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M. G. Itkis

FLEROV LABORATORY OF NUCLEAR REACTIONS

RESEARCH ACTIVITIES IN 2005

Report to the 99th Session
of the JINR Scientific Council
January 19–20, 2006

Dubna 2005

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In 2005, the FLNR scientific program on heavy ion physics included various fields of research such as 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 3 laboratory topics and 1 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).

The U400 and U400M FLNR cyclotrons running time in 2005 was close to 9000 hours foreseen for this year. All this opened wide possibilities for performing new experiments in the low and medium energy range. Beam-time distribution among experimental set-ups in FLNR during 2005 is shown in the tables:

Set-Up on U400	Beam-time
DGFRS	3000
VASSILISSA	800
CORSET	700
Chemistry	300
Appl. Res.	550
U400 development	150
Total:	5500

Set-Up on U400M	Beam-time
ACCULINNA	2150
MULTI	850
FOBOS	100
DRIBs development	400
Total:	3500

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 produced isotopes were determined from excitation functions of the 3*n*- and 4*n*-evaporation channels of the reactions ^{238}U, ^{242}Pu, and $^{248}Cm+^{48}Ca$ and 3*n*-5*n* 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 of fission barrier heights on approaching the neutron shell at N=184 leads not only to substantially higher stability of nuclei to various decay modes, but also to an increase in the evaporation residue cross section.

In this year further investigations with target nuclei ^{249}Cf and ^{245}Cm, producing compound nuclei with Z=118 and 116 were developed. 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, ^{294}118 and the dependence of their production cross sections on the excitation energies of the compound nuclei ^{293}116 and ^{297}118 were studied. In the reaction ^{249}Cf(^{48}Ca,3n)^{294}118, in addition to the decay chain observed in 2002, two more decays of ^{294}118 were produced at a higher excitation energy E^*=32.1-36.6 MeV than in the previous experiment.

The decay properties of descendant nuclei of the even-even nucleus ^{294}118 (E_α=11.65±0.06 MeV, $T_\alpha=0.89^{+1.07}_{-0.31}$ ms) agree well with those measured for the isotopes $^{290}116 \xrightarrow{\alpha}$ $^{286}114 \xrightarrow{\alpha/SF}$ $^{282}112 \xrightarrow{SF}$ previously produced in the cross bombardments ^{245}Cm(^{48}Ca,3n), ^{242}Pu(^{48}Ca,4n), and ^{238}U(^{48}Ca,4n), respectively.

In the present work nine new nuclei of the isotope ^{290}116 (E_α=10.84±0.08 MeV, $T_\alpha=7.1^{+3.3}_{-1.7}$ ms) were synthesized in the reaction ^{245}Cm(^{48}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}Cm+^{48}Ca was observed at E^*=35.9-39.9 MeV with the isotope ^{291}116 (E_α=10.74±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}Ds, ^{275}Hs, and ^{271}Sg and was terminated by the spontaneous fission of ^{267}Rf. The maximum cross section of the xn-evaporation channels for the reaction ^{245}Cm(^{48}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 $\sigma_{4n}\leq 1.0$ pb;. for the reaction ^{249}Cf(^{48}Ca,3n)^{294}118: $\sigma_{3n}=0.5^{+1.6}_{-0.3}$ pb. The measured cross sections for the fusion-evaporation reactions ^{245}Cm, ^{249}Cf+^{48}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}Cf, ^{245}Cm+^{48}Ca well agree with theoretical predictions calculated in the macroscopic-microscopic nuclear model, as well as in the Skyrme-Hartree-Fock-Bogoliubov and the relativistic mean field methods. Reasonable agreement between experiment and theory can be seen also for terminal spontaneously fissioning isotopes in the decay chains of superheavy nuclei.

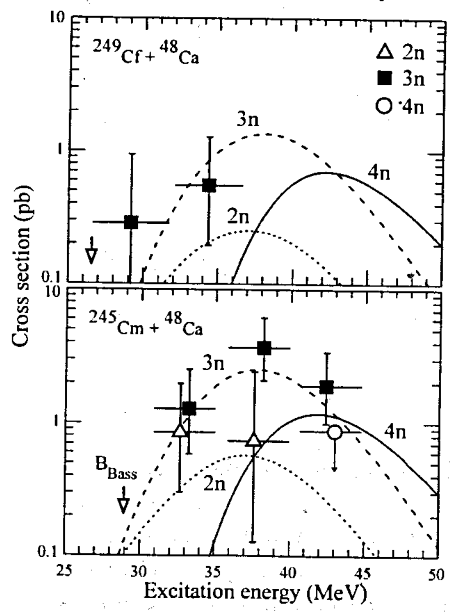

Fig. 1. Excitation functions for the 2n, 3n, and 4n evaporation channels from the complete-fusion reactions ^{249}Cf, ^{245}Cm +^{48}Ca. Lines show the results of calculations.

Chemistry of transactinides and the separator MASHA

During the year 2005extensive preparation to two experiments was carried out.

1. 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 ^{244}Pu(^{48}Ca, 3-4n) and ^{238}U(^{48}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 cryodetector system according to its predicted high volatility (Fig. 2). The purification and drying system for inert gases – carriers of the recoil atoms is developed. It is planned to use mixture of 70% He and 30% Ar with very low water vapor content (10^{-7}%). The joint experiment with PSI (Switzerland) is scheduled for April 2006.

2. 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 about the production of element 115. The decay chains consisting of five consecutive α-decays were terminated by a 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 so called chemical experiment (June 2004) in which a long-lived spontaneous fission activity, ^{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 that nuclei using the mass spectrometer MASHA. The initial compounds for introduction into the MASHA ECR ion source should be volatile.

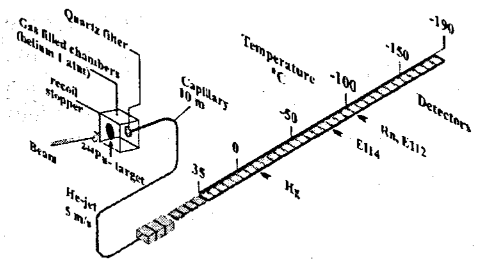

Fig. 2. Cryodetector system for the investigation of chemical properties of elements 112 and 114.

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

Nuclear fission

The experiment on the study of the fusion-fission process of the 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. The mass-energy distributions of the fragments and the excitation functions for these reactions were obtained.

The previous experiments with ^{48}Ca-ions showed that in region of superheavy elements with Z=112-116 the contribution of the QF component into the total reaction cross-sections σ_{QF}/σ_{cap} is approximately constant and makes up more than 90%. On the other hand, the heaviest element, which can be produced with ^{48}Ca-ions, is the nucleus with Z=118 (in the reaction on Cf-target). The problem of production of heavier elements requires using the projectiles with higher Z. It was found before that the competition between FF and QF strongly depends on the mass

asymmetry, deformations, orientations and shell structure in the reaction entrance channel.

Thus the spherical neutron magic nucleus ^{50}Ti (N=28) seems the promising candidate to be projectile in the reactions of synthesis of superheavies.

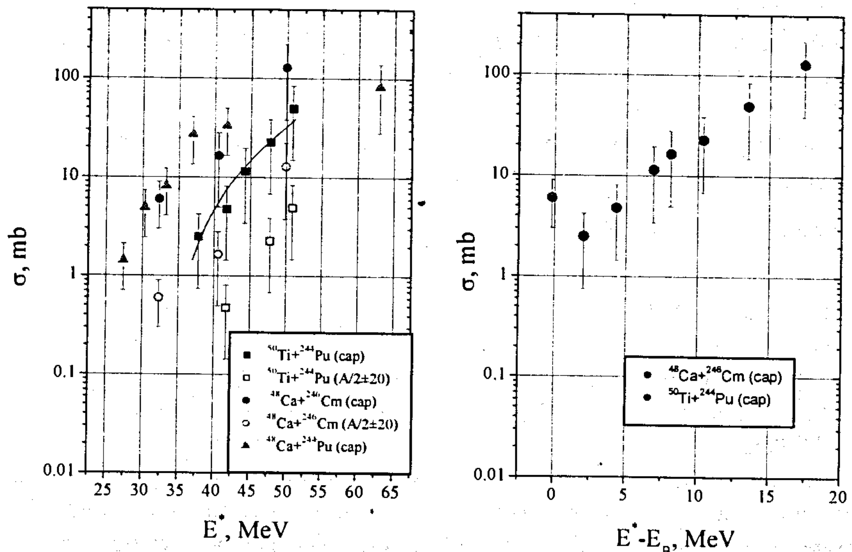

Fig. 3. The capture (σ_{cap}) and fusion-fission ($\sigma_{A/2\pm20}$) cross sections as functions of excitation energy E*(left-hand side) and excitation above the barrier E*-E*$_B$ (right hand side) for the reactions with ^{48}Ca and ^{50}Ti-ions.

For the "warm" fusion reactions of the $^{294}116$ element formation in the reactions with ^{48}Ca- and ^{50}Ti-ions at the energies close the Coulomb barriers it was observed that the shapes of the fragment mass distributions are very resembling and the ratio σ_{FF}/σ_{cap} is approximately the same for both reactions (Fig. 3).

The preliminary results of the experiment show that at the transition from ^{48}Ca to ^{50}Ti-ions the capture cross sections σ_{cap}, and hence the fusion-fission cross sections σ_{FF} decrease ≈ 3 times at the E*=45-50 MeV. At the same time, the capture cross-sections σ_{cap} as functions of excitation energy above the Coulomb barrier (E^*-E^*_B) are very similar for both reactions. That offers the challenge to use the ^{50}Ti-ions for SHE synthesis. However for further more detail study of the fusion-fission – quasi-fission competition in these reactions new high statistics experiments are required.

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

Dynamics of large scale collective motion is determined by interplay between global liquid drop properties and nuclear shell effects giving specific charge, mass and kinetic energy distributions of fission fragments.

The investigation of light-particles-induced fission of heavy nuclei at intermediate energy is connected to large extent with the problem of understanding the fission process with increasing excitation energy of the compound nucleus.

Separator VASSILISSA

The campaign using the GABRIELA (Gamma Alpha Beta Recoil Investigations with the ELectromagnetic Analyser) set-up was carried out in September/October 2005.

During the campaign, the 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 are followed by delayed gamma and electron emission (Fig. 4).

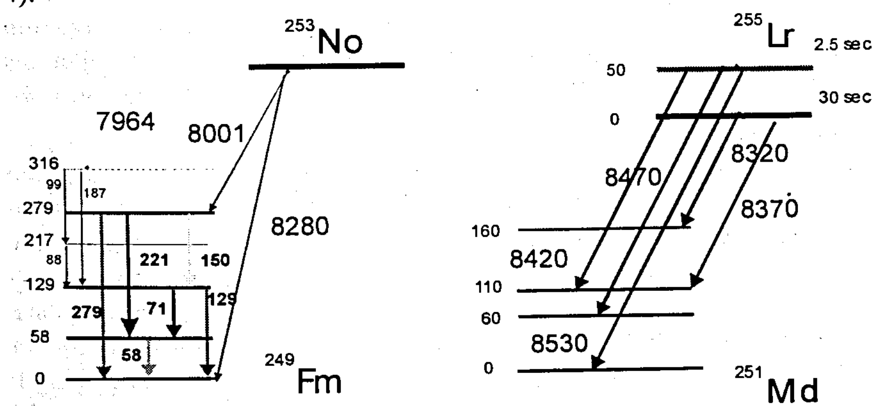

Fig. 4. Example of the decay schemes of ^{253}No and ^{255}L, produced in reactions of ^{48}Ca beam with $^{207,208}Pb$ and ^{209}Bi targets.

The existence of an isomeric state in ^{251}Fm had been reported in 1971 but 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 delayed beta-coincidence spectra, it was found that this isomeric level de-excites mainly by the emission of a highly converted M2 198 keV transition, which explains the observed lifetime.

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

Comparison with theoretical self-consistent calculations has shown a systematic discrepancy in the ordering of the lowest single particle states in N=151 isotones. The data are still being analysed.

For the year 2006 it is planned to continue the experiments on the study of decay properties of transfermium nuclei near the region of the deformed neutron shells using reactions of ^{22}Ne with $^{242,244}Pu$, and the recoil separator VASSILISSA with the new detector system.

Fragment-separator COMBAS

In 2005 year the in-flight separator COMBAS was reconstructed and retuned in the spectrometric regime to study the cluster break-up of ^{11}B. The multi-detector system from 32-strip Si- and CsI(Tl)/PD- detectors was commissioned and installed in the COMBAS intermediate focal plane (dispersive focus) to register the coincidences of ^{11}B break-up products. The multi-channel electronic system and the appropriate data acquisition system has been designed and built to satisfy the demand of multi-particle spectroscopy measurements. Using the Quantum Molecular Dynamics (QMD) model (CHIMERA code), the simulations of velocity, isotopic and element distributions of fragmentation products in the reactions ^{18}O (35 A·MeV) + ^{9}Be (^{181}Ta) has been implemented and compared with experimental data.

High-resolution beam-line ACCULINNA

Complete analysis accomplished in 2005 for the data obtained in two series of experiments, were the ^{5}H system was made in the t+t reaction, has resulted in a definitive ascertainment of resonance states inherent to this nucleus. The energy, $E_{res} \approx 1.8$ MeV, and width, $\Gamma_{res} \approx 1.3$ MeV established for ^{5}H suggest that in experiments, designed appropriately, one could 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 ^7H would imply not only the observation of a nuclear system peculiar for the unusually high enhancement in the neutron number, but it will open the way to the study of the quite unusual five-body decay dynamics.

In December 2005 an experiment was completed where the one-proton transfer reaction $^2H(^8He,^3He)^7H$ was used to populate the ground state resonance of ^7H under search. A 23 MeV/nucleon beam of ^8He ions, obtained from the ACCULINNA separator, bombarded a cryogenic target cell filled with deuterium gas. Helium-3 nuclei moving in forward direction were detected in coincidence with tritons emitted in the ^7H resonance decay (see Fig. 5). The set-up geometry was optimized for the study of the $^2H(^8He,^3He)^7H$ reaction in a range of 4 – 24 degrees in the centre-of-mass system. Sensitivity limit achieved in this experiment makes 5 µb/sr per one detected event associated with the formation and decay of ^7H. Currently, the analysis of the data collected in this experiment is being carried out.

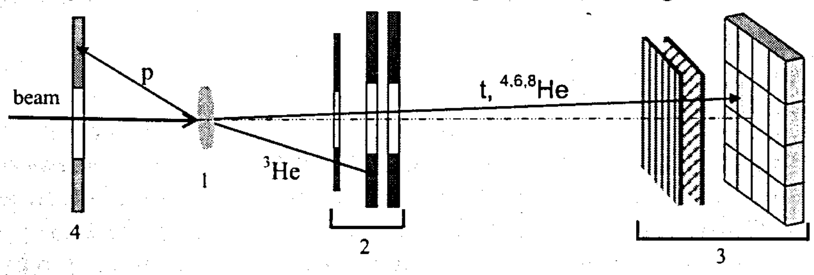

Fig. 5. Schematic diagram showing the assembly of the target and detector array. 1 – deuterium target; 2 – annular detector telescope destined for ^3He nuclei emitted in the $^2H(^8He,^3He)^7H$ reaction; 3 – detector array (a pair of Si strip detectors backed with CsI wall) for tritons and helium nuclei; 4 – annular Si strip detector for protons resulting from the $^2H(^8He,p)^9He$ reaction.

The projectile – target combination employed in the ^7H 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 ^9He which could be for the first time produced in the $^2H(^8He,p)^9He$ reaction. The d,p reaction is known as a tool which has been used extensively for getting reliable spectroscopic data for many nuclei. In the case of ^9He, 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 this nucleus. In the study of ^9He special emphasis should be laid on the still hypothetic virtual state made by the ^8He 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 p3/2

shell. The $^2H(^8He,p)^9He$ reaction employed in the present study seems to be the best one for getting transparent answer about this virtual state.

A missing mass spectrum obtained for ^9He from a part of the acquired statistics is presented in Fig. 6. The result is preliminary, as the data analysis is in a very initial state at present. Resolution of 500 keV obtained in the missing mass measurements is the best one so far achieved for ^9He. A narrow state known to be at 1.15 MeV, is well seen in the spectrum. The width of the 2.3 MeV resonance is known to be 700 keV.

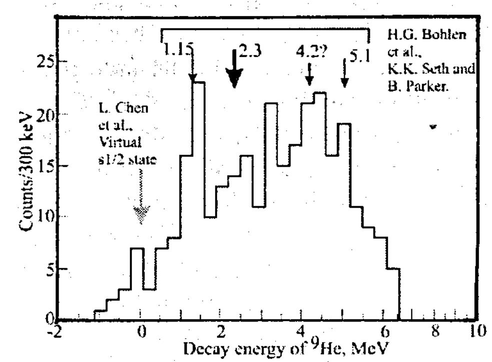

Fig. 6. Preliminary result on the missing mass spectrum obtained for ^9He from the data for the reaction $^2H(^8He,p)^9He$.

Complete data obtained for the reaction $^4He(^6He,2\alpha)2n$ were analyzed. These data were obtained in experiments where a beam of 25 MeV/nucleon ^6He nuclei bombarded a helium gas target. Cross section measured for the α,2α 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 ^6He on the basis of a three-body approximation.

Exotic decay modes. 4-π detector FOBOS

This year 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 to confirm the proposed earlier CCT mechanism. Corresponding data were obtained in experiments performed at three different double armed time-of-flight versus E (TOF-E) spectrometers installed in FLNR and in JYFL (Jyväskylä, Finland). An island of high yields of the CCT products revealed is presented in fig. 7a.

Some features of this 2D domain can be emphasized by a process, where 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 by this way in certain sections of Ma=const correspond to the total masses

Mtotal=const with the values of 204, 208 and 212 amu, respectively. Thus, the gross bump seen in figs. 7a, consists mainly of the three overlapping ridges oriented along the lines M_{total}=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 → ^{70}Ni + ^{134}Te, 208 → ^{80}Ge + ^{128}Sn for M_{total}=212 → ^{80}Ge + ^{132}Sn or ^{78}Ni + ^{134}Te, or ^{68}Ni + ^{144}Ba. The ridges discussed are crossed as well by the horizontal ridge (seen via bunching of contour lines in fig.7a), this effect can be linked with the isotopes of ^{68,70}Ni which are also magic. Inspecting the lower part of fig.7a, we observe a bump, which is well bounded by the mass of the double magic nuclei of $^{44-48}$Ca. Further 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 corner of fig. 7a (^{72,78}Ni/ ^{150}Ce). The main features of the distribution under discussion are reproduced in the data of all three experiments mentioned.

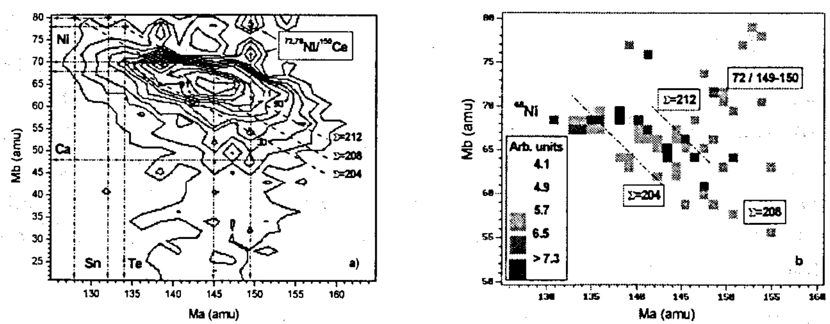

Fig.7. A 2D-contour map of the island of high yields of the CCT products of ^{252}Cf (sf) (a). Part b) is the same as a) but passed through a second derivative filter which emphasizes the two-dimensional structures.

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 ~5·10^{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 of the total reaction cross section; - enhancement of the cross section of complete fusion reactions at sub-barrier energies; - increase in the cross section of neutron transfer reactions, etc.

In the experiments, which were performed with the magnetic spectrometer MSP-144, the momentum distributions were measured for ^{4}He-fragments, produced in the breakup of ^{6}He. The observed widths of the distributions (σ ~ 28 MeV/c) were relatively narrow compared to 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 sub-barrier energies. From the obtained results it follows that in the interaction of ^{6}He with Pb- and Au-nuclei a significant enhancement of fusion takes place at sub-barrier 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 (σ ~ 1 b). It exceeds by about two orders of magnitude the cross section for the transfer of two neutrons (Fig. 9).

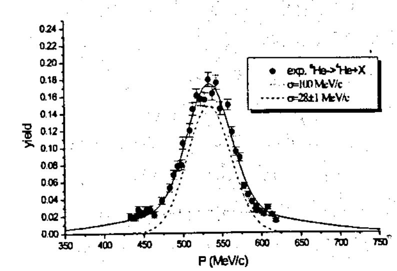

Fig. 8. Momentum distribution of ^{4}He, produced in the breakup of ^{6}He on Au.

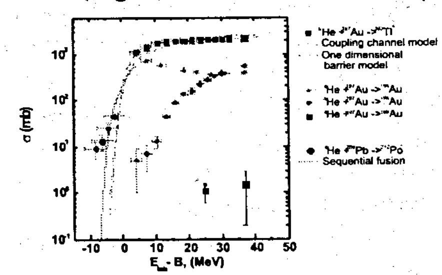

Fig. 9. Excitation functions of the complete fusion reactions and of the transfer reactions. The full line is the result of calculations within the model of sequential fusion.

New results on the total reaction cross section of ^{6}He interacting with Si were obtained using the MULTI setup and compared with data with other light nuclei (^{4}He and ^{7}LI). For ^{6}He in the energy range 5÷50 MeV/A a larger cross section is obtained compared to that of ^{4}He and ^{7}Li. It should be noted that at about 15 MeV/A a maximum is observed in the excitation function of ^{6}He with $\sigma_R \sim 1.8$ b. All the above mentioned data are evidence of the manifestation of peculiar properties of the halo nucleus ^{6}He when interacting at energies close to the Coulomb barrier.

The data were obtained with the use of the magnetic spectrometer MSP-144 characterized by high momentum resolution and a large solid angle. In addition a wide-aperture multi-wire proportional counter, designed jointly with the Yerevan Physics Institute, was used to identify and register reaction products with high position resolution and high 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 connection with the second stage of the DRIBs project. Delayed two-neutron emission and fission fragments from the photofission of ^{238}U, produced at the MT-25 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 is proposed for the unified description of strongly coupled deep inelastic scattering, fusion, fission and quasi-fission processes in heavy-ion collisions. The standard (most important) 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 gives us hope to obtain rather accurate predictions for the probabilities of superheavy element formation in near-barrier fusion reactions.

Low energy collisions of very heavy nuclei (^{238}U+^{238}U, ^{232}Th+^{250}Cf and ^{238}U+^{248}Cm) have been theoretically studied within the realistic dynamical model based on multi-dimensional 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 lifetime of the composite system consisting of two touching nuclei turns out to be rather long; sufficient for spontaneous positron formation from super-strong 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, has been analyzed for the first time by numerical solution of 3-body and 3-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 have been analyzed in details and several new experiments on study the mechanisms of sub-barrier fusion reactions of weekly bound nuclei have been proposed.

A new extended two-center shell model has been developed for a calculation of multi-dimensional adiabatic potential energy surface of 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. Difference of the potential energy in the entrance (fusion) and exit (fission and quasi-fission) channels are taken into account.

Contribution of the break-up channel into the optical model potential describing elastic scattering of weakly bound nuclei has been calculated within a semi-microscopical model. The case of ^{6}He has been studied in detail and importance of its internal structure was found. Two and three-body models of the ^{6}He ground state and continuum are considered and compared, namely, alpha-particle+di-neutron and alpha-particle+n+n .

Web-version of the knowledge base on low energy nuclear physics "Nuclear Reactions Video", allocated at the Web-site http://nrv.jinr.ru/nrv, has been significantly extended and improved. Several new computational codes on low-energy nuclear dynamics have been included into the knowledge base. All they are 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 have been filled with several hundreds 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.

Applied research

Interaction of accelerated heavy ions with polymers

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

The 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 immobilization of cells and the study of cellular activity.

Research and development of thermo-sensitive membranes was undertaken. Response of membranes to a change in temperature and their electro-surface properties were investigated. It allows creation of “intelligent” membranes with controlled properties.

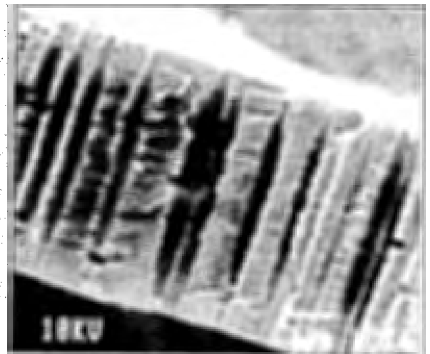

Fig. 10. Cross section of a PET membrane with pores tapered towards both ends.

The influence of plasma processing on the properties of track membranes was studied. Research was made on the applicability of the «ion transmission technique» method in the TM structure investigation. The optical properties of thick (60-100 microns) 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 creation of objects with nanostructures and using them in microengineering technology, microelectronics, optoelectronics etc.

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 the range of 10^{13} - 10^{14} ion/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 - ~ 500 atoms /ion, for chromium-nickel steel – ~ 100 atoms /ion, for W - ~ 1260 atoms /ion. The surface

structure of Al_2O_3 and silicon monocrystals, and pyrolytic graphite after the irradiation with the ^{86}Kr (305 MeV, 440 MeV 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.

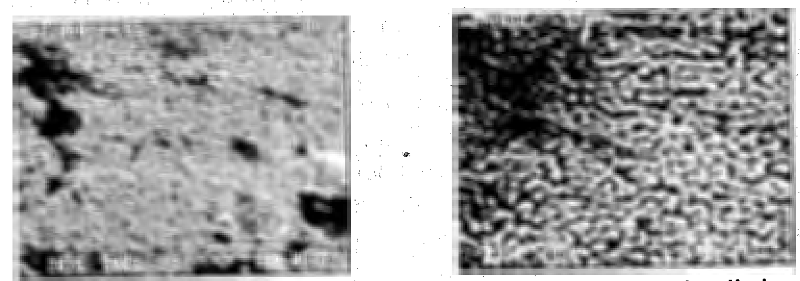

Fig.11. The stainless steel surface structure in initial (a) and after irradiation (b) with 245 MeV ^{86}Kr ions up to the fluence $F{\cdot}t = 2.6{\cdot}10^{15}$ ion/cm^2.

Research on the microstructure of spinel $MgAl_2O_4$ irradiated with Kr, I and Xe ions with energies from 70 to 600 MeV was made. For the first time it was shown that when selecting the 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. Creation of tracks in silicon by means of successive irradiation with the 17 keV He and 210 MeV Kr ions was detected. As a result of the post-irradiation annealing at 500-1000 C, re-crystallization of the amorphous Si layer created by irradiation with the 17 keV He ions was studied. The obtained results are important for understanding the mechanisms of defect formation in semi-conducting materials.

Ultra-pure radioisotopes and radioanalytical research

Methods of production of radioisotopes ^{99m}Tc(^{99}Mo), ^{225}Ac employing the (γ,n) reaction at the microtron MT25 were developed. The radiochemical extraction method of ^{149}Tb produced in 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 Flerov Laboratory of Nuclear Reactions has four heavy ion cyclotrons - U-400, U-400M, U-200, DC-40, which opened wide possibilities for basic and applied researches. Total operating time of cyclotrons is about 10000 hours/year.

The intensive beams of ^{48}Ca ions on the cyclotron U-400 have provided performance of the program on synthesis of a number of new isotopes of superheavy elements. The tritium beam with the energy of 19 MeV/n and intensity of 10^9 pps was accelerated on the cyclotrons U-400. The beams of ^6He (28 MeV/n) and ^8He (25 MeV/n with intensity $3 \cdot 10^5$ pps and $3 \cdot 10^4$ pps respectively were received in flight method using a thin Beryllium production target in the separation channel.

The realization of the I stage of the project DRIBs (Dubna Radioactive Ion Beams) based on ISOL scheme is completed at the Laboratory. It allows increasing the intensity of the ^6He and ^8He beams up to 10^{10} pps and 10^8 pps.

Last year the modernization of DC-40 cyclotron was carried out. The task of modernization is acceleration of the intensive beam of Kr with energy about 1.2 MeV/n that will be used for irradiation of various polymer materials.

Modernization of the U400 cyclotron

The modernization of the U400 has been suggested to improve the cyclotron parameters.

The aims of the modernization are:

decreasing the magnetic field level at the cyclotron center from the region of 1.93÷2.1 T to 0.8÷1.8 T, that allows us to decrease the electrical power of the U400R main coil power supply in four times.

providing the smooth ion energy variation by factor 5 for every mass to charge ratio A/Z at accuracy of $\Delta E/E=5 \cdot 10^{-3}$;

increasing the intensity of accelerated ions of rare stable isotopes at factor 3.

The planned modernization of the U400 axial injection includes sharp shortening of the injection canal horizontal part. As the result, the distance from the ECR to the AM90- bending magnet became equal to 730 mm. The changes allow to increase the $^{48}Ca^{+18}$ ion intensity at the U400 output from 0.9 to 1.4 pμA.

In the future, it is planned to search for possibility of increasing the injection voltage from 13÷20 kV up to 40÷50 kV. These improvements can give increase in the U400R accelerating efficiency by 1.5÷2 times.

To extract ions out of the U400R one suppose to use two ways: electrostatic deflector and stripping foil method.

Both the methods allow to extract ions in the directions of the existing ion transport channels.

The RF system of U400R will consists of two RF generators that will excite two separated RF dee resonators. The RF resonators will be made from iron with copper coating to decrease the outgasing rate from the surfaces.

The modernization of vacuum system will include changing five diffusion pumps VA-8-7 with N_2 pumping rate of Q=4250 l/s each to five cryopumps with Q=3000 l/s each and two turbopumps with 1900 l/s each. The given changes will allow to improve vacuum in the cyclotron chamber from $(1.5\div2)\times10^{-7}$ Torr to 10^{-7} Torr.

Beam extraction from U-400M cyclotron

Now the beam is extracted from the cyclotron by the stripping on a thin carbon foil. The beam extraction system allows the beam to be extracted with a stripping ratio Z_{int}/Z_{ext} = 1.4÷1.7 (Z_{int} - the charge of ions of the internal beam, Z_{ext} - the charge of ions of the extracted beam). The modernized this year extraction system provides a beam extraction efficiency of 70-80%.

At present a number of new set-ups have been mounted, including the ACCULINNA channel, intended for the production of radioactive ion beams. To carry out these experiments, the ECR source has been specially adjusted, which has enabled the production of high intensity beams of light ions both of gaseous and solid materials.

The intensity of beams of light ions in the range from Li to Ne with an energy of 30÷50 MeV/nucleon was $3\div5*10^{13}$ pps. This was achieved with a using a bunching system, which increases the intensity of the beam by a factor of 3÷5.