FLEROV LABORATORY OF NUCLEAR REACTIONS

In 2005, the FLNR scientific programme on heavy-ion physics included experiments on the synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes and studies of nuclear reactions, acceleration technology, heavy-ion interaction with matter, and applied research. The research is represented in three laboratory topics and one all-institute project:

- Synthesis of new nuclei and study of nuclear properties and heavy-ion reaction mechanisms (11 subtopics);
- Radiation effects, modification of materials, radioanalytical and radioisotopic investigations (5 subtopics);
- Development of the FLNR cyclotron complex for producing intense beams of ions of stable and radioactive isotopes (2 subtopics);
- Development of the U400 + U400M + MT25 accelerator complex for the production of radioactive ion beams (the DRIBs project).

Table 1

Setup at U400	Beam-time, h
DGFRS	3100
VASSILISSA	800
CORSET	800
Chemistry	450
Appl. Res.	600
U400 development	150
Total:	5900

Table 2

Setup at U400M	Beam-time, h
ACCULINNA	1850
MULTI	750
FOBOS	100
DRIBs development	200
Total:	2900

The running time of the U400 and U400M FLNR cyclotrons in 2005 was nearly 9000 h planned for that year. All this opened up possibilities for performing new experiments in the low- and medium-energy range. The beam-time distribution between the FLNR experimental setups for 2005 is shown in Tables 1 and 2.

Synthesis of New Elements

In experiments performed in 2005, production cross sections were measured and radioactive decay properties of the isotopes $^{282-285}112$, $^{286-289}114$, and $^{290-293}116$ synthesized in complete fusion reactions with ^{48}Ca projectiles were studied. The mass numbers of the isotopes were determined from excitation functions of the $3n$- and $4n$-evaporation channels of the reactions ^{238}U, ^{242}Pu, and ^{248}Cm + ^{48}Ca and $3n$–$5n$ channels of the reaction ^{244}Pu + ^{48}Ca.

From the experimental data one can conclude that the evaporation residue production cross sections in the complete fusion reactions with ^{48}Ca are determined by the survivability of nuclei and depend mostly on their fission barrier height. The expected increase in the fission barrier heights at approaching the neutron shell at $N = 184$ leads not only to a substantially higher stability of nuclei to various decay modes, but also to an increase in the evaporation residue cross section.

In 2005, further investigations with target nuclei ^{249}Cf and ^{245}Cm, producing compound nuclei with $Z = 118$ and 116 were carried out. Irradiations of the ^{249}Cf and ^{245}Cm targets by ^{48}Ca projectiles were performed in February–March and May–June 2005, respectively.

The decay properties of the isotopes $^{290,291}116$ and $^{294}118$ and dependence of their production cross sections on the compound nuclei $^{293}116$ and $^{297}118$ excitation energies were studied. In the reaction $^{249}\text{Cf}(^{48}\text{Ca}, 3n)^{294}118$, in addition to the decay chain observed in 2002, two more decays of $^{294}118$ were observed at the excitation energy $E^* = 32.1-36.6$ MeV, which is higher than that in the previous experiment.

The decay properties of descendant nuclei of the even-even nucleus $^{294}118$ ($E_\alpha = (11.65 \pm 0.06)$ MeV,

$T_\alpha = 0.89^{+1.07}_{-0.31}$ ms) agree well with those measured for the isotopes $^{290}116 \xrightarrow{\alpha} {}^{286}114 \xrightarrow{\alpha/\mathrm{SF}} {}^{282}112 \xrightarrow{\mathrm{SF}}$ previously produced in the cross bombardments $^{245}\mathrm{Cm}(^{48}\mathrm{Ca}, 3n)$, $^{242}\mathrm{Pu}(^{48}\mathrm{Ca}, 4n)$, and $^{238}\mathrm{U}(^{48}\mathrm{Ca}, 4n)$, respectively.

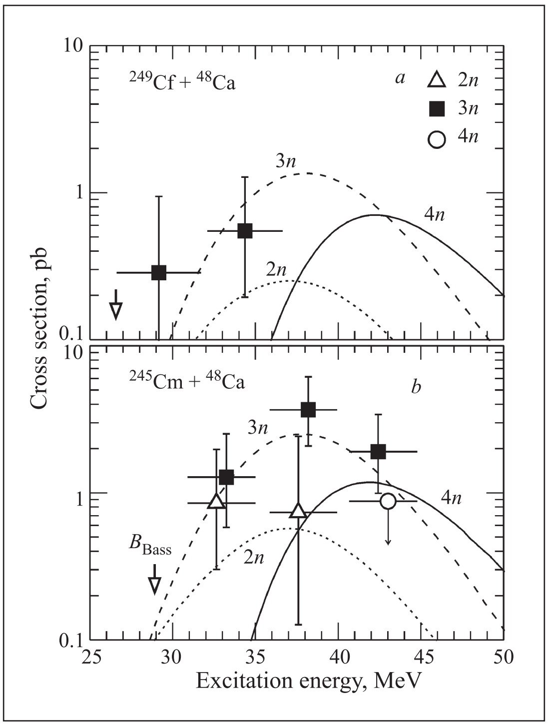

Fig. 1. Excitation functions for the $2n$-, $3n$-, and $4n$-evaporation channels from the complete-fusion reactions $^{249}\mathrm{Cf} + {}^{48}\mathrm{Ca}$ (*a*), $^{245}\mathrm{Cm} + {}^{48}\mathrm{Ca}$ (*b*). The lines show the calculation results

Presently, nine new nuclei of the isotope $^{290}116$ ($E_\alpha = (10.84 \pm 0.08)$ MeV, $T_\alpha = 7.1^{+3.3}_{-1.7}$ ms) were synthesized in the reaction $^{245}\mathrm{Cm}(^{48}\mathrm{Ca}, 3n)$, which was studied at increased excitation energies $E^* = 35.9-39.9$ and $40.7-44.8$ MeV. Furthermore, a new decay chain from the $2n$-evaporation channel of the reaction $^{245}\mathrm{Cm} + {}^{48}\mathrm{Ca}$ was observed at $E^* = 35.9-39.9$ MeV for the isotope $^{291}116$ ($E_\alpha = (10.74 \pm 0.07)$ MeV, $T_\alpha = 18^{+22}_{-6}$ ms). It consisted of six consecutive α decays of the isotopes $^{291}116$, $^{287}114$, $^{283}112$, $^{279}\mathrm{Ds}$, $^{275}\mathrm{Hs}$, and $^{271}\mathrm{Sg}$ and was terminated by the spontaneous fission of $^{267}\mathrm{Rf}$. The maximal cross sections of the xn-evaporation channels for the reaction $^{245}\mathrm{Cm}(^{48}\mathrm{Ca}, xn)^{293-x}116$ were measured to be: $\sigma_{2n} = 0.9^{+2.0}_{-0.7}$ pb, $\sigma_{3n} = 3.7^{+3.6}_{-1.8}$ pb, and $\sigma_{4n} \leqslant 1.0$ pb; for the reaction $^{249}\mathrm{Cf}(^{48}\mathrm{Ca}, 3n)^{294}118$: $\sigma_{3n} = 0.5^{+1.6}_{-0.3}$ pb. The measured cross sections for the fusion-evaporation reactions $^{245}\mathrm{Cm}$, $^{249}\mathrm{Cf} + {}^{48}\mathrm{Ca}$ leading to the isotopes of elements 116 and 118 are shown in Fig. 1, together with calculated excitation functions for the xn channels.

The decay properties of the isotopes $^{294}118$, $^{290,291}116$ and their descendant nuclei synthesized in the reactions $^{249}\mathrm{Cf}$, $^{245}\mathrm{Cm} + {}^{48}\mathrm{Ca}$ well agree with theoretical predictions calculated within the macroscopic-microscopic nuclear model, as well as using the Skyrme–Hartree–Fock–Bogoliubov and relativistic mean field methods. Reasonable agreement between experiment and theory is also seen in the case of terminal spontaneously fissioning isotopes in the decay chains of superheavy nuclei.

Chemistry of Transactinides and the Separator MASHA

In 2005, preparations were carried out for two experiments.

• ***Synthesis and Study of Chemical Properties of Elements 112 and 114.*** The rotating and stationary target assemblies for the synthesis of elements 112 and 114 in the reactions $^{238}\mathrm{U}(^{48}\mathrm{Ca}, 3-4n)$ and $^{244}\mathrm{Pu}(^{48}\mathrm{Ca}, 3-4n)$ were developed. It is expected to produce $^{288}114$ (α; 0.6 s), $^{289}114$ (α; 2.7 s), $^{284}112$ (SF; 0.1 s), $^{285}112$ (α; 34 s) and register element 112 using a cryodetector system according to its predicted high volatility (Fig. 2).

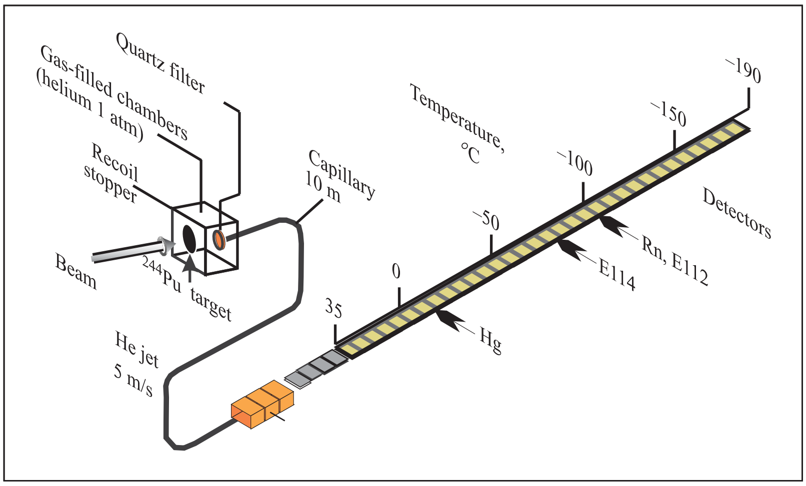

Fig. 2. Cryodetector system for the investigation of chemical properties of elements 112 and 114

A purification and drying system for inert gases — carriers of the recoil atoms was developed. It is planned to use a mixture of He (70%) and Ar (30%) with a very low water vapor content (10^{-7}%). The joint experiment with PSI (Switzerland) is scheduled for April 2006.

• ***Synthesis of Element 115.*** The results of two previous experiments (August 2003 and June 2004) designed to synthesize element-115 isotopes in the ^{243}Am + ^{48}Ca reaction gave independent evidence of the production of element 115. The decay chains consisting of five sequential α decays were terminated by spontaneous fission with a high-energy release and a lifetime of about a day. Support for the assignment of the atomic numbers of all of the nuclei in the ^{288}115 decay chain was obtained in the chemical experiment (June 2004) in which a long-lived spontaneous fission activity of ^{268}Db (15 events) was found to be chemically consistent with the fifth group of the periodic table. To confirm the mass assignment it is planned to determine the mass of these nuclei using the mass spectrometer MASHA. The initial compounds to be introduced into the MASHA ECR ion source should be volatile.

In the model experiments on the separation of the 5th group elements from the catcher of recoiling reaction products, the method of selective and quantitative separation of Nb and Ta on cation exchange resins was developed. The separation procedure is based on the difference of the strength of MF_6^- complexes. It is also possible to separate Zr and Hf complexes. That approach allows one to suggest experiments aimed at the study of chemical properties of Db and Rf.

Nuclear Fission

The experiment on the study of the fusion–fission process of element ^{294}116 in the reactions ^{48}Ca + ^{246}Cm and ^{50}Ti + ^{244}Pu was carried out in 2005 with the use of the time-of-flight spectrometer CORSET. Mass–energy distributions of the fragments and excitation functions for these reactions were obtained.

The heaviest element that can be produced with ^{48}Ca ions is the nucleus with $Z = 118$ (in the reaction at a Cf target). The production of heavier elements requires the use of projectiles with higher Z. The previous experiments with ^{48}Ca ions show that in the region of superheavy elements with $Z = 112$–116 the contribution of the QF (quasi-fission) component into the total reaction cross sections $\sigma_{\rm QF}/\sigma_{\rm cap}$ is approximately constant and exceeds 90%. It had been found that the competition between FF (fast fission) and QF strongly depends on the mass asymmetry, deformations, orientations and shell structure in the reaction entrance channel.

In the case of the «warm» fusion reactions of the ^{294}116 element formation in the interactions with ^{48}Ca and ^{50}Ti ions at energies close to the Coulomb barriers, it was observed that the shapes of the fragment mass distributions were similar and the ratio $\sigma_{\rm FF}/\sigma_{\rm cap}$ was also approximately the same for both reactions (Fig. 3).

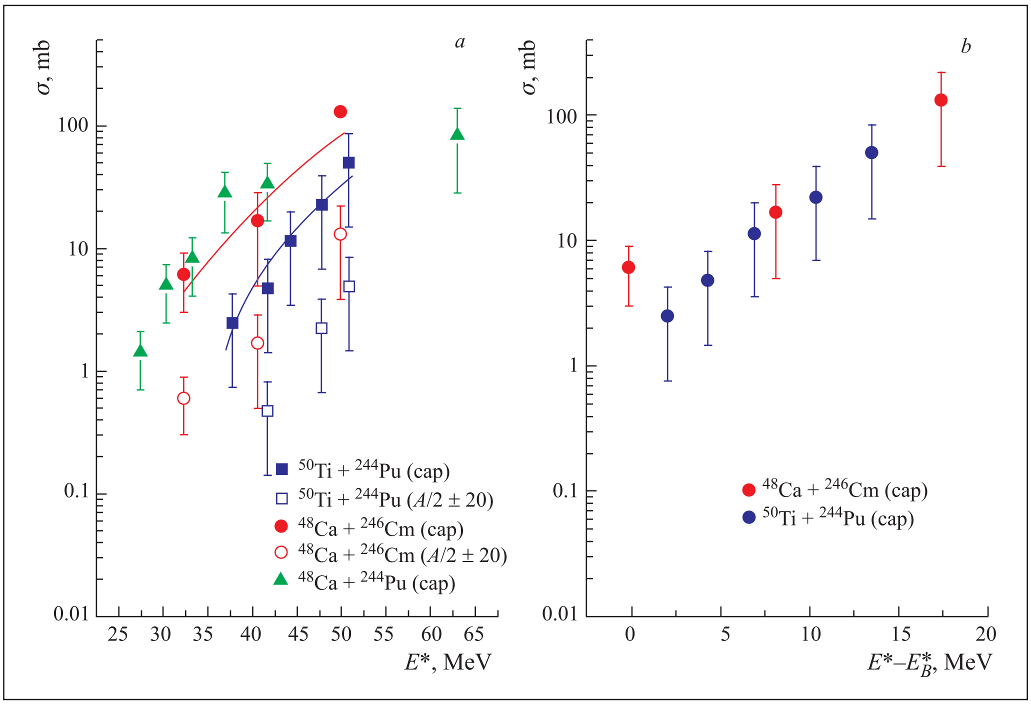

Fig. 3. The capture ($\sigma_{\rm cap}$) and fusion–fission ($\sigma_{A/2\pm20}$) cross sections as functions of the excitation energy E^* (*a*) and $\sigma_{\rm cap}$ as a function of the excitation energy above the barrier $E^*-E^*_B$ for the reactions with ^{48}Ca and ^{50}Ti ions (*b*)

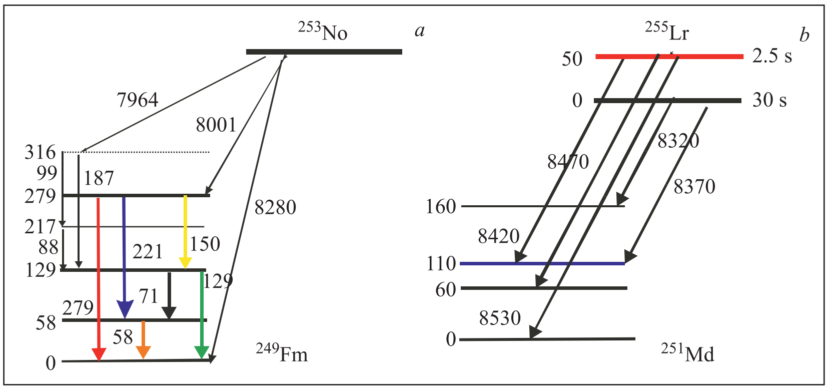

Fig. 4. Decay schemes of ^{253}No and ^{255}Lr, produced in the reactions of ^{48}Ca ions with ^{207,208}Pb and ^{209}Bi targets

Preliminary results of the experiment show that at the transition from ^{48}Ca to ^{50}Ti ions the capture cross sections $\sigma_{\rm cap}$ and hence the fusion–fission cross sections $\sigma_{\rm FF}$ decrease approximately thrice at $E^* = 45{-}50$ MeV. At the same time, the capture cross sections $\sigma_{\rm cap}$ as functions of the excitation energy above the Coulomb barrier $(E^* - E^*_B)$ are very similar in both reactions. It suggests the use of ^{50}Ti ions for the SHE synthesis. However, new high-statistics experiments are needed in order to continue the study of the fusion–fission — quasi-fission competition in these reactions.

The problems of the fission dynamics are still far from being solved. The multimodal analysis will give insight into the nature of fission modes and their competition. In this investigation, properties of the superasymmetric fission mode (at $A_F < 80$ amu) are of great interest. These data will help to clarify the prospects of producing exotic very neutron-rich double magic ^{78}Ni nuclides in the fission process.

Separator VASSILISSA

A large series of experiments using the GABRIELA (Gamma Alpha Beta Recoil Investigations with the ELectromagnetic Analyzer) setup was carried out in September–October 2005.

During the experiments, odd isotopes of ^{253,255}No and ^{255}Lr were produced with an intense 0.6-pμA ^{48}Ca beam impinging on rotating ^{207,208}Pb and ^{209}Bi targets.

In the case of the ^{253,255}No evaporation residues, gamma rays as well as conversion electrons were detected in prompt coincidence with the characteristic alpha emission of both nuclei. Spins and parities of the nuclear levels in ^{249}Fm populated by the alpha decay of ^{253}No could be firmly established for the first time. For ^{255}No, it was observed that many alpha decays were followed by delayed gamma and electron emission (Fig. 4).

The existence of an isomeric state in ^{251}Fm was reported in 1971 but was never confirmed in the literature. The half-life of the isomeric state was measured to be 26.8 μs. From the alpha delayed gamma- and beta-coincidence spectra, it was found that that isomeric level de-excited mainly by the emission of a highly converted M2 198-keV transition, which explains the observed lifetime.

An isomeric state decaying by a retarded and converted M2 transition was also observed in ^{253}No. Its lifetime was measured to be 43.5 μs.

The comparison of the experimental data with theoretical self-consistent calculations showed a systematic discrepancy in the ordering of the lowest single-particle states in the $N = 151$ isotones. The data are still being analyzed.

High-Resolution Beam-Line ACCULINNA

Performed in 2005, complete analysis of the data obtained in two series of experiments, in which the ^{5}H system was made in the $t + t$ reaction, resulted in the unambiguous discovery of resonance states inherent in this nucleus. The energy $E_{\rm res} \approx 1.8$ MeV and width $\Gamma_{\rm res} \approx 1.3$ MeV established for ^{5}H suggest that in the experiments, designed appropriately, one can find out an even lower lying and narrower ground state for ^{7}H.

If ^{7}H is found, it will be a quite unusual case exhibiting the five-body disintegration, $t + 4n$, the only decay mode allowed by the energy conservation law. Accordingly, the discovery of ^{7}H would imply not only the observation of a nuclear system peculiar of the unusually high enhancement in the neutron number, but it will also open the way to the study of the quite unusual five-body decay dynamics.

In December 2005, an experiment was carried out in which the one-proton transfer reaction ^{2}H(^{8}He,^{3}He)^{7}H was used for the population of the ground-state resonance of the sought ^{7}H. A 23-MeV/nucleon beam of ^{8}He ions, produced by the ACCULINNA separator, bombarded a cryogenic target cell filled with deuterium gas. Helium-3 nuclei moving in a forward direction were detected in coincidence with tritons emitted in the ^{7}H resonance decay (see Fig. 5). The setup geometry

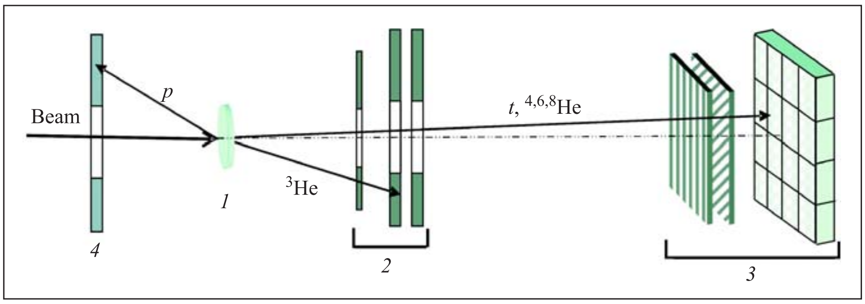

Fig. 5. Scheme of the target and detector array: *1* — deuterium target; *2* — annular detector telescope destined for ^{3}He nuclei emitted in the ^{2}H(^{8}He, ^{3}He)^{7}H reaction; *3* — detector array (a pair of Si strip detectors backed with CsI wall) for tritons and helium nuclei; *4* — annular Si strip detector for protons resulting from the ^{2}H(^{8}He, p)^{9}He reaction

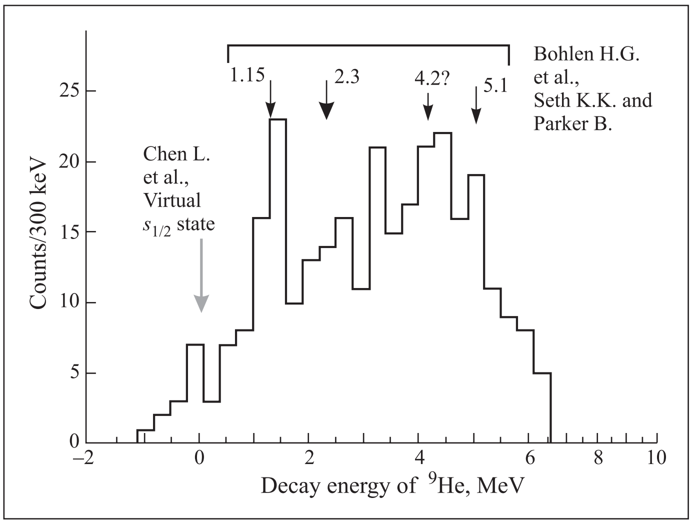

Fig. 6. Preliminary result on the missing mass spectrum obtained for ^{9}He from the data from the reaction ^{2}H(^{8}He, p)^{9}He

was optimized for the study of the ^{2}H(^{8}He,^{3}He)^{7}H reaction in a range of 4–24 degrees in the centre-of-mass system. The sensitivity limit achieved in this experiment was 5 μb/sr per one detected event associated with the formation and decay of ^{7}H. Currently, the data collected in this experiment are being analyzed.

The projectile–target combination employed in the ^{7}H experiment was a match for an experiment dedicated to another nucleus being a crucial point in the study of the lightest neutron-excess nuclei. The matter concerns ^{9}He, which could be for the first time produced in the ^{2}H(^{8}He, p)^{9}He reaction. This reaction is promising for the unambiguous assignment of quantum numbers and correct estimation of single neutron spectroscopic factors for the three narrow resonances known for ^{9}He. In the study of ^{9}He, special emphasis should be placed on the virtual state, still hypothetic, made by the ^{8}He core and a $2s$ neutron. Such intruder states are known in the ^{10}Li and ^{11}Be nuclei having one neutron in addition to the filled $p_{3/2}$ shell. The ^{2}H(^{8}He, p)^{9}He reaction employed seems to be the best one for getting transparent answer on this virtual state.

A missing mass spectrum obtained for ^{9}He from a part of the acquired statistics is presented in Fig. 6. A resolution of 500 keV obtained in the missing mass measurements is the best one so far achieved for ^{9}He. A narrow state at 1.15 MeV is well seen in the spectrum. The width of the 2.3-MeV resonance is known to be 700 keV.

Complete data obtained for the reaction ^{4}He(^{6}He, 2α)$2n$ were analyzed. These data were obtained in experiments in which a beam of 25-MeV/nucleon ^{6}He nuclei bombarded a helium gas target. The cross section measured for the $\alpha, 2\alpha$ quasi-free scattering (QFS) reaction in a range of 60–120° was analyzed in terms of a plane wave impulse approximation (PWIA) making use of a wave function available from theory evaluation made for ^{6}He on the basis of a three-body approximation.

Exotic Decay Modes. 4π Detector FOBOS

The year of 2005 was devoted to further investigations of the collinear cluster tripartition (CCT) effect, discovered earlier in the experiments at the FOBOS setup. Comparative analysis of the mass–mass distributions of the fragments originated from ^{252}Cf (SF) allowed one to confirm the earlier proposed CCT mechanism. Corresponding data were obtained in experiments performed at three different double-armed time-of-flight

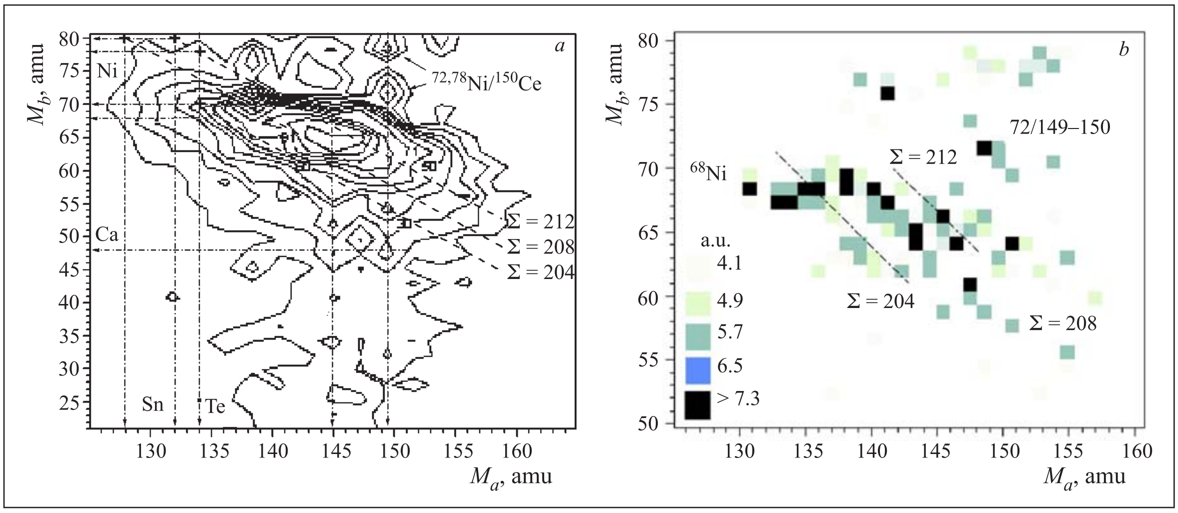

Fig. 7. *a*) 2D-contour map of the island of high yields of the CCT products of ^{252}Cf (SF). Part *b*) is the same as *a*) but passed through a second derivative filter which emphasizes two-dimensional structures

versus E (TOF-E) spectrometers installed at FLNR and JYFL (Jyväskylä, Finland). An island of high yields of the CCT products revealed is presented in Fig. 7, *a*.

Some features of this 2D domain can be emphasized by a process in which a second derivative filter is applied, and a method which is typically used in the search for peaks in gamma spectra. The tops of the peaks found in this way in certain sections of M_a = const correspond to the total masses $M_{\rm tot}$ = const with the values 204, 208 and 212 amu, respectively. Thus, the gross bump seen in Figs. 7, *a* and *b* consists mainly of the three overlapping ridges oriented along the lines $M_{\rm tot}$ = const. The ridges (marked by the dashed lines) go through crossing points corresponding to different combinations of two fragments with «magic» nucleon numbers (marked by the dash-dot arrows). These marked points can be related to the mass values with magic subsystems as follows: $204 \to {}^{70}$Ni + ^{134}Te, $208 \to {}^{80}$Ge + ^{128}Sn for $M_{\rm tot} = 212 \to {}^{80}$Ge + ^{132}Sn or ^{78}Ni + ^{134}Te, or ^{68}Ni + ^{144}Ba. The discussed ridges are also crossed by the horizontal ridge (seen via the bunching of contour lines in Fig. 7, *a*). This effect can be linked with the isotopes of ^{68,70}Ni which are also magic. On the lower part of Fig. 7, *a* one observes a bump, which is well connected with the mass of the doubly magic nuclei of $^{44-48}$Ca. Moreover, there is a strong manifestation of the formation of the deformed magic ^{150}Ce nucleus, which is seen as two peaks (all in all, 355 events) in the upper right-hand corner of Fig. 7, *a* (^{72,78}Ni/^{150}Ce). The main features of the distribution under discussion are reproduced in the data of all the three mentioned experiments.

Reactions Induced by Stable and Radioactive Ion Beams of Light Elements

First experiments with a ^{6}He beam were performed at the accelerator complex for radioactive beams DRIBs. The energy of the ^{6}He beam was (60.3 ± 0.4) MeV and the intensity $\sim 5 \cdot 10^6$ pps. ^{6}He belongs to the type of light exotic nuclei with a neutron halo — it is regarded as composed of two valence neutrons and a compact α-particle core. Such an unusual structure is expected to be manifested in interactions with other nuclei in the following:

• increase in the total reaction cross section;

• enhancement in the cross section of complete fusion reactions at subbarrier energies;

• increase in the cross section of neutron transfer reactions, etc.

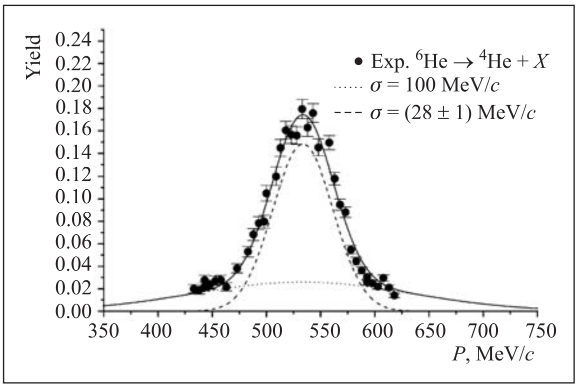

Fig. 8. Momentum distribution of ^{4}He, produced in the breakup of ^{6}He at Au

In the experiments which were performed with the magnetic spectrometer MSP144, the momentum distributions were measured for ^{4}He fragments, produced in the breakup of ^{6}He. The observed widths of the distributions ($\sigma \sim 28$ MeV/c) were relatively narrow compared with those expected for ordinary nuclei (Fig. 8). This result confirmed the existence of an extended distribution of nuclear matter due to the valence neutrons in ^{6}He (the neutron halo).

In addition, different exit channels were investigated in ^{6}He-induced reactions. The excitation functions for the formation of evaporation residues were measured in a wide energy range down to subbarrier energies. From the obtained results it follows that in the interaction of ^{6}He with Pb and Au nuclei a significant enhancement in fusion takes place at subbarrier energies (Fig. 9). This enhancement can be attributed to the peculiar structure of ^{6}He and can be explained within a model implying the sequential transfer of two neutrons to the target nucleus followed by the fusion with the residual ^{4}He core forming a compound nucleus. Also, quite high is the cross section for the transfer of one neutron from ^{6}He to the target nucleus ($\sigma \sim 1$ b). It exceeds by about two orders of magnitude the cross section for the transfer of two neutrons (Fig. 9).

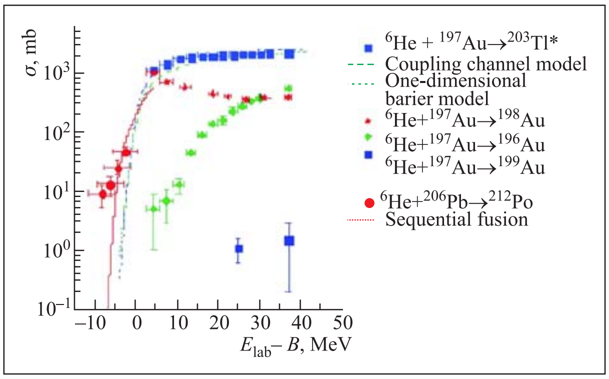

Fig. 9. Excitation functions of the complete fusion reactions and transfer reactions. The solid line is the result of calculations within the model of sequential fusion

New results on the total reaction cross section of the ^{6}He–Si interaction were obtained using the MULTI setup and compared with data for other light nuclei (^{4}He and ^{7}Li). For ^{6}He, in an energy range of $5-50$ MeV/A, a larger cross section was obtained as compared with that for ^{4}He and ^{7}Li. Note that at ~ 15 MeV/A a maximum was observed in the excitation function of ^{6}He with $\sigma_R \sim 1.8$ b. All the data discussed above are the evidence of the manifestation of the peculiar properties of the halo nucleus ^{6}He in the interaction at energies close to the Coulomb barrier.

The data were obtained with the use of the magnetic spectrometer MSP144 characterized by a high momentum resolution and large solid angle. In addition, a wide-aperture multiwire proportional counter, designed jointly with the Yerevan Physics Institute, was used for the identification and registration of the reaction products with high position resolution and counting rate (up to 10^6 pps).

The investigation of the yields of neutron-rich nuclei in the mass region of fission fragments was continued in accordance with the second stage of the DRIBs project. Delayed two-neutron emission and fission fragments from the photofission of ^{238}U, produced at the MT25 microtron of FLNR, were also studied. The ratio of two-neutron to one-neutron emission was estimated to be about $4.2 \cdot 10^{-4}$.

Theoretical and Computational Physics

A new approach was proposed for the unified description of strongly coupled deep inelastic scattering, fusion, fission and quasi-fission processes in heavy-ion collisions. The standard degrees of freedom of the nuclear system — unified driving potential and a unified set of dynamic equations of motion — are used in this approach. This makes it possible to perform a full (continuous) time analysis of the evolution of heavy nuclear systems, starting from the approaching stage, moving up to the formation of the compound nucleus and eventually emerging into two final fission fragments. The calculated mass, charge, energy and angular distributions of the reaction products agree well with the corresponding experimental data. It offers hope of obtaining rather accurate predictions for the probabilities of superheavy element formation in near-barrier fusion reactions.

Low-energy collisions of very heavy nuclei ($^{238}\mathrm{U} + {}^{238}\mathrm{U}$, $^{232}\mathrm{Th} + {}^{250}\mathrm{Cf}$ and $^{238}\mathrm{U} + {}^{248}\mathrm{Cm}$) were theoretically studied within the realistic dynamical model based on multidimensional Langevin equations. Large charge and mass transfer was found due to the «inverse quasi-fission» process leading to formation of survived superheavy long-lived neutron-rich nuclei. In many events the lifetime of the composite system consisting of two touching nuclei turns out to be rather long, sufficient for spontaneous positron formation from a superstrong electric field — a fundamental QED process.

The process of «sequential fusion» of heavy nuclei at near-barrier energies, in which the intermediate transfer and collectivization of valence neutrons play a significant role, was analyzed for the first time by numerical solution of a three-body and three-dimensional time-dependent Schrödinger equation. Neutron collectivization (spreading of the neutron wave function over the volumes of two colliding nuclei) starts just before approaching the Coulomb barrier and affects the fusion probability. The intermediate neutron motion and its influence on the near-barrier fusion of heavy nuclei were analyzed in detail, and several new experiments on the study of the mechanisms of subbarrier fusion reactions of weekly bound nuclei were proposed.

A new extended two-centre shell model was developed for the calculation of multidimensional adiabatic potential energy surface of a strongly deformed heavy nuclear system including the configuration of two touching nuclei. This model properly describes the fusion barriers of heavy ions and gives correct values of the ground-state masses of two separated nuclei. A difference between the potential energy in the entrance (fusion) channel and that in the exit (fission and quasi-fission) channel was taken into account.

The Web version of 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. Several new computational codes on low-energy nuclear dynamics were included into the knowledge base. They are all provided with animated visual graphic interfaces for input of initial data and treatment of obtained results. The digital databases on fusion and yield of evaporation residues were filled with several hundreds of experimental cross sections. All the resources of the knowledge base are available on-line via the standard Web browsers using CGI technology and Java applets.

Interaction of Accelerated Heavy Ions with Polymers

New methods of producing track membranes with profiled pore channels ensuring high selectivity and efficiency of filtering dispersible species of various natures were developed (Fig. 10).

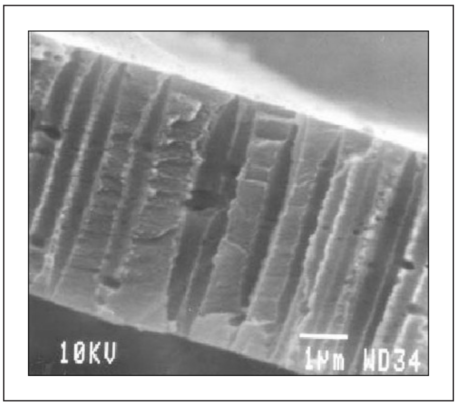

Fig. 10. Cross section of a PET-membrane with pores tapered towards both ends

A feasibility of producing thick «blotting» membranes and membranes of the «wells with porous bottom» type was investigated. The membranes of this structure are promising as permeable substrates for the immobilization of cells and the study of cellular activity.

Research and development of thermosensitive membranes was undertaken. Response of membranes to a change in temperature and their electrosurface properties were investigated. It allows the creation of «intelligent» membranes with controlled properties.

Interaction of Accelerated Heavy Ions with Metals and Monocrystals

A change in the properties of crystalline silicon was investigated in the process of implantation of B, P, Ga, In and Bi ions with energies from 100 to 300 keV. At a fluence in a range of $10^{13}-10^{14}$ ions/cm^2, an increase in the diffusion coefficients of dopants was detected. These results can be applied to the development of new technologies for semiconductor industry.

The sputtering of metals and alloys, exposed to heavy ions with high specific energy losses, was investigated. Using the SEM method the sputtering yields were estimated: for Ni $\sim$ 500 atoms/ion, for chromium-nickel steel $\sim$ 100 atoms/ion, for W $\sim$ 1260 atoms/ion.

The surface structure of stainless steel, Al_2O_3, silicon monocrystals, and pyrolytic graphite after the irradiation with the ^{86}Kr (245, 305, 440 and 750 MeV), ^{136}Xe (605 MeV) and ^{209}Bi (705 MeV) ion was studied using the scanning tunnel microscopy (STM) and atomic force microscopy (AFM) (Fig. 11).

The results are important for selecting the materials for the first wall of thermonuclear reactors and for understanding the physics of interaction between high-energy ions and condensed matter.

The microstructure of spinel $MgAl_2O_4$ irradiated with Kr, I and Xe ions with energies from 70 to 600 MeV was studied. For the first time it was shown that when selecting candidate materials — inert matrix fuel hosts in fission reactors, it is necessary to take into account high-density ionization effects.

With the help of transmission electron microscopy (TEM), the ordering of helium pores in ion-irradiated amorphous silicon was observed. The creation of tracks

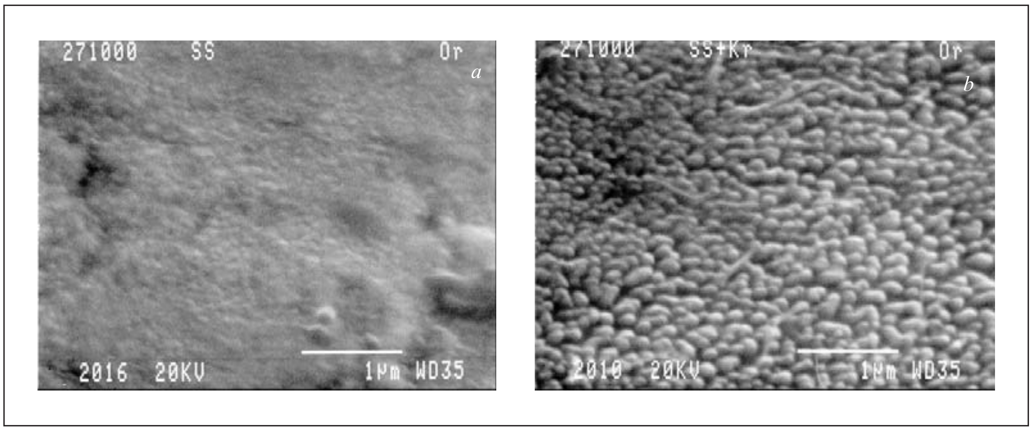

Fig. 11. The stainless steel surface structure — initial (*a*) and after irradiation (*b*) with 245-MeV ^{86}Kr ions up to the fluence $2.6 \cdot 10^{15}$ ions/cm^2

in silicon by means of successive irradiation with the 17-keV He and 210-MeV Kr ions was detected. The obtained results are important for understanding the mechanisms of defect formation in semiconducting materials.

Research was made on the applicability of the «ion transmission technique» method in the TM structure investigation. The optical properties of thick (60–100 μm) porous systems produced by the method of ion tracks were studied. New approaches to the creation of metal nanometric wires and submicrometric pipes of strictly specified sizes were proposed. It allows the creation of objects with nanostructures and their use in microengineering technology, microelectronics, optoelectronics, etc.

Production of Ultra-Pure Radioisotopes

Methods of producing the radioisotopes ^{99m}Tc(^{99}Mo) and ^{225}Ac at the MT25 microtron employing the (γ, n) reaction were developed. A radiochemical extraction method of ^{149}Tb produced in the reactions ^{142}Nd(^{12}C, xn)^{149}Dy 4.1 min $\rightarrow$ ^{149}Tb ($x = 5{-}7$) was developed.

Physics and Heavy-Ion Accelerator Techniques

Presently, at the Flerov Laboratory of Nuclear Reactions there are four heavy-ion cyclotrons: U400, U400M, U200 and DC40, which opened strong possibilities in basic and applied research. The total operating time of the cyclotrons is about 9000 h/y.

Stage I of the DRIBs (Dubna Radioactive Ion Beams) project based on the ISOL scheme was realized at the Laboratory. It allows increasing the intensity of ^{6}He and ^{8}He beams up to 10^{10} pps and 10^8 pps, respectively.

In 2005, the modernization of the DC40 cyclotron was performed. The aim of modernization is the acceleration of an intense Kr beam with an energy of about 1.2 MeV/nucleon which will be used for the irradiation of various polymer materials.