FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2009, 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 of new nuclei and study of the nuclear properties and heavy-ion reaction mechanisms (9 subtopics);
- Radiation effects and physical bases of nanotechnology, radioanalytical and radioisotopic investigations at the FLNR accelerators (5 subtopics);
- Development of the FLNR cyclotron complex for producing intense beams of accelerated ions of stable and radioactive isotopes (2 subtopics);
- Development and construction of an accelerator complex for producing radioactive ion beams (the DRIBs project).

In 2009, the operation time of the U400 and U400M FLNR cyclotrons amounted to $\sim$ 11200 h which is in agreement with the plan.

Synthesis of New Elements

Since July 2009, the experiment has been underway aimed at the synthesis of the new element 117 in the complete-fusion reaction ^{249}Bk+^{48}Ca. The experiment is performed employing the Gas-Filled Recoil Separator of the JINR FLNR in collaboration with the laboratories of Oak Ridge (ORNL), Livermore (LLNL) and Vanderbilt University (USA). The target material was produced in Oak Ridge and the target itself was manufactured in RIAR, Dimitrovgrad (Russia). The target thickness was 0.31 mg/cm^2. Owing to the short lifetime ($T_{1/2} = 320$ d), this isotope cannot be produced and accumulated in advance, and after production should be «used» immediately.

At the first stage of the experiment the energy of the accelerated ^{48}Ca ions delivered by the U400 cyclotron corresponded to the calculated maximum of the production of the isotopes $^{293}117$ and $^{294}117$, the products of evaporation of three and four neutrons from the compound nucleus $^{297}117$, and was about 252 MeV in the middle of the target layer which results in the excitation energy of the compound nucleus of about 39 MeV. The total accumulated beam dose of ^{48}Ca was $2.4 \cdot 10^{19}$. Five decay chains were observed in the experiment. Three α decays and spontaneous fission of the isotope ^{281}Rg were detected in each chain.

In late October, 2009, a second stage of the experiment was started at a lower ^{48}Ca energy that corresponds to the excitation of $^{297}117$ of about 35 MeV. By the end of December the total accumulated beam dose of ^{48}Ca was $2.4 \cdot 10^{19}$. As a result, the decay chain including six α decays and spontaneous fission was detected.

Thus, the experiment has led to obtaining the isotopes of element 117 which can be associated with $3n$ and $4n$ channels of the complete fusion reaction $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$. They give birth to the long chains of sequential α decays that end up in spontaneous fission of ^{281}Rg ($T_{\mathrm{SF}} = 26^{+25}_{-8}$ s) and ^{270}Db ($T_{\mathrm{SF}} = 23^{+110}_{-10}$ h). Decay characteristics of the 11 new isotopes produced in the reaction $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$ are in a good agreement with the properties of the neighboring even-Z nuclei. They substantially expand the systematic of properties of odd-Z nuclides in the region of the most neutron-rich isotopes of elements 105–117 and display considerable increase in the stability of the superheavy elements with increase of the neutron number.

From November 2008 to February 2009, a second run of experiments aimed at the study of the complete-fusion reaction of ^{226}Ra and ^{48}Ca was held at the gas-filled separator.

The target of ^{226}Ra with a thickness of 0.36 mg/cm^2 was irradiated with the ions of ^{48}Ca accelerated at the U400 cyclotron. The total doses of the ^{48}Ca nuclei on the target were $3.3 \cdot 10^{18}$, $1.1 \cdot 10^{18}$ and $2.3 \cdot 10^{18}$ at energies of 228.5, 233.5 and 240.5 MeV, respectively. According to the calculations, these energies correspond to the maximum yield of the products of complete-fusion reaction ^{226}Ra$\,+\,^{48}$Ca with evaporation of three, four and five neutrons, respectively, which results in the formation of the isotopes $^{269-271}$Hs.

The measured α-particle energy was (9.02 ± 0.08) MeV and the half-life of this nucleus is $7.6^{+4.9}_{-2.2}$ s. For the spontaneously fissioning isotope ^{266}Sg the half-life was measured to be $0.28^{+0.19}_{-0.08}$ s.

The cross section of the reaction ^{226}Ra(^{48}Ca, $4n$)^{270}Hs at a ^{48}Ca energy of 233.5 MeV is $8.3^{+6.7}_{-3.7}$ pb. At energies of 228.5 and 240.5 MeV no nuclei of element 108 have been observed.

Separator VASSILISSA

In 2009, the analysis of the data obtained in the experiment on the study of symmetric fusion reaction ^{136}Xe+^{136}Xe was brought to an end [1].

In February–March 2009 the 5th one-month campaign was performed at the recoil separator VASSILISSA. The measurements were done with the use of the detection system GABRIELA consisting of seven Ge detectors for the detection of γ rays, four segmented Si detectors for the detection of conversion electrons and a position-sensitive Si detector for the detection of recoils, α, β particles and fission products. The main goal of the experiment was a detailed study of the isomeric- and α-decay properties of ^{253}No. About 10^4 events of a decay from the isomeric state having a lifetime of ~ 700 μs were observed. The analysis of the γ and conversion electron spectra associated with these decays is still in progress [2].

The analysis of data obtained in the experiment dedicated to the study of the complete-fusion reaction ^{40}Ar$\,+\,^{208}$Pb has been complete [3]. In this experiment for the study of spontaneous fission of ^{244,246}Fm isotopes, a big neutron detector with 62 ^{3}He counters, surrounding the focal plane semiconductor detector assembly, was used.

Modernization of the VASSILISSA separator was in progress in 2009. At present, two new dipole magnets are manufactured at the Efremov Institute (St. Petersburg). The drawings of vacuum tanks for electrostatic deflectors and a vacuum chamber of dipole magnets have been prepared.

Chemistry of Transactinides

As part of the research work on the chemical properties of elements 112 and 114 [4], joint experiments with the PSI team (Switzerland) were continued. In the previous thermochromatographic experiments, three atoms of element 114 were identified. It has been shown that this element is at least as volatile as element 112. Since such behavior is rather unexpected for a typical metal of group 14, there was a need for more experimental data. The cryogenic detector COLD was used in the experiments as it had been done before. In order to produce element 114, the fusion reaction ^{242}Pu(^{48}Ca, $3n$)^{287}114 was used. A stationary ^{242}PuO$_2$ target was irradiated at the U400 cyclotron with $2.7 \cdot 10^{18}$ ^{48}Ca ions at the energies 270 and 315 MeV. Volatile products of the nuclear reactions were transported to the detector with a stream of dry argon. At a beam dose of $4.3 \cdot 10^{18}$ only one atom of element 112 ($^{283}112 \rightarrow {}^{279}$Ds (SF)) was detected on the gold surface of the detector at a temperature of $-7\,^{\circ}$C.

An installation to study the chemistry of superheavy elements, particularly, of volatility of element 113, was tested in 2009. The installation comprises a gas transport system, a target chamber and a trap for aerosol particles, water, oxygen.

The radionuclide ^{284}113 ($\sim$ 0.5 s) obtained as a result of α decay of ^{288}115 was studied in the fusion reaction ^{243}Am(^{48}Ca, $3n$)^{288}115. The ^{243}AmO$_2$ target was irradiated at the U400 cyclotron with $\sim 10^{18}$ ^{48}Ca ions at an energy of 274 MeV. Gas mixture of He and Ar was used as a transport gas. At a rate of 1.5 l/min the time of a gas transport from the target chamber to the detector (1.5 s) was measured with the use of ^{219}Rn ($\sim$ 4 s).

The results obtained were reported to the international conferences in Tobolsk (the conference dedicated to 175th anniversary of D. I. Mendeleev), Beijing (NNC2009), Messina (Nuclear Reactions on Nucleons and Nuclei) and Sochi (EXON2009).

Dynamics of Heavy-Ion Interaction, Fission of Heavy and Superheavy Nuclei

In 2009 the main attention was paid to processing the experimental data obtained in previous experiments, as well as the development of project, methods and creation of the new setup CORSAR (correlation setup for the reaction products registration) intended for the production of new neutron-rich heavy nuclei and investigation of their properties in the region of nuclei near $N = 126$ (Xe + Pb, Kr + Pb). For the registration of the reaction products, a new gas detector was developed and produced.

The analysis of the experimental data obtained in the measurements of mass and energy distributions of the fusion–fission and quasi-fission fragments in coincidence with neutrons, gamma rays and light charged particles in the reaction ^{36}S$\,+\,^{238}$U, leading to the formation of ^{274}Hs, was finished. The role of the entrance channel mass asymmetry in the fusion dynamics of superheavy nuclei was studied. The capture and quasi-elastic cross sections were measured for this reaction [5].

The experimental data obtained in the study of decay characteristics of superheavy compound nucleus with $Z = 112$, formed in the reaction ^{48}Ca$\,+\,^{238}$U at energies close to the Coulomb barrier, have been processed.

The experiment was carried out at TANDEM accelerator in LNL (Legnaro, Italy) in 2008; the mass-energy distributions of the binary channel with simultaneous measurement of the cross section of quasi-elastic scattering were obtained. In the experiment $10^4 - 10^5$ fission-like fragments were measured depending on the incident ion energy. It was shown for the first time that the quasi-fission leads to the formation of not only asymmetric fragments, but also gives contribution to the symmetric fragment mass region [5, 6].

Within the collaboration between JINR FLNR and the University of Jyväskylä, Finland, in October 2008, the experiment devoted to the investigation of the dynamics of the reaction ^{64}Ni + ^{238}U as a possible tool for the synthesis of superheavy element with $Z = 120$ was carried out. The paper dedicated to the results of this experiment was submitted to «Phys. Lett. B». The mass-energy distributions of binary reaction products obtained in the reactions ^{48}Ca + ^{238}U, ^{58}Fe + ^{244}Pu and ^{64}Ni + ^{238}U at the energies near the Coulomb barriers, as well as the capture and quasi-fission cross sections and estimation of fusion probability of superheavy compound nuclei were presented in papers [5, 6].

The main results were also presented at the international conferences in Sochi (EXON2009) and Beijing (NNC2009).

Exotic Decays

In the previous experiments, strong indications of true ternary fission with almost collinear kinematics of the products and clustering as a physical reason of the process were obtained. This decay channel was called «collinear cluster tri-partition» (CCT) due to the features revealed. The most populated CCT mode observed shows extremely high yield of more than 10^{-3} per binary fission. The existence of this mode was confirmed as a result of the analysis of mass and charge distributions, ionization losses of the reaction products and the neutron multiplicity of the fission events [7, 8].

In the experiment on studying the ^{232}Th + d (10 MeV) reaction, performed recently within the collaboration FLNR (JINR)–ATOMKI (Hungary), all decay products were detected. In order to measure fragment masses, two micro-channel plates (MCP) based timing detectors and mosaic of nine 2×2 cm Si surface-barrier detectors were used. A total of $5.5 \cdot 10^6$ fission events were analyzed and approximately 50 true ternary coincidences were found. The results agree well with corresponding spectra obtained in other relevant works.

Structure of Exotic Nuclei

The experiment on the study of the structure of the nucleus ^{6}He in the reactions of quasi-free scattering from clusters bound in ^{6}He was carried out in 2009 at the fragment-separator ACCULINNA. The secondary beam of ^{6}He with the energy $41A$ MeV bombarded the target cell filled in with helium at the pressure 2.5 atm and the temperature 11°K.

Two scattered particles were detected in the kinematical range corresponding to the process of quasi-free scattering. Two identical telescopes consisting of position-sensitive Si detectors and scintillation crystals were installed at the angles $\theta = \pm 35°$ for the detection of coincident $\alpha{-}\alpha$, $\alpha{-}t$ and $\alpha{-}p$ in a wide angular range. The third telescope intended for the detection of a charged spectator was installed at the smaller angle 15°.

These measurements were intended to clarify if the quasi-free reaction mechanism is applicable to the study of few-body correlations specific for weakly bound nuclei at the drip lines. In the previous experiment performed at a beam energy of $25A$ MeV, the dineutron and cigar-like components of the ^{6}He wave function were directly observed [9].

In the framework of the research on the structure of heavy helium target in transfer reactions, the analysis of the data obtained in the reactions ^{3}H(^{8}He, p)^{10}He and ^{3}H(^{6}He, p)^{8}He was completed. The obtained results were published in [10].

Reactions with Beams of Light Stable and Radioactive Nuclei

The scientific activity of Department No. 7 during 2009 covered development of experimental techniques as well as performance of experiments at the accelerators at FLNR and other scientific centres in France and Finland, with which the Department has a long-standing and fruitful collaboration on the basis of contracts and joint grants.

In June 2009 a test experiment with the use of a secondary ^{9}Li beam at the fragment separator COMBAS was performed. The results obtained showed that COMBAS is capable of providing separated beams of light radioactive nuclei. With a ^{9}Li ions intensity of 10^5 s^{-1}, it was possible to measure the momentum distribution of the ^{9}Li breakup fragments. The obtained result points to the possible existence of a halo in ^{9}Li. These experiments are to be continued in 2010.

At the GANIL accelerator complex, the experiments on formation cross section measurements of neutron-rich nuclei in the vicinity of ^{48}Ca were performed. 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 [11]. At the cyclotron of the University of Jyväskylä, a joint experiment was carried out with the aim to observe the ($t{-}t$)-cluster decay of highly excited states of ^{6}He. The cross section of such processes was measured. In order to compare the obtained results with other data, experiments were performed at the U20 cyclotron of the Institute of Nuclear Physics in Rez (Czech Republic) using deuterium beams with energies close to the Coulomb barrier.

The obtained data on the complete fusion of ^{6}Li ions with Pt and Bi nuclei, as well as information on the breakup channels of the loosely bound nuclei ^{6}He and ^{6}Li, followed by the sequential fusion of the produced fragments, give evidence about the enhancement of the cross sections for the transfer of clusters from these weakly bound nuclei ($2n$ in the case of ^{6}He and d in the case of ^{6}Li) [12, 13].

The obtained results were reported to the International Conference on Nuclear Spectroscopy (Cheboksary) and International Symposium on Exotic Nuclei (EXON2009) (Sochi).

Theory and Computational Physics

A generalized optical potential for elastic scattering induced by light nuclei is calculated within the Feshbach projection operator method [14]. The method proposed in earlier papers is extended here to avoid simplifying assumptions. Within the method, a structureless target nucleus interacts with a projectile treated as a system of a few bound clusters. An explicit expression for the optical potential is derived which takes into account explicitly the coupling with projectile breakup channels. Good agreement with available experimental data is obtained.

A new way was suggested to discover and examine unknown neutron-rich heavy nuclei in the «north-east» part of the nuclear map (this 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 [15]. Several tens of new nuclides can be produced, for example, in near-barrier collision of ^{136}Xe with ^{208}Pb. This finding may spur new studies at heavy-ion facilities and should have significant impact for future experiments. The experimental data on the mass distribution of fission fragments and the fusion cross sections were analyzed for the reactions $^{36}S+{}^{238}U$ and $^{30}Si+{}^{238}U$ at several incident energies [16]. Using the unified dynamical model, the incident energy dependence of the mass distribution of fission fragments was investigated. This study is the first attempt to treat such experimental data systematically.

The knowledge base on low-energy nuclear physics, «Nuclear Reactions Video», available at the Web-site http://nrv.jinr.ru/nrv, was significantly extended and improved: (i) Computer codes for calculation of the evaporation residue cross sections in fusion of heavy nuclei were written and included into the knowledge base. (ii) The digital databases on elastic scattering, fusion reactions and yields of evaporation residues have been extended by including several hundreds of experimental cross sections.

Radiation Effects and Physical Bases of Nanotechnology, Radioanalytical and Radioisotope Investigations on FLNR Accelerators

Research in the Radiation Damages in Solids and Creation of Nanostructures

It has been found that irradiation of the SiO_2 layers with Si-containing nanocrystals by high-energy ions leads to strong structural changes: vertical ordered arrays of nanocrystals along the ion tracks with the same orientation of the atomic planes are formed. This induces essential changes in optical and electrical properties of the modified nanocrystals arrays [17, 18]. Numerical methods were applied to investigate temperature effects in a nonlinear thermal spike model with regard to irradiation with high-energy ^{80}Kr and ^{209}Bi ions. The values of the coefficient of electron–phonon interaction have been estimated. The electrochemical properties of asymmetric membranes with nanopores of various length and shape were studied [19]. A procedure of producing track membranes with a special smooth surface has been developed for early cancer detection.

Production of Ultra Pure Radioisotopes

New methods of separation and concentration of radioisotopes (selective nuclear reactions, recoil, radiochemical separation) as well as new methods of separation of ^{237}U and ^{238}U with the enrichment factor of 10^5-10^6 have been developed [20]. An express method is developed to analyze U in soils (for Bulgaria and Vietnam).

Design of Accelerator Complexes

A project of a cyclotron complex for production of track membranes has been proposed [21]. The project comprises a compact accelerator DC-110 using the ECR ion source as an injector. The cyclotron complex will allow one to get intense beams of accelerated ions of Ar, Kr and Xe with an energy of 2.5 MeV/nucleon required for the industrial production of track membranes.

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