FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2010, 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) (4 subtopics);

In 2010, the operation time of the U400 and U400M FLNR cyclotrons amounts to $\sim$10900 hours.

SYNTHESIS OF NEW ELEMENTS

In January-March 2010 experiments on the synthesis of the new element 117 in the complete fusion reaction ^{249}Bk + ^{48}Ca were carried out [1]. Experiments were performed using the FLNR (JINR) gas-filled separator in collaboration with the USA laboratories of Oak Ridge (ORNL), Livermore (LLNL), and the Vanderbilt University. The target material was accumulated at Oak Ridge; the 0.31 mg/cm^2 target was manufactured in Dimitrovgrad (Russia).

The first run was undertaken in the first half of 2009, the energy of ^{48}Ca ions delivered by U400 cyclotron was 252 MeV and the total beam dose made $2.4 \cdot 10^{19}$. In this experiment, the new superheavy element with atomic number 117 was synthesized for the first time (see Fig. 1). In the reaction ^{249}Bk(^{48}Ca,4n)^{293}117 we detected five nuclei of the isotope ^{293}117 ($E_\alpha = 11.03$ MeV, $T_{1/2} = 14$ ms). This nuclide undergoes three sequential α decays that lead to the nuclei ^{289}115, ^{285}113, and spontaneously fissioning ^{281}Rg ($T_{1/2} = 26$ s). The cross section of producing ^{293}117 was measured to be 1.3 pb.

The next experimental run carried out in the period from October 2009 to March 2010 was aimed at synthesizing a heavier isotope ^{294}117. Here the beam dose of ^{48}Ca ions with the energy of 247 MeV was $2.0 \cdot 10^{19}$. A new decay chain involved six α decays of the nuclei ^{294}117 ($E_\alpha = 10.81$ MeV, $T_{1/2} = 78$ ms), ^{290}115, ^{286}113, ^{282}Rg, ^{278}Mt, ^{274}Bh, and spontaneous fission of ^{270}Db ($T_{1/2} = 23$ h). The cross section of the reaction ^{249}Bk(^{48}Ca,3n)^{294}117 was measured to be 0.5 pb.

Radioactive properties of the eleven new nuclides demonstrate a considerable increase of nuclear stability with the increase of the number of neutrons and approach to the area of influence of the spherical shells $Z = 114{-}126$ and $N = 184$. The new nuclei, together with those synthesized in the reactions with ions of ^{48}Ca before, establish a consistent picture of nuclear properties in the region of the heaviest nuclides. They show the primary importance of the nuclear shells and provide experimental evidence of the existence of the predicted domain of superheavy elements.

CHEMISTRY OF TRANSACTINIDES

In 2010, the volatility of the element 113 was investigated in the framework of studying the chemical properties of transactinide elements. The fusion reactions ^{249}Bk + ^{48}Ca leading to the synthesis of the isotopes ^{294}117 (3n channel) and ^{293}117 (4n channel) was used to produce the decay products ^{284}113 ($\sim$8 s) and ^{286}113 ($\sim$30 s).

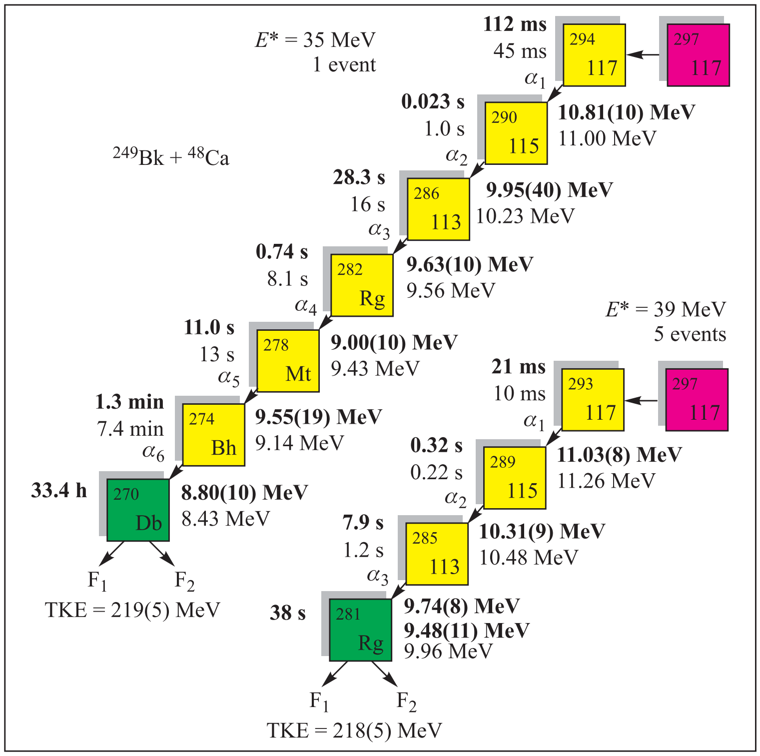

Fig. 1. Decay chains of the nuclei $^{294}117$ and $^{293}117$. The measured and the predicted lifetimes and α-particle energies are shown in black and light, respectively

The setup for studying chemistry of superheavy elements included a closed gas-transport system, a target chamber, and a trap for aerosol particles, water, and oxygen. A detection system consisted of four detecting arrays. Each array consisted of two position sensitive silicon detectors covered with gold [3]. A detector surface was kept at the temperature 0^o C. He-Ar mixture was used as a transport gas. Transport time was estimated with the use of short-lived Hg.

Two same ^{249}Bk targets (0.5 mg/cm^2+ +30 μ gNd/cm^2) were irradiated with ^{48}Ca ions at the energy of 249 MeV at the U400 cyclotron. The dozes made $3.5 \cdot 10^{18}$ and $5.6 \cdot 10^{18}$, respectively.

Simultaneously, adsorption of mercury atoms was studied. For this purpose, the isotope ^{185}Hg obtained in the reaction Nd(nat.) + ^{48}Ca was used. Two decay chains starting from the element 113 were observed. The decay energies and lifetimes were found to be in good agreement with the results presented in previous works, particularly, in [1]. Basing on the experimental data we concluded that the element 113 is volatile.

SEPARATOR VASSILISSA

In 2010, the experiment aimed to the study of spontaneous fission characteristics of ^{244}Fm and ^{252}No isotopes was performed at FLNR with the use of the VASSILISSA separator. Previous experiments were dedicated to the study of SF of ^{246}Fm isotope [2]. Complete fusion reactions ^{40}Ar + ^{206}Pb and ^{48}Ca + ^{206}Pb were studied in the experiment. Neutron detector including 62 ^{3}He-filled counters was used at the focal plane of separator together with a silicon strip detector. Lifetimes, TKE, and multiplicity of prompt neutrons were measured. The data obtained in the experiment are under analysis now.

At the present time, the modernization of the separator is being performed [3]: The required optical elements have been purchased, new HV power supplies for the electric dipoles have been delivered. The schematic layouts of the facility before and after the upgrade are shown in Fig. 2.

MASS-SPECTROMETER MASHA

In 2010, the adjustment of systems of the mass-spectrometer was carried out. In particular, different operation modes of the ECR ion source and the hot trap were tested. It was shown that efficiency of the source is maximal and constant in the range of microwave power 25–40 W. The efficiency of the source

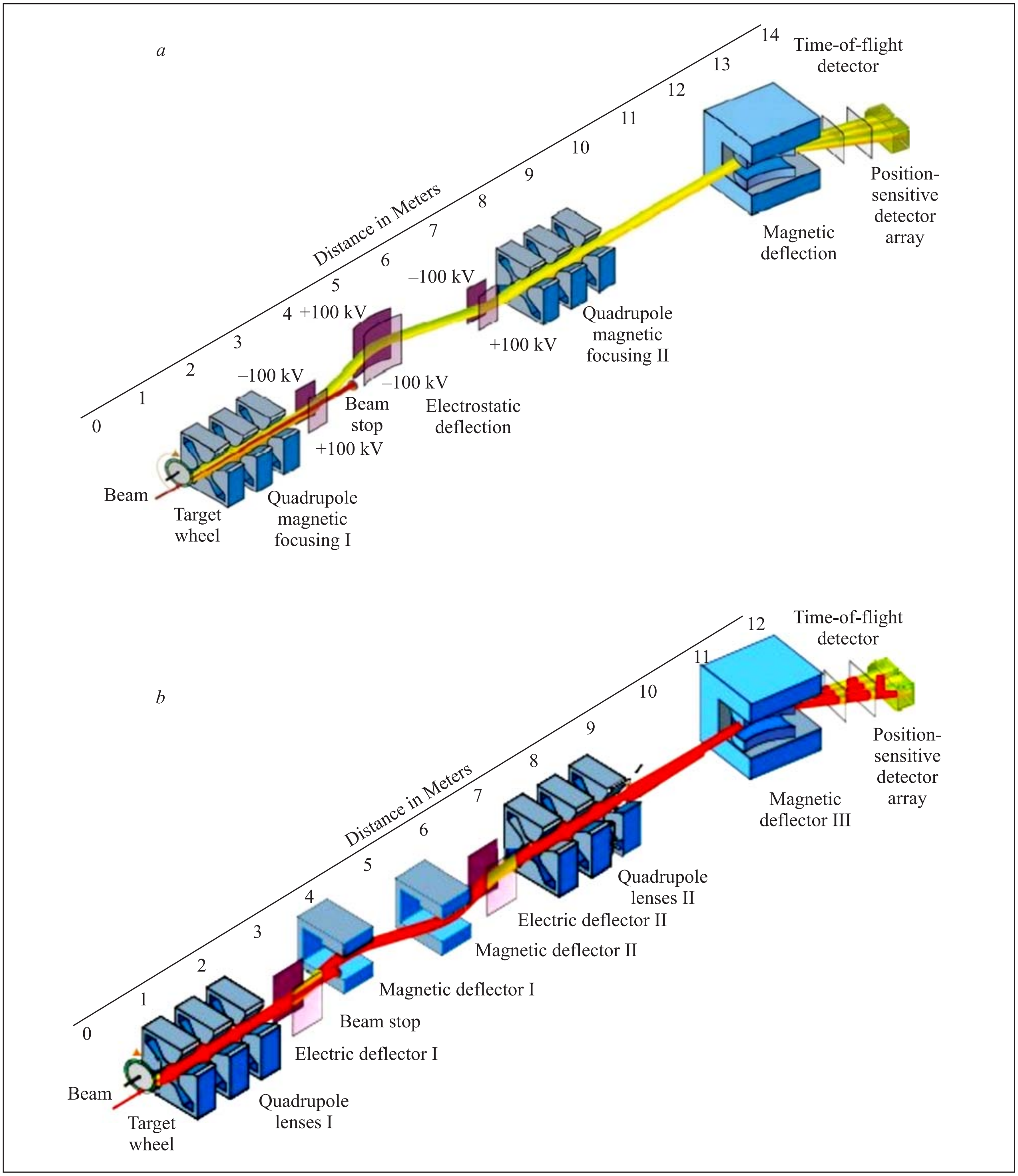

Fig. 2. Schematic view of the VASSILISSA separator before (a) and after (b) the upgrade

increases with increasing the atomic mass of the gas. We found the optimal operation mode of the hot trap operating together with the ion source. The speed of the ISOL methodics was found to be 2.5 s. The total measured efficiency of the system «hot trap + ECR-source + mass-spectrometer»makes 25%.

The first test measurements at the mass-spectrometer have been carried out. In the reactions $^{40}\mathrm{Ar} + {}^{\mathrm{nat}}\mathrm{Sm} \rightarrow {}^{180-185}\mathrm{Hg} + xn$ and $^{40}\mathrm{Ar} + {}^{166t}\mathrm{Er} \rightarrow {}^{200-205}\mathrm{Rn} + xn$ the Hg and Rn isotopes were detected and identified. The setup provides for the mass and energy resolution about 10^{-2} amu and 5 keV, respectively.

In 2010, a new facility CORSAR, intended for the study of neutron-rich heavy nuclei in vicinity of $N = 126$ and created in cooperation with PNPI (Gatchina), Universite Libre de Bruxelles, (Belgium), and University of Jyvaskyla (Finland), was put into operation. The first test run was carried out in October 2010. The mass and energy distributions of reaction products were obtained at the ^{136}Xe ions c.m. energies of 423, 483, 634 MeV.

The analysis of the experimental data on the study of properties of superheavy nuclei $Z = 112$ and $Z = 120$ obtained in the reactions of the magic projectiles ^{48}Ca and ^{64}Ni with the same target ^{238}U at energies around the Coulomb barrier, was completed [4]. The experiments were carried out in the Physics Department of the University of Jyvaskyla (Finland) and in the Laboratori Nazionali di Legnaro (Italy). Binary reaction products were detected by the two-arm time-of-flight spectrometer CORSET.

The results of detailed analysis of mass and energy distributions of fragments, fission and quasifission cross sections for a wide range of nuclei with $Z = 102{-}122$ produced in reactions with ^{22}Ne, ^{26}Mg, ^{36}S, ^{48}Ca, ^{58}Fe, and ^{64}Ni ions at energies close and below the Coulomb barrier, were presented in the works [5, 6]. For the region of very heavy nuclei with compound masses from $A \approx 256$ to $A \approx 280$, the fragment mass distributions are symmetric in most cases. When both fragments are close to either $Z = 50$ or $N = 82$, bimodal fission shows up. The bimodal fission caused by clustering phenomena was observed for fission of superheavy nuclei ^{271,274}Hs. In the case of fission of superheavy nuclei the light fragments with mass 132–134 amu play the stabilizing role.

The major part of the quasifission fragments was observed in the vicinity of the $Z = 82$ and $N = 126$ (double magic lead) and $Z = 28$, $N = 50$ shells, and the maximum of the yield of the quasifission component is a mixing between all these shells. Hence, shell effects are present in transfer reactions, fission, and quasifission and determine the basic characteristics of fragment mass distributions. At the transition from Ca to Ni projectiles, the contribution of the quasifission process rises sharply, and thus, Ni is not an optimal projectile for the synthesis of element $Z = 120$ in the complete fusion reactions.

EXOTIC DECAYS

Comparative analysis of two experiments aimed at searching for a new type of cluster decay called «collinear cluster tri-partition» (CCT), was completed in 2010.

Two different fissionig systems, namely, ^{252}Cf(sf) and ^{236}U* from the reaction ^{235}U$(n_{\rm th}, f)$ were studied with the use of the missing mass method. Masses of two coincident fission fragments (FF) were determined by measuring the velocity-energy correlations. The key methodical problem was the presence of the background of scattered fragments imitating the CCT products. In order to increase a reliability of the identification of the CCT events in the second experiment we have additionally measured parameters sensitive to the nuclear charge. This let us to confirm directly an existence of the specific CCT mode manifesting itself in the increased yields of the FF mass distribution lines at the lines $M1 + M2 = \text{const}$. The constants are supposed to correspond to total masses of pairs of magic clusters, namely (Ni/Sn) or (Ge/Sn). Comparison of the experiments under analysis provides strong evidence in favor of this hypothesis. The systems under analysis differ by 16 mass units, however the position of the lines stays unchanged.

One can treat the observed mode of the ternary fission as a new type of cluster decay as compared to the well-known heavy ion or lead radioactivity. Key features of both processes are illustrated in Fig. 1. The relatively high CCT yield ($\sim 10^{-3}$ per binary fission) can be understood if one assumes collective motion through hyperdeformed prescission shapes of the mother systems. This assumption is supported by the fact that the linear arrangement provides for the lowest Coulomb potential energies of three clusters [7, 8].

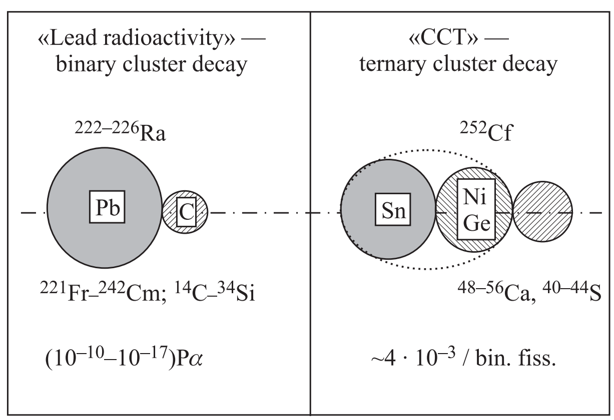

Fig. 3. Cluster scheme for the comparison of the known lead radioactivity with collinear cluster tri-partition

The structure of a proton-rich nuclear system ^{6}Be was studied in the charge-exchange reaction ^{1}H(^{6}Li,^{6}Be)n. As a result of measurements, the ground 0^+ and the first excited state 2^+ were observed in the experimental spectra. Measured angular and energy correlations of decay products allowed us to identify the ^{6}Be spectrum in the energy range 4–15 MeV as a isovector soft dipole excitation mode. At the present time the experimental data are under analysis.

Rare decay modes of the extremely neutron-rich nucleus ^{8}He were studied in collaboration with Warsaw University and CSIC (Madrid, Spain). The optical time projection chamber (OTPC) was used in the experiment [9]. Detection of the neutron emitted from a highly excited ^{8}Li state, which is a product of ^{8}He β-decay, indicates that the standard decay scheme of ^{8}He is incomplete. Experiments with OTPC are a new promising method for the study of β decay of ^{8}He into the $\alpha + t + n$ continuum. It was shown that information obtained with the use of the OTPC can clarify the mechanism of such decays.

The experimental search for the reputed two-proton emitter ^{26}S was performed in the reaction of fragmentation of a $50.3A$ MeV ^{32}S beam [10]. Neither ^{26}S nor ^{25}P were observed. The upper half-life limit $T_{1/2} < 79$ ns was established on the base of the production systematics. Together with theoretical lifetime estimates for two-proton decay this result gives a decay energy limit of $Q_{2p} > 640$ keV for ^{26}S. We conclude that the ^{26}S lifetime is in the picosecond range and a further search for this isotope should be done with the use of the decay-in-flight technique.

The project of a new in-flight fragment separator ACCULINNA-2 was proposed [11]. The new facility will allow us to increase the secondary beam intensity by a factor 10–15, improve ion optics and extend the range of radioactive beams up to $Z \sim 20$.

REACTIONS WITH BEAMS OF LIGHT STABLE AND RADIOACTIVE NUCLEI

In the framework of studies of the effect of enhanced interaction cross sections of ^{6}He at sub-barrier energies, the peculiarities of interaction of weakly bound cluster nuclei (d, ^{6}Li) were investigated at the U120 cyclotron in INP, Rez (Czech Republic), and at the tandem of INIT, Bucharest (Romania). New results demonstrating the influence of the cluster structure of loosely bound nuclei on the interaction cross section at energies close to the Coulomb barrier, were obtained [12].

We continued to develop the setups consisting of multiwire proportional chambers, which were used as position-sensitive detectors and diagnostic systems for low beam intensities (down to 10^7 pps) [13]. In 2010, the chambers were additionally supplied with semiconductor $\Delta E{-}E$-detectors and an E-detector composed of a mosaic of scintillation detectors for measuring correlated reaction products. This made it possible to improve the characteristics of the chamber and to make of it a unique charged-particle spectrometer with high luminosity. This work is being performed jointly with colleagues from GANIL (France).

At the accelerator complex GANIL, we performed measurements on formation cross sections of neutron-rich nuclei in the vicinity of ^{48}Ca. The preliminary results give evidence of the perspectives of using deep inelastic transfer reactions at relatively high energies (50 MeV/nucleon) for the synthesis of new nuclides at the limits of nucleon stability [14].

At the cyclotron of the University of Jyvaskyla, a joint experiment was carried out with the aim to observe the $t{-}t$ decay of highly excited states of ^{6}He. The proportional chamber designed and manufactured in FLNR, allowing the simultaneous detection and identification of more than two particles, was used in this experiment.

The results, obtained in our department, were reported at the International Conference on Nuclear Spectroscopy (Peterhof) and at the International Symposium on Clusters (Brussels, Belgium). The series of investigations, carried out in the department, received the 2nd award of JINR in 2010. In 2010, Professor Yu. E. Penionzhkevich received the G. N. Flerov Prize for successful work on the synthesis and investigation of the properties of light nuclei at the limits of nucleaon stability.

THEORY AND COMPUTATIONAL PHYSICS

In the works performed in 2010 it was found that true ternary fission with formation of a heavy third fragment is quite possible for superheavy nuclei because of the strong shell effects leading to a three-body clusterization with the two doubly magic tin-like cores [15]. The simplest way to discover this phenomenon in the decay of excited superheavy nuclei is a detection of two tin-like clusters with appropriate kinematics in low-energy collisions of medium-mass nuclei with actinide targets. The three-body quasifission process could be even more pronounced for giant nuclear systems formed in collisions of heavy actinide nuclei. In this case, a three-body clusterization might be proved experimentally by the detection of two coincident lead-like fragments in low-energy $\mathrm{U}+\mathrm{U}$ collisions. A new way is found [16] to discover and examine unknown neutron-rich heavy nuclei at the «north-east» part of the nuclear map (that is extremely important for nuclear astrophysics investigations and, in particular, for the understanding of the r-process of astrophysical nucleogenesis) via low-energy multinucleon transfer reactions. Several tens of new nuclides can be produced, for example, in near-barrier collision of ^{136}Xe with ^{208}Pb.

In 2010, the knowledge base on low-energy nuclear physics, «Nuclear Reactions Video», allocated at the Web-site http://nrv.jinr.ru/nrv, was significantly extended and improved [17]: (i) Computational code for a calculation of the evaporation residue cross sections in fusion of heavy nuclei were written and included into the knowledge base. (ii) The knowledge base was extended by the possibility of analyzing the cross section of few nucleon transfer processes within the distorted wave approximation. (iii) The digital databases on elastic scattering, fusion reactions and yields of evaporation residues have been extended by including several hundreds experimental cross sections. Within the JINR–SAR collaboration, the mirror server of the nuclear knowledge base was established and opened for common access. The server is placed at University of Stellebosch, SAR and is accessible at http://nrv.sun.ac.za/nrv/. The results of the collaboration were reported on the 55th Annual Conference of South African Physical Society (SAIP-2010) and at the 2nd South Africa – JINR Symposium: Models and Methods in Few- and Many-Body Systems.

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

1. Detailed data on transport properties of asymmetrical electrically charged track nanopores, that are of fundamental importance for understanding the processes taking place in constrained volumes including living matter, are obtained. The obtained experimental data are compared with theoretical models.

2. For the first time, nanopores in thin (200–300 nm) films of silicon nitride are fabricated and studied (in the nanofiltration mode).

3. A structure and charge transport properties of the track membrane modified by the tetrafluoroethane plasma have been studied. The effect of conductivity asymmetry in electrolyte solutions has been established.

4. The mechanical stresses and microstructure of nanocrystalline ZrN irradiated with Xe ions have been studied.

5. The formation of ordered helium nanobubbles in the samples of molybdenum as a result of their irradiation with 20 keV helium ions and with 150 keV iron ions, is investigated. A conclusion about opportunity of the formation of nanoinclusions of other phases in materials with the preformed ordered gas porosity during low-dose irradiation, is deduced.

6. Process of radiation resistance of nanomultilayered structures after irradiation by Ar and Xe has been studied. It was shown that the layered structures kept high radiation resistance. That behavior has very important value for applications of such layered structures at strong ionizing radiation fields as radiation resistant covers.

7. The new methods of separation and concentration of radioisotopes (selective radiochemical separation) are developed.

8. The reaction $^{118}\mathrm{Sn}(\gamma,n)$ was investigated with the purpose of ^{117m}Sn production for biomedical researches

9. Modernization of the FLNR accelerator complex for carrying out the studies on nanostructural modification of materials and production of radioisotopes has been carried out. A detection system for control over the low-intensity ion beams at the specialized channel of IC-100 has been created. A specialized channel for testing microchips for radiation-induced upsets (simulation of space radiation) has been designed and installed at the U400M cyclotron.

The main results obtained in 2010 are published in [18–20].

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