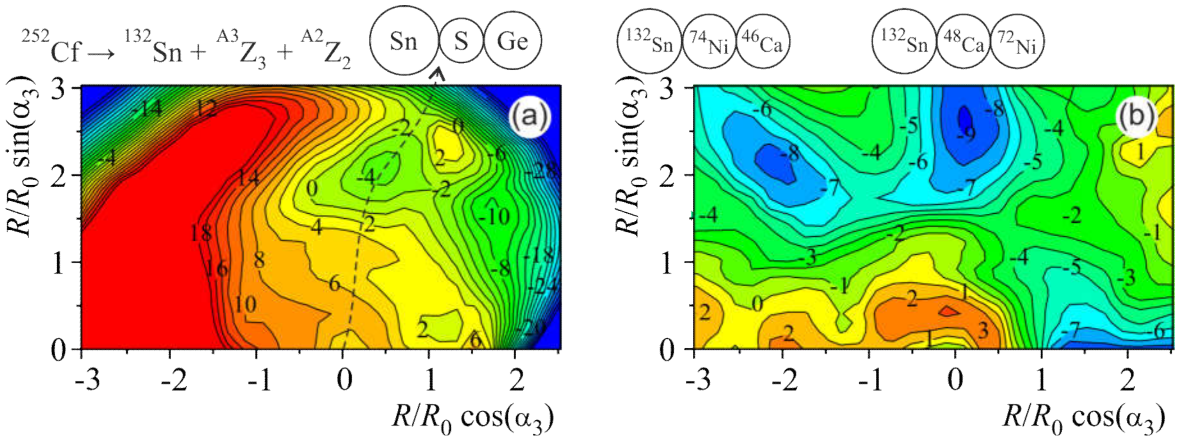

Fig.7. Potential energy (a) and shell corrections (b) for ternary fission of the ^{252}Cf nucleus as a function of elongation, R, and mass of the third fragment, $\alpha_3 = \pi A_3/100$.

With partial support of RFBR and JINR-RSA cooperation program, the knowledge base on NRV low-energy nuclear physics (http://nrv.jinr.ru) was extended [20]. In particular, the databases containing experimental data on the properties of atomic nuclei were updated, and the interface of the NRV sections dedicated to working with the experimental data was improved. The functionality of a number of the knowledge base resources was extended: a possibility to analyze the multiplicities of particles accompanying the decay of a compound nucleus formed in heavy-ion fusion reactions was added; a possibility to simulate reactions of few-nucleon transfer under the FRESCO code was implemented, etc.

RADIATION EFFECTS AND PHYSICS OF NANOTECHNOLOGY, RADIOANALITICAL AND RADIOISOTOPE INVESTIGATIONS AT FLNR ACCELERATORS.

The morphology of bismuth (700 MeV, 1 GeV) and xenon (167 MeV) induced latent tracks in TiO_2 single crystalline was studied using high resolution transmission electron microscopy [21]. The radiation hardening of EP450 and KP4 ODS steels irradiated with krypton and xenon ions of fission fragment energy was studied using the nanoindentation technique [22]. It was shown that the hardening level is about 20 % for radiation damage doses of 0.1÷1 dpa.

Using scanning electron microscopy of high resolution, detailed studies of the structure of track-etched membranes in the nanometer range were performed. Special attention was paid to the investigations of the features of asymmetrical nanopores. For the first time, the contribution of osmotic effects to the asymmetrical chemical etching of heavy ion tracks was revealed and analyzed [23].

The surface and electro-transport properties of composite track-etched membranes with a polymeric hydrophobic layer were studied. Composite track-etched membranes with a photocatalytic layer of titanium dioxide were synthesized and its structure and phase composition were investigated in detail [24]. The results obtained can be employed when designing self-cleaning filters for water purification to separate organic pollution.

New methods for separation and concentration of radioactive isotopes ^{99}Mo(^{99}Tc), ^{97}Ru, ^{117}mSn, ^{178}W(^{178}Ta), ^{186}Re, ^{188}Re, ^{211}At, ^{225}Ac, ^{237}U, ^{236}Pu, ^{237}Pu for nuclear medicine and environmental research were developed.

The investigations carried out at FLNR in 2015 were supported by 7 grants from RFBR.

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