FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2013, 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 using the FLNR accelerators (5 subtopics);

• Accelerator complex of ion beams of stable and radioactive nuclides (DRIBs-III) (9 subtopics).

In 2013, the operation time of the U400 and U400M FLNR cyclotrons amounted to 11400 h.

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

DRIBs-III (Dubna Radioactive Ion Beams) is one of the core JINR projects. The high-priority tasks approved by JINR's Programme Advisory Committee (PAC) for Nuclear Physics and Scientific Council, which have to be fully implemented within the Seven-Year Plan for JINR Development, include the following:

• development of the world's first SHE Factory, commissioning of a new DC-280 accelerator, construction of a new experimental hall and experimental setups for synthesis and investigation of the properties of SHEs;

• implementation of the scientific programme on SHE synthesis (U400 accelerator);

• completion of works on the U400M modernization and the development of a new ACCULINNA-2 separator for carrying out research on exotic radioactive nuclei;

• completion of preparatory and design works for the renovation of the U400 experimental hall and the modernization of the U400 accelerator to enable timely reconstruction in 2017;

• construction of a new JINR FLNR building (total of 1500 m^2) to conduct scientific research on the application of heavy-ion beams in nanotechnology.

The following project tasks were fulfilled in 2013:

1. The DC-280 cyclotron:

• The cyclotron magnet construction is underway under the contract with the Novokramatorsk Machine-Building Plant.

• The construction of the axial injection system was completed.

• The tendering process continued for the manufacture of the main parts of the accelerator.

2. Experimental hall:

• The design works (project preparatory phase I) were completed. The project was approved by the State Expert Evaluation Department (Glavgosekspertiza of Russia).

• Bulk earthworks were completed, deep foundation was laid.

3. Laboratory building:

• General construction works were completed.

• Engineering and manufacturing equipment was assembled.

• Experimental equipment assembly is underway.

4. Reconstruction of the U400 experimental hall:

• Design works were completed (project preparatory phase I) under the contract with Kometa, a joint-stock company.

5. While developing the ACCULINNA-2 setup in 2013, the following equipment was manufactured under the contract with SigmaPhi:

• a dipole D2 magnet,

• 13 quadrupole magnets,

• 2 sextupole magnets.

In 2013, technical specifications were prepared covering requirements for equipment location in the experimental hall of the JINR FLNR building No. 101. The load-bearing structures of the building were examined and a 2014 equipment assembly schedule was prepared. Moreover, power cables were purchased, requirements and technical specifications for the zero spectrometer were prepared, and a proposal from SigmaPhi to manufacture the magnet was received.

6. As part of the GALS Project, optical tables and a dye laser were purchased in 2013. Laser rooms and a measuring room were made ready for experiments, and a ventilation and cooling system was installed. The rest of the equipment (i.e., a Nd:YAG laser, optoelectronics, etc.) is to be purchased, installed, and tested in 2014. Hence, first experiments on selective resonance laser ionization will be conducted in 2014.

7. In 2013, vacuum and high-voltage testing of the VASSILISSA separator was successfully completed. The modernized recoil separator was commissioned in May 2013. Transmission measurements and separator tuning were carried out using an α-source mounted at the target position and a ^{22}Ne beam incident on a ^{198}Pt target. The measurements showed an increase in the transmission efficiency up to 5% (the size of the focal plane detector was $\sim 60 \times 60$ mm).

Overall, the implementation of the DRIBs-III project can be evaluated as satisfactory. However, it is worth noting that the construction of the experimental hall has fallen behind schedule.

Ion Sources. The production of new rare-isotope ion beams is one of the core scientific activities at FLNR. The Metal Ions from Volatile Compounds (MIVOC) Method was chosen to produce ions, such as ^{58}Fe and ^{50}Ti. The $(C_5H_5)_2Fe$ compound was used to produce Fe ion beams. The experiments on production of Ti ion beams were conducted at an ion-source test bench using natural and enriched compounds of titanium $(CH_3)_5C_5Ti(CH_3)_3$. Following a series of successful tests, the $^{50}Ti^{5+}$ ion beam was accelerated at the U400 cyclotron. The intensity of the injected $^{50}Ti^{5+}$ beam was about 50 μA. The operational experience with the ion source has been excellent in terms of stability and reliability during the commissioning period. The compound consumption rate was 2.4 mg/h, and consequently, the ^{50}Ti consumption amounted to 0.52 mg/h.

A new compact type of liquid He-free superconducting electron-cyclotron-resonance (ECR) ion source, designed and built jointly with the Laboratory of High Energy Physics (LHEP), JINR, will be used as a high-charge-state heavy-ion injector for the MC400 cyclotron. The axial magnetic field was produced by a superconducting magnet, whereas the radial plasma confinement was achieved by a hexapole magnet made of NdFeB. To improve the performance of the ion source when producing high-charge-state ions (e.g., Xe^{+30}), the source was upgraded by increasing the microwave frequency up to 18 GHz. Preliminary tests at this frequency demonstrated that the ion source could successfully produce medium-charge-state ions.

SYNTHESIS AND PROPERTIES OF NUCLEI AT STABILITY LIMITS

Synthesis of New Elements. In 2013, the analysis of the results of experimental study on the properties of radioactive isotopes of elements 115 [1] and 117 [2] was completed, and their α-decay products formed in the $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ and $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$ complete fusion reactions were studied. The experiments were carried out using the JINR FLNR gas-filled recoil separator in collaboration with the laboratories at Oak Ridge (ORNL), Livermore (LLNL), Knoxville (UT), Nashville (VU), and Dimitrovgrad (RIAR).

Three ^{294}117 and eleven ^{293}117 nuclei were registered in the $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$ reaction. The radioactive properties of the 12 nuclei in the decay chains of ^{294}117 and ^{293}117 are the same as those found in the first experiment on synthesis of element 117 in 2009–2010. The ^{289}115 isotope was observed in the cross reactions $^{243}\mathrm{Am}\,(^{48}\mathrm{Ca}, 2n)\,^{289}115$ and $^{249}\mathrm{Bk}\,(^{48}\mathrm{Ca}, 4n)\,^{293}117 \rightarrow {}^{289}115$. When formed as a result of a direct nuclear reaction with subsequent α decay of the mother nucleus ^{293}117, the decay properties of the nucleus and its α-decay products (Fig. 1) are identical in both reactions.

Chemistry of Transactinides. The cryodetector working at the temperature gradient from room temperature to $-60°$C was considerably upgraded in 2013. The setup comprises a sealed gas transport system,

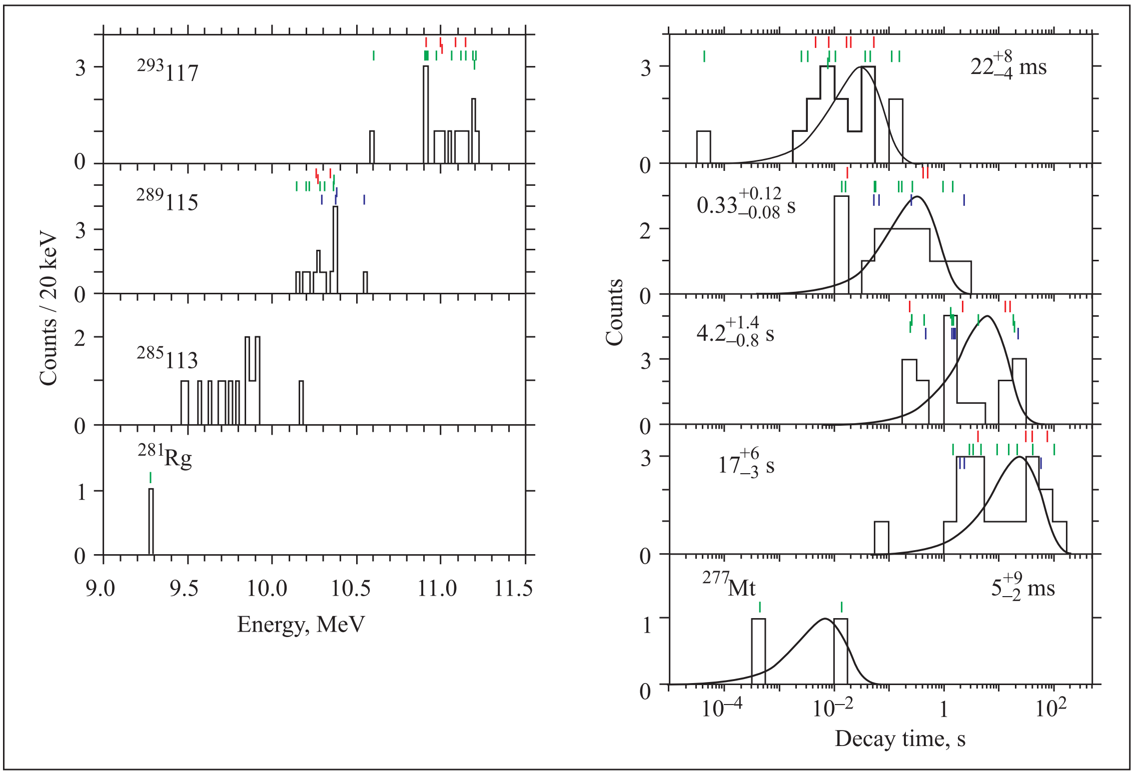

Fig. 1. Energy spectra of α particles (left) and decay time distributions (right) for ^{277}Mt–^{293}117. The values measured earlier in the reactions ^{249}Bk (^{48}Ca, $4n$) ^{293}117 and ^{243}Am (^{48}Ca, $2n$) ^{289}115 are represented by the spectral lines. The curves represent exponential distributions $dN/d\log(t)$ for the given half-lives

a target chamber, and a trap for aerosol particles, water, and oxygen.

The detection system consists of four detecting modules containing semiconductor detectors. Each module comprises two four-strip silicon detectors covered with gold. The He–Ar mixture was used to transport radionuclides to the detection system. The cryodetector was used to study the properties of element 113 in the fusion reaction ^{243}Am (^{48}Ca, $3n$) ^{288}115. The ^{284}113 isotope was produced as a result of the α decay of the isotope ^{288}115. The ^{243}Am targets were irradiated with a ^{48}Ca beam at 273 MeV delivered by the U400 cyclotron of FLNR. A total radiation dose amounted to $2.0 \cdot 10^{19}$. Five decay chains of element 113 were observed in the experiment. The results on the isotope decay energy and lifetimes were compared with those of previous studies and showed good agreement with them. The measurements confirmed the volatility of element 113. Moreover, two decay chains of the isotope ^{283}Cn and five decay chains of the isotope ^{285}Cn were produced with a 278-MeV ^{48}Ca ion beam impinging the ^{242,244}Pu targets.

VASSILISSA Separator. The recoil nuclei separator SHELS (Separator for Heavy ELements Spectroscopy) was put into operation in 2013, following successful vacuum and high-voltage tests. An α source and the fusion reactions ^{22}Ne (^{238}U, $4{-}5n$) $^{255-256}$No, ^{22}Ne (^{208}Pb, $4n$) ^{226}U, and ^{22}Ne (^{206}Pb, $4n$) ^{224}U were used to carry out transmission measurements, equipment tests, and fine tuning of the separator. The obtained data are under analysis. In November 2013, test measurements were carried out using a ^{50}Ti ion beam. As a result, the transport efficiency of Rf evaporation residues was measured at the target position of the SHELS separator. The transmission efficiency for the ^{209,210}Ra evaporation residues produced in the reaction with the ^{50}Ti beam and the ^{164}Dy target was estimated at 40%. The spontaneous fission of ^{256}Rf and the α decay of ^{257}Rf were measured in the complete fusion reaction $^{50}\mathrm{Ti} + {}^{208}\mathrm{Pb} \rightarrow {}^{258}\mathrm{Rf}^*$. The most important results are published in [3, 4].

Mass Spectrometer MASHA. In 2013, the data obtained in test experiments aimed at measuring the operating speed and efficiency of separation of short-lived mercury isotopes produced in the $^{40}\mathrm{Ar} + {}^{144}\mathrm{Sm}$ fusion reaction were analyzed. The separation time and efficiency were found to be (1.8 ± 0.5) s and 7%, respectively [5]. The results are consistent with the data obtained at the ISOLDE (CERN) facility.

The mass measurements of ^{283}Cn synthesized in the $^{48}\mathrm{Ca} + {}^{238}\mathrm{U}$ reaction were performed at the U400M cyclotron. A rotating uranium oxide target, irradiated for a total of 670 h, was deposited on the titanium-backing foil. The flux of ^{48}Ca ions which passed through the target was $1.9 \cdot 10^{18}$. No decay events of ^{283}Cn were registered.

Dynamics of Heavy-Ion Interaction, Fission of Heavy and Superheavy Nuclei. An experiment aimed to investigate the fission channel $^{260}\mathrm{No} \to {}^{208}\mathrm{Pb} + {}^{48}\mathrm{Ca} + 4n$ in the reaction ^{22}Ne (106 MeV) + ^{238}U was conducted at the FLNR U400M cyclotron. Fission fragments were detected by the two-arm time-of-flight spectrometer CORSET. The mass-energy distributions of fission fragments of ^{260}No were measured. As a result, an increase was observed in the fragment yield in the mass region around 52/208 amu, which corresponded to the formation of a fissioning pair of two magic nuclei Ca/Pb. It is worth of note that the largest mass asymmetry ever recorded for neutron-induced fission of actinide nuclei is $\eta = 2.5$, whereas in the experiment super asymmetric fragments exhibit $\eta = 4.3$.

Within the framework of cooperation with the Accelerator Laboratory of the University of Jyväskylä (Finland), the Department of Physics of the University of Naples (INFN, Italy), and GSI (Germany), the mass-energy distributions of binary fragments were measured in the reaction $^{88}\mathrm{Sr} + {}^{176}\mathrm{Yb}$ at the JYFL K130 accelerator, energy and the centre-of-mass angles being $E_{\rm lab} = 435$ MeV and 30°–140°, respectively. The dissipation of large amounts of kinetic energy was observed for a significant part of binary fragments, which indicated the presence of deep inelastic transfer reactions. An enhanced yield was observed of heavy fragments with masses around 190–200 amu, caused by the influence of proton shells with $Z = 28$, 82. This behavior can be attributed to the net mass transfer of about 20–25 nucleons between the projectile and target. The data analysis revealed that the relative contribution of multinucleon transfer reactions to the capture cross section mainly depends on the reaction entrance channel properties. For target-like fragments heavier than the target, the excitation was about 30–50 MeV, which ledto an increased probability of the formation of nuclei surviving after the emission of 3–5 neutrons. Unexpected high yields of products heavier than the target confirm the possibility of producing neutron-rich isotopes in multinucleon transfer reactions at low energies. This result is particularly important for the synthesis of new superheavy elements [6, 7].

Yu. M. Itkis defended her Ph.D. thesis in 2013. The thesis was devoted to the study of the properties of mass and energy distributions of fission and quasifission fragments produced in reactions induced by ^{22}Ne, ^{26}Mg, ^{36}S, and ^{58}Fe, leading to the formation of $^{266,271,274}\mathrm{Hs}^*$ ($Z = 108$) at energies below and above the Coulomb barrier.

Structure of Exotic Nuclei. In 2013, experiments were carried out at the ACCULINNA fragment separator to study the two-proton decay ($2p$ decay) branches of the excited state in ^{17}Ne formed in the $^{18}\mathrm{Ne} + {}^{1}\mathrm{H} \to d + {}^{17}\mathrm{Ne}$ reaction. The experiments were aimed to acquire data on the decay branches for the "true" $2p$ decay of the first excited state of ^{17}Ne ($J^\pi = 1/2^+$, $E^* =$ 1.288 MeV). The $1/2^+$ state undergoes an M1 γ transition from an excited state back to the nuclear-stable ground state. The observation of a weak branch for the "true" $2p$ decay is important. The investigation of this new type of radioactive decay can provide more information on the nuclear structure of ^{17}Ne, which can be treated as the so-called "Borromean" three-body ($^{15}\mathrm{O} + 2p$) cluster structure. The astrophysical aspects are also essential. As found earlier, even a very weak ($\Gamma_{2p}/\Gamma_\gamma \approx 0.01{-}0.001\%$) $2p$ decay branch for the $1/2^+$ state would testify to the bypass of the ^{15}O waiting point in the rp-process nucleosynthesis by the two-proton capture reaction $^{15}\mathrm{O} + 2p$. A new approach was used to carry out experimental measurements for ^{17}Ne undergoing $2p$ decay, overall energy resolution being no less than 100 keV FWHM. Such a high resolution is required to unambiguously isolate a "true" $2p$-decay signal of the $1/2^+$ state from protons sequentially emitted from the decay of two high-lying ^{17}Ne states at an energy of 1.908 MeV and $E^* = 1.764$. The partial data analysis together with the measurements to date yields a limit of $\Gamma_{2p}/\Gamma_\gamma < 0.1\%$. A limit of $\Gamma_{2p}/\Gamma_\gamma < 0.01\%$ is expected following the complete data analysis.

In 2013, the data obtained in experimental studies on the low-energy excitation spectrum of the superheavy helium isotope ^{10}He formed in the two-neutron transfer reaction $^{8}\mathrm{He} + {}^{3}\mathrm{H} \to {}^{10}\mathrm{He} + p$ [8] continued to be analyzed.

Reactions with Beams of Light Stable and Radioactive Nuclei. In 2013, the FLNR group continued developing multiwire proportional chambers and diagnostic systems for low-intensity ion beams ($\leqslant 10^7$ pps). The specialists of the GANIL group, who actively designed and tested these systems, are interested in their future implementation at the SPIRAL2 facility at GANIL, France.

In 2013, the FLNR group conducted a series of experiments aimed to shed additional light on structural peculiarities of the isotopes ^{9,10}Be and ^{10}B. The experiments were carried out at the U120 cyclotron at the Nuclear Physics Institute (NPI), Řež (Czech Republic), and the cyclotron of the Jyväskylä University (Finland). As a result, the angular distributions of differential cross sections were measured for the $^{9}\mathrm{Be}\,(\alpha,\alpha')\,{}^{9}\mathrm{Be}^*$, $^{9}\mathrm{Be}\,(\alpha,{}^{3}\mathrm{He})\,{}^{10}\mathrm{Be}$, and $^{9}\mathrm{Be}\,(\alpha,t)\,{}^{10}\mathrm{B}$ reactions. The optical model (OM) and the distorted-wave Born approximation (DWBA) were used to analyze the calculated dependencies. As an example, the experimentally measured angular distributions of differential cross sections for the $^{9}\mathrm{Be}\,(\alpha,\alpha')\,{}^{9}\mathrm{Be}^*$ reaction and the results of the data analysis are presented in Fig. 2. The value of $9/2^-$ was assigned to the spin and parity for the excited state in ^{9}Be at 11.28 MeV. The obtained data are also essential for astrophysics.

Fruitful scientific cooperation with other research centres continued. In particular, an experiment was conducted at the ALTO radioactive beam complex,

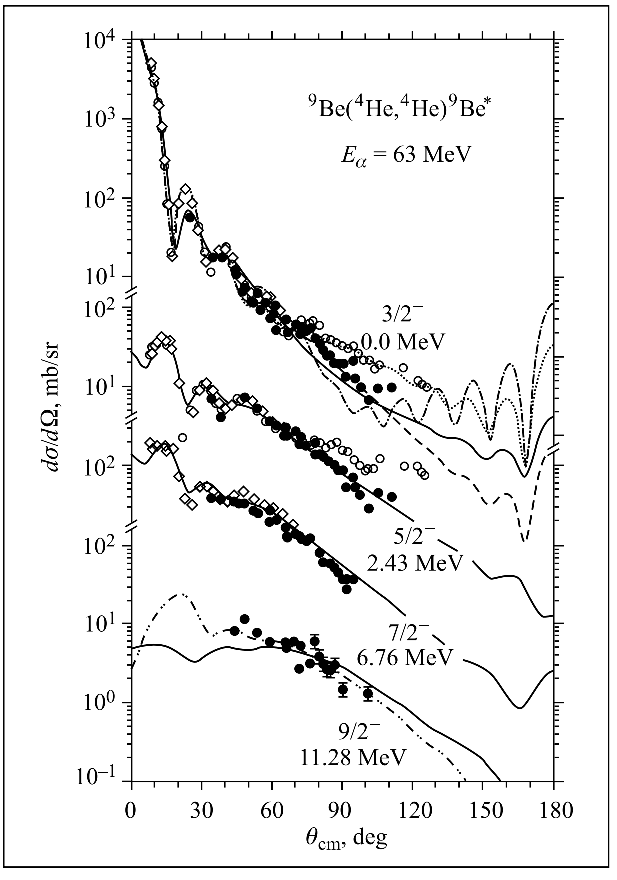

Fig. 2. The differential angular distributions of the ground and excited states of ^{9}Be in the ^{9}Be(α, α') ^{9}Be* reaction. The symbols denote experimental data, and the curves represent the analysis results within the optical model and the distorted-wave Born approximation

Orsay (France), aimed to measure beta-delayed neutron emission probabilities for ^{82,83,84}Ga using the TETRA 4π neutron detector developed in Dubna.

The most important 2013 results are published in [9, 10].

Theoretical and Computational Physics. The problems related to the production of neutron-rich heavy nuclei in multinucleon transfer reactions at low-energy collisions of heavy ions were studied [11]. It has been shown that reactions with actinide beams and targets are of special interest for synthesis of new neutron-rich transfermium nuclei and yet unknown nuclei with the closed neutron shell $N = 26$, which have the greatest impact on the process of nucleosynthesis. Calculated cross sections appeared to be high enough and the experiments proposed can be carried out at the existing accelerators.

Fast fall of cross sections and a drastic decrease of life-times of nuclei with $Z > 120$, obtained in the fusion reactions, make considerable difficulties and are responsible for uncertainties in further development of the physics of superheavy elements. All possible reaction mechanisms (fusion of stable and radioactive nuclei, multinucleon transfer and processes of neutron capture) that may be used for synthesis of superheavy elements were studied in detail [12]. New experiments were proposed aimed at the synthesis of superheavy nuclei located between those synthesized in the reactions of "cold" and "hot" fusion, as well as at the production of long-lived neutron-rich isotopes of superheavy elements, including those located in the centre of the "stability island".

The effect of channels of collective excitations and neutron rearrangement on subbarrier fusion cross sections for atomic nuclei was investigated [13]. Comparison with previous studies suggests that the subbarrier fusion enhancement is not limited to the case of intermediate neutron transfer with positive Q values. A significant subbarrier fusion enhancement was also observed in the case when colliding nuclei are resistant to collective excitations. Moreover, experimental studies with several prjectile-target combinations were proposed.

The knowledge base on low-energy nuclear physics allocated on the website http://nrv.jinr.ru/nrv was extended with the partial support from the JINR–RSA cooperation programme. Several new models were added to the knowledge base, including: (i) a GRAZING code based programme for calculating few-nucleon transfer cross sections; (ii) an EPAX code based programme for calculating yields of reaction products in intermediate-energy heavy-ion fragmentation processes.

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

The investigation of track-etched nanopores continued in several directions. A method was developed based on measurements of electrical conductivity as a function of time. It allows reconstruction of longitudinal profiles of symmetric nanopores. The new approach can be useful for sensor applications of nanopores. Recrification properties of single- and multi-pore asymmetric membranes were experimentally compared. The pore profiles in PET track-etched membranes were also studied using the ion energy-loss spectroscopy [14].

A method was developed for producing photocatalytic nanocomposite membranes by directly modifying the surface of PET track-etched membranes with silver and titanium. It was found that membrane surface has excellent self-cleaning and superhydrophobic properties.

An investigation was undertaken on changes of metal elemental composition in an atmosphere of high-pressure hydrogen and deuterium irradiated with 10–23-MeV γ quanta [15].

The cross-sectional transmission electron microscopy (XTEM) and scanning electron microscopy (SEM) were used to study nanocrystalline ZrN samples implanted with a 30-keV He beam ($5 \cdot 10^{16}$ cm^{-2}) and subsequently irradiated with 167-MeV Xe ions (10^{14} cm^{-2}). It was found that post-irradiation heat treatment induced formation of blisters due to helium segregation. The XTEM and SEM analyses showed helium blistering was suppressed under high-energy Xe ion irradiation. This result has considerable practical value for simulation of radiation damage in reactor materials caused by fission fragments [16, 17].

The influence was studied of high ionization induced by swift Bi ions ($E = 710$ MeV) on the development of gas blisters in silicon implanted with deuterium ($E = 12.5$ keV) and helium ($E = 25$ keV) ions during 500°C post-radiation annealing. The light microscopy, TEM, ERD, and thermal desorption spectroscopy (TDS) were used.

For the first time ever, significant reduction (even full suppression, e.g., in deuterium) of blister and flake formation was accomplished. The analysis results revealed that radiation-induced desorption of deuterium and helium occurs during their irradiation with swift bismuth ions.

Nanostructured materials were used to study the distribution of 4- and 5-valent elements. The reactions ^{118}Sn$(\gamma, n)\,^{117m}$Sn and ^{196}Pt$\,(\gamma, n)\,^{195m}$Pt were studied to produce radioisotopes for biomedical research.

A rapid method is currently being developed for the analysis of Po in soil and plants. Studies have also been initiated on the behaviour of volatile elements and decay products of uranium and thorium in the oil shale fly ash [18, 19].

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