JOINT INSTITUTE FOR NUCLEAR RESEARCH

2000-309

M. G. Itkis

FLEROV LABORATORY OF NUCLEAR REACTIONS

RESEARCH ACTIVITIES IN 2000

Report to the 89th Session
of the JINR Scientific Council
January 18–19, 2001

Dubna 2000

M. G. Itkis

FLEROV LABORATORY OF NUCLEAR REACTIONS

RESEARCH ACTIVITIES IN 2000

Report to the 89th Session
of the JINR Scientific Council
January 18–19, 2001

Dubna 2000

The traditional for the Flerov Laboratory of Nuclear Reactions fields of activity are experiments with heavy ion beams of stable and radioactive isotopes, the heavy and exotic nuclei synthesis, the nuclear reactions study, acceleration technology and heavy ion interaction with matter and applied research.

These activities will be performed in a wide international collaboration using the accelerators of the Laboratory and other scientific centers.

The U400 and U400M FLNR cyclotrons running time in 2000 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.

Synthesis of new elements

An important achievement of the Laboratory is the experimental confirmation of the predictions of the macro-microscopic theory about the existence of spherical shells with $Z\approx114$ and $N\approx184$. One may hope to approach at least the boundaries of this unknown region so as to come under the influence of the N=184 spherical shell in fusion reactions using the heaviest isotopes of U, Pu, Cm as targets and a ^{48}Ca ion beam.

Contrary to "cold" fusion reactions the dynamical limitations on the fusion of interacting nuclei are not expected due to the high asymmetry in the entrance channel ($A_p/A_t\approx0.2$; $Z_p \cdot Z_t\approx1880$). On the other hand, the excitation energy of the compound nucleus at the Coulomb barrier amounts to only about 30 MeV as a result of the significant mass excess of the doubly magic ^{48}Ca nucleus. This circumstance should increase the survival probability of the evaporation residues (EVRs) compared to the case of "hot" fusion reactions.

Because the superheavy element production cross section even at the maximum of the excitation function is expected to be in the range of 1 pb, the cornerstone in our experiments was the production of a stable and intense ion beam of the ^{48}Ca isotope at the minimal material consumption. Due to the high efficiency in producing ^{48}Ca beams a world level competitive program on the super heavy elements synthesis has been started.

The experiments were carried out at the FLNR Dubna heavy ion cyclotron U400 using the electrostatic separator VASSILISSA and the Dubna Gas-Filled Recoil Separator (DGFRS) in the framework of a large collaboration with GSI (Darmstadt), LLNL (Livermore), RIKEN (Wako-shi, Saitama) and the Comenius University (Bratislava). Experimental results are summarized in the table 1.

Table1.

Date		Target	Excitation energy, E^* MeV	Beam dose10^{18}	Nuclide detected	Cross section, pb
March,	1998	^{238}U	31.0	3.5	^{283}112	5
Nov. - Dec.	1998	^{244}Pu	35.0	5.2	^{289}114	1
March,	1999	^{242}Pu	33.5	7.5	^{287}114	2.5
Jun. - Oct.,	1999	^{244}Pu	35.3	10	^{288}114	1
Jun. - Dec.,*	2000	^{248}Cm	33.1	18*	^{292}116	0.5*

*- experiment is running.

The first positive result was obtained at the separator VASSILISSA in spring 1998 after irradiating the ^{238}U target with a total ^{48}Ca beam dose of $3.5\cdot10^{18}$ ions. In this experiment two spontaneous fission events with the TKE values 190 and 212 MeV were observed, which were assigned to the decay of a new isotope of element 112 produced in the reaction $^{238}U(^{48}Ca,3n)^{283}112$ (see Fig. 1b) with a cross section of $\sigma_{3n}\approx5$ pb.

In March-April, 1999 the ^{242}Pu target was bombarded with $7.5\cdot10^{18}$ ions of ^{48}Ca at the separator VASSILISSA. Two decay chains were assigned to the α-decay of the parent nucleus $^{287}114$ (see Fig. 1a). Both decay chains were terminated after the first α-decays by spontaneous fission of the previously observed daughter nucleus $^{283}112$.

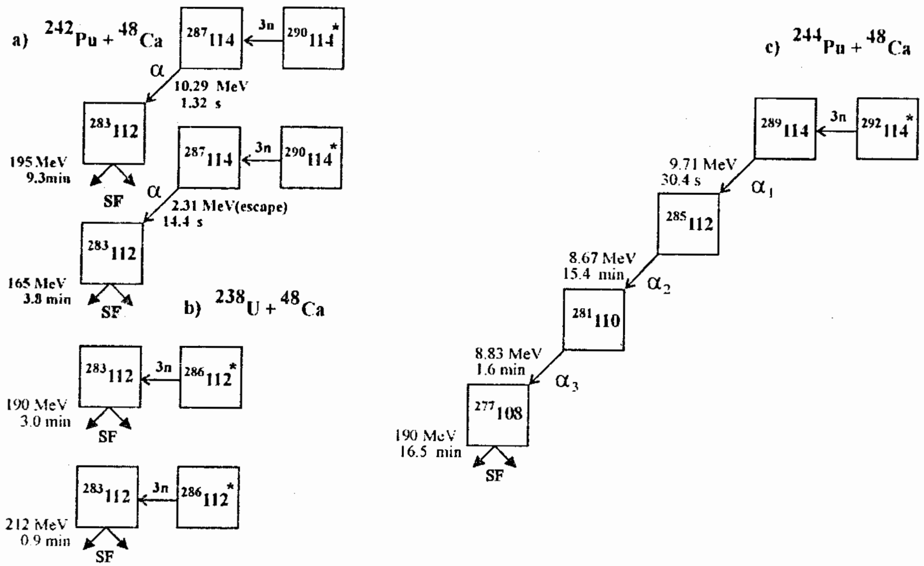

Fig. 1. Position-correlated decay chains: a) of $^{287}114$, produced in reaction $^{48}Ca+^{242}Pu$; b) of $^{283}112$, produced in reaction $^{48}Ca+^{238}U$ and c) of $^{289}114$, produced in reaction $^{48}Ca+^{244}Pu$.

In the $^{48}Ca+^{244}Pu$ and ^{48}Cm fusion reaction, isotopes of elements 114 and 116, which most closely approach the peak of the "island of stability" can be synthesized. The experiments with the ^{244}Pu target were performed at the DGFRS during the period November 1998 - December 1999.

After irradiation of the ^{244}Pu target with a beam dose of $5.2\cdot10^{18}$ ions an α-decay sequence was observed terminating by spontaneous fission. In this decay chain, all 5 signals - recoil nucleus, α_1, α_2, α_3 and SF (see Fig. 1c) - appeared within a position interval of ≈1 mm, which is a strong indication that there is a correlation between the observed decays. Considering the experimental conditions and the observed decay characteristics, the origin of the decay chain is most probably found in the isotope $^{289}114$, which has been produced in the 3n-evaporation channel.

In the next irradiation with the projectile energy, corresponded to the excitation energy of the compound nucleus $^{292}114$ equal to E^*=(33 ÷ 40) MeV, at a beam dose of 10^{19} ions two identical α-decay chains terminated by spontaneous fission were registered. All 4 signals from EVR, α_1, α_2 and SF (see Fig. 2a) appeared within a position interval of 0.5 mm and they were assigned to the α-decay of the parent nucleus $^{288}114$.

The experiment aimed to synthesize the precursor of the isotopes $^{288}114$ and $^{289}114$ by the irradiation of the ^{248}Cm target started in June 2000. On the 35th day of irradiation, with the accumulated beam dose of $6.6\cdot10^{18}$ ions, the first event sequence was observed, that can be assigned to the implantation and decay of the isotope $^{292}116$ (see Fig. 2b). After the implantation of a heavy recoil followed in 46.9 ms by an α-particle with E_α=10.56 MeV the ion beam was switched off and α_2, α_3 and SF have been detected under low-background conditions.

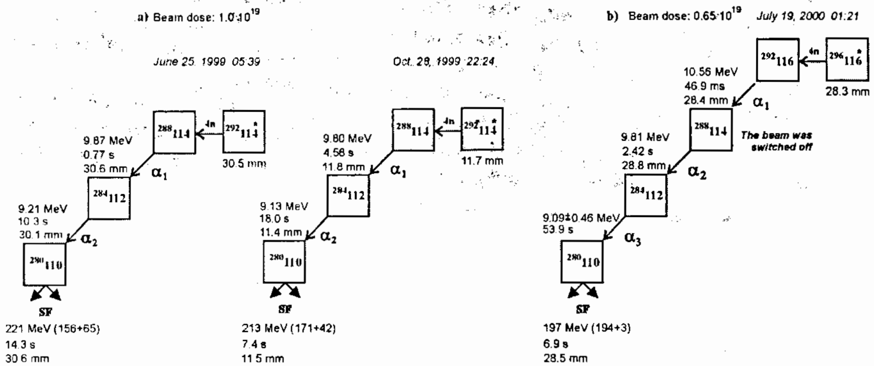

Fig. 2: a) two decay sequences of $^{288}114$ observed in the $^{244}Pu(^{48}Ca,4n)$ reaction; b) the time sequence in the observed $^{292}116$ decay chain.

Decay properties of the heaviest Hs - $^{292}116$ isotopes are presented in the Table 2.

Future investigations at the FLNR will be aimed at the synthesis of nuclei with Z=110÷118 in ^{232}Th, $^{236,238}U$, ^{237}Np, $^{242,244}Pu$, $^{241,243}Am$, $^{246,248}Cm$, $^{249}Cf+^{48}Ca$ reactions. The use of ^{36}S, ^{50}Ti, ^{58}Fe and radioactive beams is discussed.

Table 2.

Isotope	Decay mode	E_α (MeV)	TKE_{mes} (MeV)	$T_{1/2}$
^{277}Hs	SF		170	11 m
$^{280}110$	SF		210	6.6 s
$^{281}110$	α	8.83		1.1 m
$^{283}112$	SF		190	3 m
$^{284}112$	α	9.17		19 s
$^{285}112$	α	8.67		11 m
$^{287}114$	α	10.29		5 s
$^{288}114$	α	9.83		1.8 s
$^{289}114$	α	9.71		21 s
$^{292}116$	α	10.56		33 ms

In 2000 the first stage of DGFRS (electronic and detector systems) and VASSILISSA (installation of a new bending dipole, electronic and detector systems) is completed. All necessary tests will be performed in December 2000 and at the end of January 2001 it is planned to start experiments aimed to determine the mass of the superheavy nuclides, formed in the reactions $^{48}Ca + ^{236,238}U \to ^{284,286}112^{*}$.

Chemistry of transactinides

The isotopes of SHE, obtained in ^{48}Ca induced reactions, make it possible to study chemical properties of the elements. First of all, the chemical identification of the proton number is very important, because no members of the decay chains have been known before.

The 3-min $^{283}112$ can be produced with a cross section of about 5 pb. Element 112 (E112) must belong to the IIB group Zn-Cd-Hg and have some unique chemical properties. As the first step we developed a separation and detection method for Hg.

For the experiments with short-lived Hg isotopes at U-400 cyclotron a flow-through detection chamber was constructed (Fig.3) with a pair of square (2x2 cm) PIPS (passivated ion-implanted planar silicon) detectors. The deposition efficiency in one separate detection chamber depended on gas composition and flow rate.

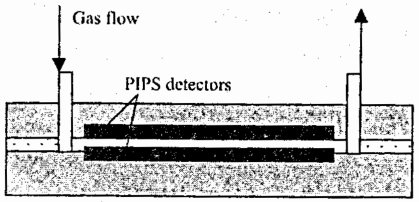

Fig. 3. Schematic of detector chamber.

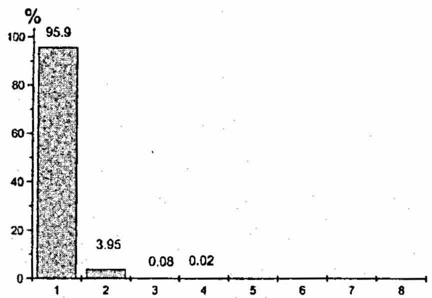

Fig. 4. The distribution of adsorbed mercury in detection chambers.

The first attempt on chemical identification of element 112 was performed at the Dubna U-400 cyclotron in January 2000. A 2-mg/cm^2 $^{238}U_3O_8$ target contained also 100 μg of natural Nd. It was deposited onto a 2 μm HAVAR. After 10 days of irradiation with ^{48}Ca ions an integral beam dose of $6.9 \cdot 10^{17}$ was accumulated. Recoils were thermalized in pure helium and transported through 25 m long capillary to the detection apparatus. There were 8 detection chambers in series. The detectors number 1 to 6 were covered with Au, last two chambers contained detectors with Pd. The chambers were positioned inside an assemblage ^3He-filled neutron counters. The adsorption of the Hg atoms formed in reaction Nd(^{48}Ca; xn) was measured through 5.65-MeV α-particles of ^{185}Hg. A typical distribution of Hg over detectors is shown in Fig.4.

During this bombardment, no SF events were observed. This experiment undoubtedly showed possibility of chemical identification of nuclei produced with picobarn cross sections. The experiment does not give an unambiguous answer about physical and chemical properties of element 112. As the next step of this work we plan to increase the beam dose two or more

times and to upgrade our detector system to measure α-decays and SF events in the gas exiting the chambers with the PIPS detectors using a special ionization chamber.

A series of collaborative experiments was conducted together with scientists from Switzerland, Germany and USA. New results on the properties of Bh (Z=107) were obtained.

Nuclear fission

In 2000 the time-of-flight spectrometer CORSET designed at the Flerov Laboratory was modernized. It is intended for the registration of fission fragments in correlation with emission of pre- and post-scission neutrons and γ-quanta. The modernization was performed in view of using the CORSET set-up in tandem with the multidetector neutron spectrometer DEMON. An important peculiarity of the work was the use of the "neutron clock" method for the study of time characteristics of the process of formation and decay of superheavy nuclei formed in reactions with heavy ions.

At the FLNR U-400 accelerator experiments devoted to the study of fusion-fission of superheavy nuclei with Z=102÷122 in reactions with ^{48}Ca and ^{58}Fe ions using ^{208}Pb, ^{238}U, ^{244}Pu and ^{248}Cm targets as well with ^{86}Kr ions using a ^{208}Pb target at E*-15, 28 MeV were carried out. Fig. 5 shows the results of measurements of the capture cross-section σ_c and the fusion-fission cross-section σ_{ff}.

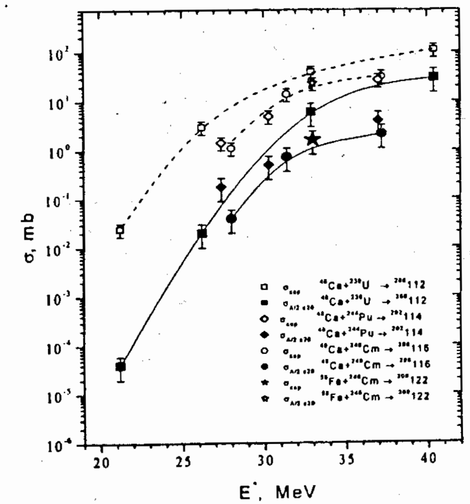

Fig. 5 The capture cross section σ_c and the fusion-fission cross-section σ_{ff} for the reactions ^{48}Ca+^{238}U, ^{244}Pu, ^{248}Cm and ^{58}Fe+^{248}Cm as a function of the excitation energy.

For the detection of neutrons 24 DEMON modules were used. Obtained mass-energy distributions point to a clear evolution from the symmetric fission of the compound nucleus in the case of ^{256}No to the situation of the $^{286}112$ and $^{292}114$ nuclei in which a more asymmetric process of quasi-fission becomes predominant. In the case of $^{294}118$ the process of quasi-fission seems to be dominating even in the region of symmetric fission.

In the study of the regularities of the process of the superheavy element fusion-fission the novel and important result was obtained which consists in the first observation of asymmetry of the heavy nucleus fission, which is determined by the nucleon shells of the light fragment.

It, in a way, closes the circle of modern theoretical knowledge on the modality of nuclear fission, which is extremely important for further development of fission physics as well as nuclear physics on the whole.

Emission of neutrons and γ-quanta in correlation with fission fragments in the decay of superheavy compound systems at excitation energies of near or below the Coulomb barrier had not been properly studied before. At the same time such investigations may be extremely useful for an additional identification of fusion-fission and quasi-fission processes and thus a more precise determination of the cross sections of the above-mentioned processes in the total yield of fragments. On the other hand, the knowledge of the value of the fission fragment neutron multiplicity may be used in the identification of SHE in the experiments on their synthesis. The first results of such investigation are presented in Fig. 6.

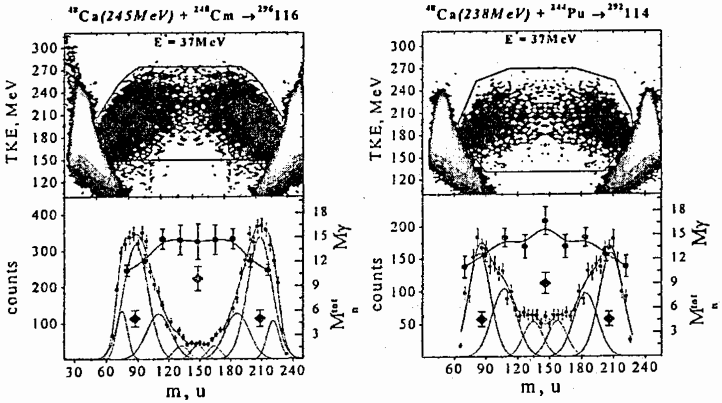

Fig. 6. Two-dimensional TKE-mass matrices (top panels) and the mass yields and neutron and γ-multiplicities in dependence on the fission fragment mass (bottom panels) for the reactions $^{48}Ca+^{248}Cm \rightarrow ^{296}116$ and $^{48}Ca+^{244}Pu \rightarrow ^{292}114$.

The investigations were carried out at the FLNR JINR U-400 accelerator. Physicists from the Institute of Subatomic Research (Strasbourg), Freedom University (Brussels, Belguim), Texas A&M University (USA), The Institute of Corpuscular Physics (Caen, France), University of Messina (Italy) took part in the investigations.

Using a 4π-multidetector neutron spectrometer DEMON and a fission fragment trigger CORSET it is planned to measure at subbarrier energies the differential characteristics of mass and energy distributions of fission fragments in coincidence with neutrons and γ-quanta in the reactions induced by ^{22}Ne, ^{40}Ar, ^{48}Ca, ^{50}Ti, ^{58}Fe and ^{86}Kr ions and leading to formation of compound nuclei in the region of Z=102-122. It is also planned to analyze the experimental data on the fission modes for weakly excited compound nuclei.

Fragment-separator COMBAS

On the fragment-separator COMBAS a number of experiments has been carried out devoted to the study of the reaction mechanisms in nucleus-nucleus collisions at intermediate energies. The production of isotopes with the mass numbers $4 \leq A \leq 30$ and atomic numbers $2 \leq Z \leq 13$ in reaction $^{22}Ne + ^{9}Be$ (^{181}Ta) at the Fermi energy domain (45 A·MeV) has been

studied in zero-angle measurements (Fig. 7). No evidence was found for any dramatic reaction mechanism change at the Fermi energy domain in comparison with the same in the low energy range (lower 20 A·MeV).

It was shown, that in interaction of light projectile (^{22}Ne) with light and heavy targets (^{9}Be and ^{181}Ta) nuclear reactions of stripping, pick-up and exchange are dominant at the Fermi energy domain. For isotopes close to the stability line considerable contributions from deexcitation process were registered. The exponential approximation by Q_{gg}-systematics of isotopic distributions for all detected elements confirms a binary type of reactions. The simple exponential approximation realized by Q_{gg}-systematics is a powerful tool to predict correctly expected yields of unknown drip-line nuclei.

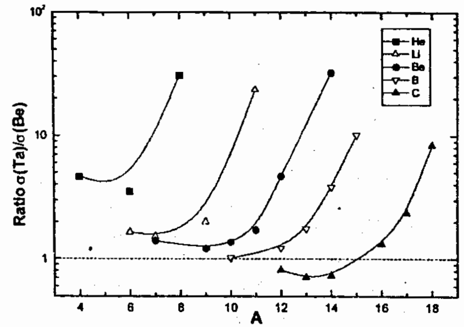

Fig. 7. Comparison of production cross-sections of neutron rich isotopes of He, Li, Be, B and C in reactions of ^{18}O(35 A·MeV) with heavy (^{181}Ta) and light (^{9}Be) targets.

High-resolution beam-line ACCULINNA

Separator ACCULINNA was upgraded in order to install a liquid-tritium target. The beam line was extended beyond the 2-meter concrete wall to a newly built hall housing the reaction chamber of ACCULINNA (Fig. 8). The beam monitoring and detector arrays were upgraded in order to fit experiments aimed at the study if ^{5}H produced in t+t reaction with a 51-MeV primary triton beam. New, improved performance particle telescopes are installed in the reaction chamber. Neutrons will be detected with the DEMON detector array.

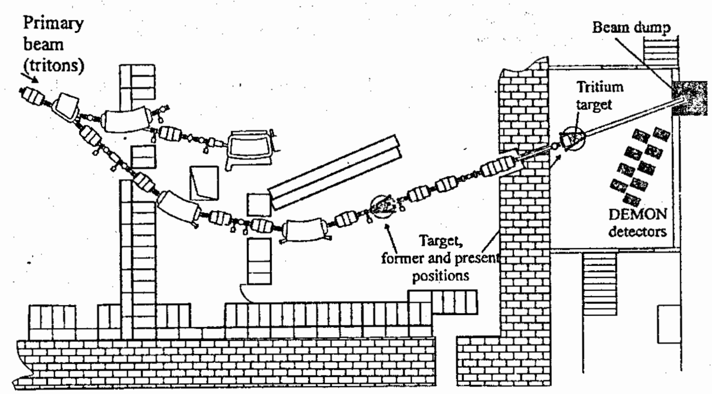

Fig. 8. The ACCULINNA set-up upgraded for experiments with the cryogenic tritium target.

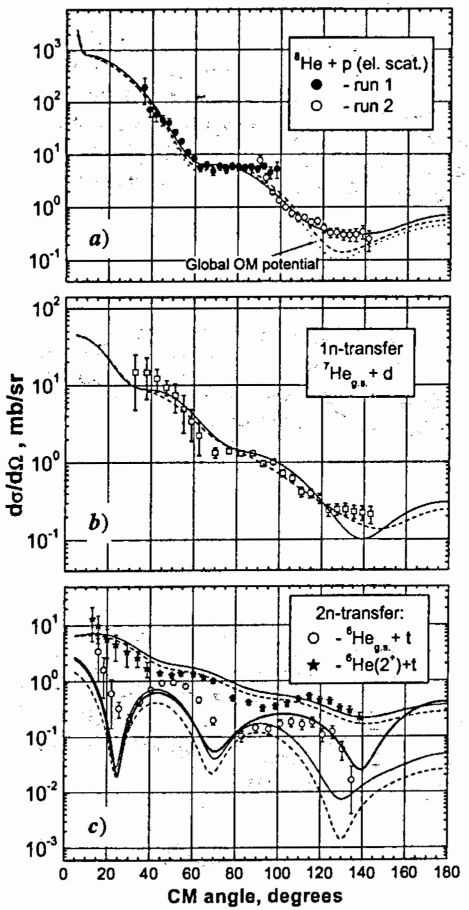

Fig. 9. Cross sections for ^{8}He elastic scattering, 1n transfer, 2n transfer to ground-state ^{6}He, and 2n transfer to ^{6}He in 2+ state.

Direct reactions occurring with a 26-A·MeV ^{8}He beam bombarding hydrogen were investigated. Cross sections for elastic scattering, 1n transfer, 2n transfer to ground-state ^{6}He, and 2n transfer to ^{6}He in 2+ state, respectively, were measured in angular ranges of 35°–142°, 33°–143°, 15°–135°, and 13°–138° (Fig. 9). Unlike other weakly bound nuclei, the elastic scattering of ^{8}He is relatively well described by the global OM without any adjustment. The transfer reaction data were analyzed with finite range DWBA. Spectroscopic amplitudes (SA) for ^{7}He(3/2–)+n, ^{6}He(0+)+2n, and ^{6}He(2+)+2n clustering of ^{8}He predicted by the translation invariant shell model (TISM) were tested. OM potentials for different exit channels were found. Data for 2n transfer leading to ^{6}He(2+) point at a large rms radius for the two-body ^{8}He=^{6}He(2+)+2n wave function exceeding that following from the COSMA model. Calculations performed in a consistent way with a minimum number of free parameters and SA from TISM underestimate the experimental ^{6}He(0+)+t exit-channel cross section. The data suggest that ^{5}H+t clustering is large in ^{8}He.

Angular distribution of ^{8}He ions elastically scattered from a gaseous helium target was measured in CM angular range of 20° – 70° at beam energy of 26 *A*MeV. Cross-section limits of 5 to 0.8 μb/sr were obtained in a range of CM angles 130° – 165°. The forward-angle data were analyzed in terms of microscopic and phenomenological OM. A large value of the total reaction cross section obtained suggests an anomaly of ^{8}He structure. In spite of low cross-section limits attained at the backward angles any enhancement pointing at a one-step 4n transfer was not observed. Finite range DWBA calculations of one- and two-step transfer reactions predict even lower values for this cross section. These calculations show that the two-step 2n transfer is more important than the one-step 4n transfer.

MULTI project

Within the framework of the MULTI project, the U-400M accelerator's beam transportation channel has been modernized and a Q4DQ spectrometer has been created around it (Fig. 10).

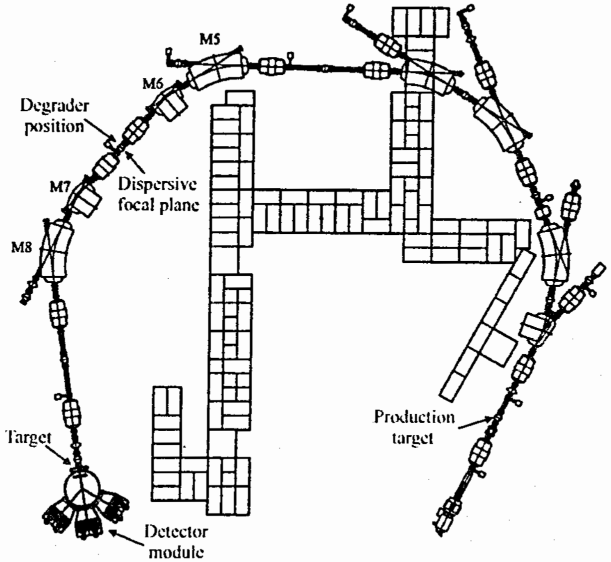

Fig. 10. Q4DQ-spectrometer for secondary beams production.

In the ^{7}Li+Be reaction (^{7}Li beam intensity 1μA), a 10^5 s^{-1} beam of ^{6}He nuclei was produced. For the purification from other nuclear reaction products a degree of 98% was achieved. With that spectrometer on secondary ^{6}He beams experiments were carried out on measuring the energy dependence of the fission cross section for the compound nucleus of ^{215}At produced in the ^{6}He+^{209}Bi reaction.

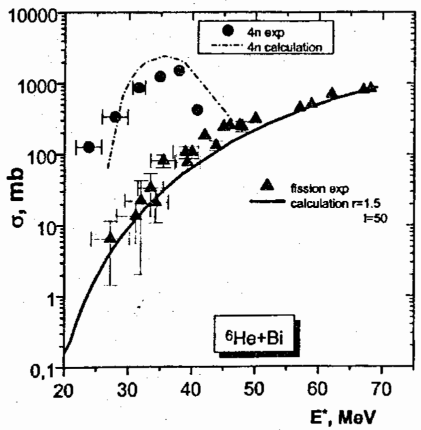

Fig. 11. Excitation functions of ^{209}Bi(^{6}He,f), ^{209}Bi(^{6}He,4n)^{211}At reactions measured at Q4DQ-spectrometer and the results of calculations.

The excitation function was also measured for the channel of compound nucleus break-up accompanied by 4 neutrons emission - ^{209}Bi(^{6}He,4n)^{211}At. Fig. 11 presents the excitation functions measured in those experiments for the channel of ^{215}At compound nucleus fission and 4 neutrons emission.

The results obtained for the ^{6}He beam were compared with those obtained with ^{4}He beams in the same experiments for analogous fusion and fission channels. The measurements were carried out in a wide range of bombarding energy ($20 \le E_b(^{6}He) \le 170$ MeV. A marked increase was observed in the fission cross section everywhere over the energy region for the ^{4}He beam as compared with the ^{4}He beam. The obtained results were compared with the results of calculations done using an ALICE-MP-based statistical model with variable parameters of radius r_0 and critical angular moment L. The same method was used to analyze the data on the excitation functions for the $^{209}Bi+^{4}He$ reaction, for which $r_0=1.29$ Fm and $L_{cr}=35$ were obtained. To achieve a good fit to the experimental data for the $^{209}Bi+^{6}He$ reaction, $r_0=1.5$ and $L_{cr}=50$-60 were required. Such a change in the parameters for ^{6}He can be accounted for by the influence of the other reaction channels on the fission process.

The collaborative JINR (Russia)-GANIL (France)-Hahn-Meitner Institute (Germany) research on the properties of light neutron-rich nuclei has been continued. In those experiments, the deformation and γ-transitions of nuclei were measured in the N=20-shell region, and it was found that there is strong deformation ($\beta \approx 0.3$) in that region. In a collaborative Dubna-GANIL experiment, the masses were measured of 31 neutron-rich nuclei with A=27-29, the masses of 12 of them being measured for the first time. It was shown that in the N=28 shell region, Cl, S and P nuclei change their properties described by shell models; those nuclei can occur in two forms – spherical and deformed ones. In a collaborative Dubna-Hahn-Meitner Institute experiment, data was obtained on the structure of neutron-rich isotopes $^{13,14,15,16}B$.

In the laser group measurements have been carried out on the hyperfine splitting of optical lines in the atomic spectra of the Eu isotopes with A=151 - 155. Resonance laser fluorescence in a parallel beam of Eu atoms was used. From the measurements, the hyperfine splitting constants were determined; from the constants, the values were deduced of the magnetic dipole and electric quadruple moment. Those values of the moment allow one to judge the nucleonic configuration and quadruple deformation of the indicated Eu isotopes.

In the optical spectra of Eu isotopes, a hyperfine magnetic anomaly was observed – a deviation of the ratio of the hyperfine splitting constants from the ratio of the magnetic moment for the isotopes under comparison. The largest deviation (~5%) was observed for the pair of the isotopes ^{151}Eu and ^{152}Eu, which points to the fact that nucleonic structure changes drastically in going from spherical nuclei (^{151}Eu) to deformed nuclei (^{152}Eu).

Applied research

Interaction of accelerated heavy ions with polymers

New methods of obtaining track membranes with profiled pore channels ensuring a high selectivity and high efficiency when filtering dispersible species of various natures have been developed. The possibility of obtaining thick "blotting" membranes and membranes of the type of «wells with porous bottom» has been investigated. The membranes of this structure have promising perspectives as non-tight substrates for immobilization and research of cells metabolism and other biological objects.

Research and development of thermo-sensible membranes has been undertaken. Investigated were a response of membranes to a change in temperature and their electro-surface

properties (together with IPC, Moscow, and TRCRE, Takasaki, Japan). It allows one to create "clever" membranes with the adjustable properties.

The influence of the plasma processing on track membranes properties has been studied. Research on using the method of «ion transmission technique» for the TM structure investigation (in cooperation with IPI, Rez, and HMI, Berlin) has been conducted. The optical properties of the thick (60-100 microns) porous systems produced by the method of ion tracks were studied. New methodical approaches to the creation of metal nanometric wires and submicrometric pipes of a strictly predetermined size have been advanced. It allows one to create nanostructural objects applied to the problems of microtechnology in microengineering, microelectronics, optoelectronics, etc.

Interaction of accelerated heavy ions with metals and monocrystals

When implanting the ions of B, P, Ga, In, Bi with the energies from 100 keV up to 300 keV and the flux in the range from 10^{13} up to 10^{14} ion/cm^2, in silicon monocrystals the increase of the diffusion coefficients has been revealed. These results can find application in the creation of new processes of semi-conducting materials manufacturing.

The processes of dispersion of metals and alloys exposed to heavy ions with high specific losses of energy on the samples of Ni, W and of chromo-nickel steel were investigated. A study in the structure of the surface by the SEM method has allowed one to evaluate the dispersion coefficients: Ni (~ 500 atoms / ion), steel (~ 100 atoms / ion), W (~ 1260 atoms / ion). The surface structure of model monocrystals Al_2O_3, silicon, pyrolytical graphite after irradiation with ions ^{86}Kr (305 MeV, 440 MeV and 750 MeV), ^{136}Xe (605 MeV) and ^{209}Bi (705 MeV) was studied with the use of the methods scanning tunnel (STM) and nuclear power microscopy (NPM). The results are important for selection of the material for the first wall of thermonuclear reactors and for understanding the physics of processes of interaction of high energy ions with condensed matter.

In cooperation with the Oak-Ridge Laboratory (USA) and the Institute of trans-uranium elements (Karlsruhe, Germany), research on the microstructure of spinelle $MgAl_2O_4$ irradiated with high-energy ions of Kr, I and Xe with the energies from 70 up to 600 MeV was undertaken. For the first time it was shown that when selecting the candidate materials - matrixes for inert nuclear fuel in the fission reactors, it is necessary to take into account the effects of the high density of ionization.

For the first time with the help of the PEM-research, the ordering of helium pores in amorphous silicon has been detected both in longitudinal and in transversal directions as well as the creation of tracks by irradiation with 17 keV He- and 210 MeV Kr- ions. As the result of post-radiation burning in an interval of 500-1000C, recrystallization of the layer of amorphous Si created by irradiation with 17 keV He ions has been studied. The obtained results are important for understanding the mechanisms of forming defects in semi-conducting materials.

Ultra-pure radioisotopes and radioanalytical research

1. Methods for obtaining radioisotopes $^{99m}Tc(^{99}Mo)$, ^{225}Ac etc. by the use of (γ,n) reaction at the microtron MT25 have been developed.
2. A technique of the radiochemical separation of ^{149}Tb has been developed, and a dependence of the yield of ^{149}Tb on the ^{12}C ion energy has been determined.

3. Complex evaluation of a spontaneous effect of radionuclides and chemical pollution in Saratov region and determination of natural radionuclides and research in the geochemistry of microelements in seismically active regions (France, Tadjikistan, Krasnodar) have been performed.

Physics and heavy ion accelerator techniques

A reliable performance of the accelerators has been a necessary prerequisite for all performed experiments and technical developments at the FLNR.

In 2000 the emphasis was put on the optimization of the U-400 cyclotron and of the ECR-4M ion source aiming at performing the experiments on the superheavy element synthesis. Optimizing the beam capture system increased the efficiency of the source material using. The routine beam intensity of ^{48}Ca on the target was typically close to $4 \cdot 10^{12}$ 1/s.

Formation of the magnetic field in the U-400M cyclotron central region for the optimization of the acceleration regime and a buncher installation resulted in a considerable increase in the light ion beam intensities on physical targets up to $2 \div 3 \cdot 10^{13}$ 1/s.

Any further accelerator techniques developments were connected with the realization of the DRIBs-project (production of radioactive ion beams at Dubna cyclotrons). For many systems during 2000 R&D are finished: target unit, low energy ion separator, beam channels, vacuum pumping system, beam diagnostics and control systems. 2.45-GHz ECR ion source for production of ^{6}He and ^{8}He radioactive beams was manufactured and tested.

A full scale modeling of the DRIBs production module was performed with a 3-mm (550 mg/cm^2) Be target bombarded with a 34-AmeV Li ion beam and with a TiC_n (porous graphite containing 6.25 % of Ti) installed behind the target. At the stopper temperature $\geq$1700K nearly 100 % of ^{6}He nuclei that left the target and were stopped in the porous graphite were vaporized and detected in the vacuum chamber holding the stopper. Separate experiments involving the detection of ^{8}He showed that the release time of He nuclei from the catcher is of the order of 50 – 100 ms. Energy and angular distributions and absolute yield values were measured for ^{6}He nuclei emerging from thick Be targets bombarded with beams of ^{7}Li, ^{11}B and ^{15}N ions with energies of 34, 32 and 48 A·MeV, respectively.

In the period December 2000 – February 2001 the assembling and adjustment of low energy $^{6,8}He$ beam systems are to be carried out. The first stage of DRIBs – production of the light radioactive ion beams – should be realized in 2001.

For the second stage of the DRIBs-project the yields of Xe isotopes with A = 137-143 have been measured in the photofission of ^{232}Th, ^{238}U and ^{244}Pu. The experiments were carried out on the bremsstrahlung of the FLNR microtron MT-25. The fission fragments escaped from the target were retarded in an inert gas and transported by a gas flow along a capillary to a criostat, in which the xenon condensed. A filter at the capillary inlet trapped all the other fragments. The mass numbers of the Xe isotopes were identified by their γ spectra and half-lives. The distribution of the independent yields of Xe fragments as a function of their mass numbers was obtained. The average mass number for this distribution is 139, the dispersion increased from 1.48 for ^{232}Th photofission up to 1.60 for ^{244}Pu. Those results point to the fact that a photofission reaction is promising for producing neutron-rich Xe isotopes intended for further acceleration on a cyclotron.

The second stage – acceleration of fission fragments – should be realized in 2002.

Received by Publishing Department
on December 21, 2000.