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M. G. Itkis

FLEROV LABORATORY OF NUCLEAR REACTIONS

RESEARCH ACTIVITIES IN 2003

Report to the 95th Session
of the JINR Scientific Council
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The FLNR scientific program on heavy ion physics included in 2003 experiments on the synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes, studies of nuclear reaction mechanisms, heavy ion interaction with matter and applied research.

Reliable performance of the FLNR accelerators opened wide possibilities for performing new experiments in the low and medium energy range and for accelerator technology development. In 2003, the operation time of the FLNR cyclotrons - U400 was close to 6200 hours and that of the U400M – 3300 hours, which is in accordance with the plan.

Synthesis of new elements

In experiments on the synthesis of the super heavy nuclei located mostly close to the predicted neutron magic number N=184, complete fusion reactions of the target and projectile nuclei having largest neutron excess ^{242,244}Pu+^{48}Ca, ^{248}Cm+^{48}Ca and ^{249}Cf+^{48}Ca leading to even-Z (Z=114,116,118) super heavy elements were investigated [1–4].

For the neighboring odd-Z elements, especially their odd-odd isotopes, the probability of α-decay with respect to SF should increase due to hindrance for SF. For such odd-Z nuclei one might expect longer consecutive α-decay chains terminated by the SF of relatively light descendant nuclides ($Z \leq 105$).

The decay pattern of these super heavy nuclei is of interest for nuclear theory. In the course of α-decays, the increased stability of nuclei caused by the predicted spherical neutron shell N=184 (or perhaps N=172) should gradually become weaker for descendant isotopes. However, the stability of these nuclei at the end of the decay chains should increase again due to the influence of the deformed shell at N=162.

The observation of nuclei passing from spherical to deformed shapes in the course of their consecutive α-decays could provide valuable information about the influence of significant nuclear structure changes on the decay properties of these nuclei.

The main attention in 2003 was paid to the experiments aimed at the synthesis of elements with Z=115 and Z=113 in fusion-evaporation reactions ^{243}Am+^{48}Ca. According to calculations based on the results of experiments on the synthesis of even-Z nuclei, the 3n- and 4n-evaporation channels leading to isotopes ^{288}115 (N=173) and ^{287}115 (N=172) were expected to be observed with the highest yields. The experiments were performed at the U400 cyclotron with the Dubna gas-filled recoil separator (DGFRS) [5].

The 32-cm^2 rotating target consisted of the enriched isotope ^{243}Am (99.9%) in the form of AmO_2. The target material was deposited onto 1.5-μm Ti foils to a thickness corresponding to ~0.36 mg cm^{-2} of ^{243}Am. The average incident beam intensity was 1.3 pμA. The equal beam doses of 4.3×10^{18} ^{48}Ca projectiles were delivered to the target at two bombarding energies: 248 MeV and 253 MeV in the middle of the target.

In the course of the irradiation of a ^{243}Am target with a ^{48}Ca ion beam, the detector system of the Dubna gas-filled recoil separator registered two types of decay chains.

The three similar decay chains observed at 248 MeV are shown in Fig. 1a. The implantations of recoils in the focal-plane detector were followed by α-particles with $E_\alpha = 10.46 \pm 0.06$ MeV. These sequences switched the ion beam off, and four more α-decays were detected in the absence of a beam-associated background.

The SF-decays of the final nuclei in these chains were detected 28.7 h, 23.5 h and 16.8 h, respectively, after the last α-decay.

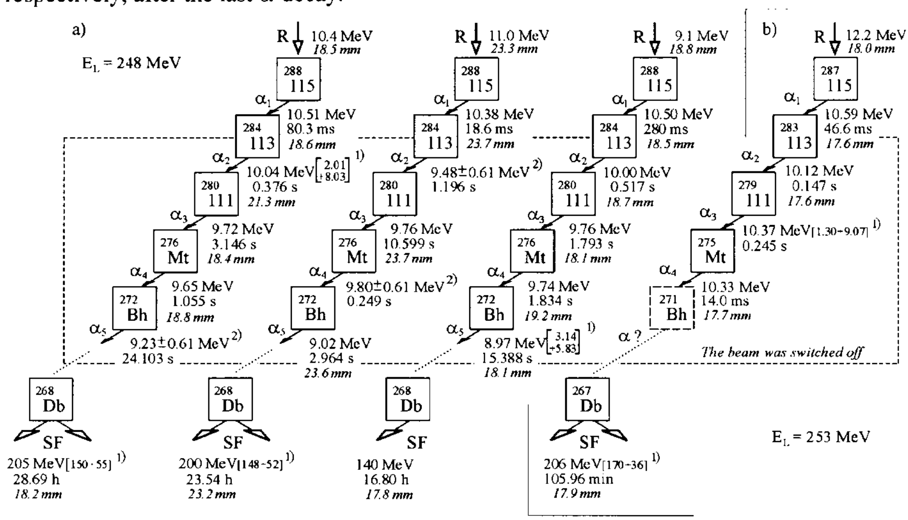

Fig. 1. Time sequences in the decay chains observed at two ^{48}Ca energies E_L=248 MeV (a) and E_L=253 MeV (b). An unobserved nuclide in the fourth decay chain is inserted.

At 253 MeV, the aforementioned EVR-α_1-...-α_5-SF decay chains were not observed. However, a different decay chain, consisting of four α-decays and a spontaneous fission, was registered (see Fig. 1b). The beam was switched off after the detection of an EVR signal followed in 46.6 ms by an α-particle with E_α=10.50 MeV in the same position. Three other α decays were detected in a time interval of about 0.4 s in the absence of beam-associated background. After 106 minutes, the terminal SF-event was detected in-beam with a sum energy of 206 MeV in the same position (see Fig. 1b).

The radioactive properties of nuclei in this decay chain differ from those of the nuclei observed at the lower bombarding energy. The total decay time of this chain is about 10 times shorter and the α-decays are distinguished by higher α-particle energies and shorter lifetimes. Its production also required increasing the beam energy by about 5 MeV, so this decay chain must originate from another parent nucleus.

It is most reasonable that the different decay chains originate from neighboring parent isotopes of element 115, produced in the complete fusion reaction ^{243}Am+^{48}Ca followed by evaporation of three and four neutrons from the compound nucleus ^{291}115.

In the experiment aimed at the investigation of radioactive properties of the isotopes of element 116 (the α-decay daughters of *Z*=118 isotopes), the new nuclide ^{291}116 was identified in the reaction ^{245}Cm+^{48}Ca using DGFRS [6].

As a whole, the results obtained during past five years demonstrate that in ^{48}Ca-induced reactions one can produce and study new nuclei over a wide range of Z and N. Decays of the heaviest isotopes of Rf, Db, Bh, Hs, Mt, Ds and of the new elements 111 ÷ 116 and 118 were observed [1–6] (Fig. 2).

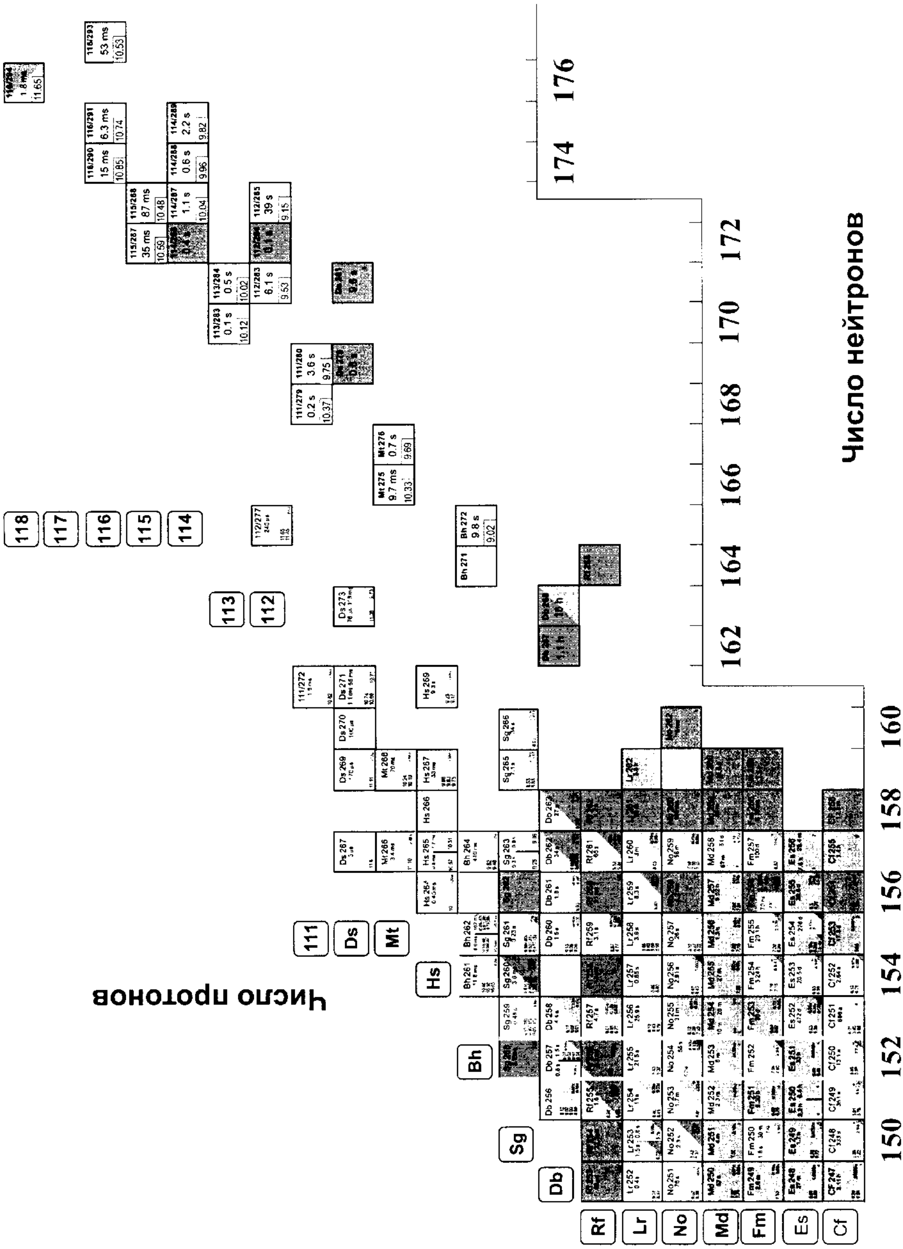

Fig. 2. Chart of the nuclides of transactinide elements.

Chemistry of transactinides

Relatively long half-lives of the isotopes with Z=108 ÷114, produced in the ^{48}Ca-induced reactions, open up new opportunities for the investigation of chemical properties of super heavy elements.

According to theoretical predictions, element 112 (E112) must belong to the IIB group: Zn-Cd-Hg-E112. Long-lived isotopes of element 112 can be produced in reactions ^{238}U+^{48}Ca. As a first step a method for the separation and detection of Hg-like atoms was developed. Two experiments on chemical isolation of element 112 were performed in 2002–2003.

The values of the adsorption energy enthalpy calculated from the experimental data confirm the fact, that interaction of element 112 with the Au surface is much weaker than that of Hg by about 60 kJ/mol and stronger than that of Rn by no more than 20 kJ/mol. These facts point to "noble gas like" rather than "Hg-like" behaviour of element 112 in the given chemical environment [7].

The new on-line setup able to detect α-decay and spontaneous fission of volatile elements is under construction and testing (Fig. 3). Reaction products formed in the fusion reaction between ^{48}Ca ions and ^{244}Pu target (thickness of about 1.5 mg/cm^2) will be thermalized in helium at atmospheric pressure. The atoms of volatile elements will be continuously transported with the carrier gas (He) through PTFE capillary (about 5 m long) to the counting device – so called cryodetector. The cryodetector includes two opposite arrays of 32 pairs of PIN detectors coated with Au or Pd (each 1x1 cm) covering temperature gradient from ambient temperature (entrance) to –180 ^{0}C (exit).

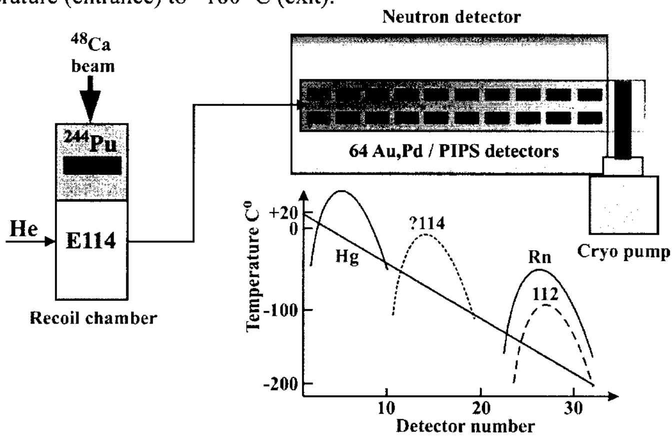

Fig. 3. Schematic view of the set-up for isolation and identification of element 114

Separator “MASHA”

The properties of superheavy elements with Z=112÷120 are predicted to be similar to those of volatile elements Hg ÷ Ra, thus a separator of the ISOL-type can be employed for the precise measurement of masses and the investigation of chemical and physical properties of super heavy elements. In 2001 started the R&D of the Mass Analyzer of Super Heavy Atoms “MASHA”, providing the mass resolution of about 1000 [8]. In February 2003 the manufactured separator was installed in the special testing room at the FLNR (Fig. 4).

The layout of MASHA can be described as DQQDQSDDSE. The tests of the whole setup will be performed both with the plasma ion source FEBIAD and the special designed ECR ion source. First experiments with the use of this separator on the beam of U400 cyclotron are scheduled for 2005.

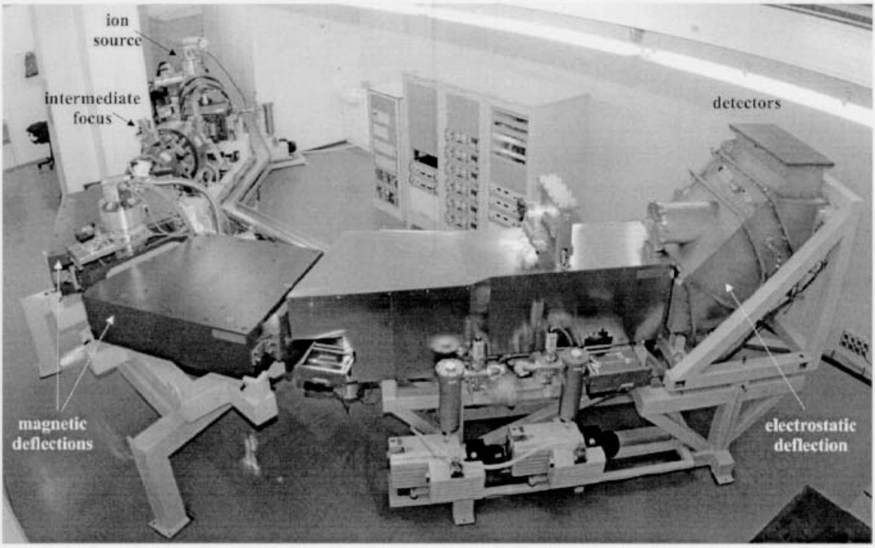

Fig. 4. Mass Analyzer of Super Heavy Atoms "MASHA"

Nuclear fission

Mechanisms of formation and decay of heavy and super heavy nuclei in the reactions with ^{12}C, ^{18}O, ^{22}Ne, ^{26}Mg, ^{48}Ca, ^{58}Fe, ^{86}Kr ions were investigated using the CORSET + DEMON +HENDES set-up which allows measurements of mass-energy distributions of fission fragments, pre-equilibrium, pre- and post-scission neutrons, mean multiplicities and γ-quantum energies.

At energies close to and below the Coulomb barrier, fission properties of the compound nuclei ^{256}No, ^{270}Sg, $^{266,271,274}Hs$, $^{286}112$, $^{292}114$, $^{290,296}116$, $^{294}118$, $^{302}120$ and $^{306}122$ were studied. It was found, that the mass distribution of fission fragments for compound nuclei $^{286}112$, $^{292}114$, $^{290,296}116$, $^{302}120$ and $^{306}122$ is an asymmetric one, whose nature, in contrast to the asymmetric fission of actinides, is determined by the shell structure of the light fragment with the average mass 132-134. It was also found that the cross sections of the fusion-fission reactions between ^{48}Ca and ^{58}Fe changed very slowly with an increase in the charge and mass of the target nuclei, which is of great importance for planning the new experiments on the synthesis of super heavy nuclei with Z>110 [9].

The dynamics of super heavy system with Z=122 in the reaction $^{64}Ni + ^{242}Pu$ at different energies of ^{64}Ni ions (355, 380 and 420 MeV) has been studied.

The fragment mass and kinetic energy distributions at the lowest measured energy E_{Ni}=355 MeV are shown in the Fig. 5. Only a small part of fragments in the region of symmetric masses can be attributed to the fission of compound nucleus. This region of the fission fragment mass distribution has its own structure connected with double magic ^{132}Sn nucleus in the light fragment group. The shell structure observed in the symmetric fragment mass region is considered as manifestation of fusion-fission channel which can lead to the formation of super heavy nuclei. Mass dependence of the γ-quanta multiplicity also supports the conclusion about formation of a compact compound configuration.

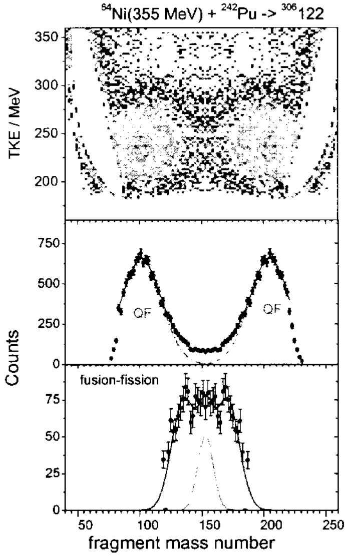

Fig. 5. Fragment mass and kinetic energy distributions.

Mass-energy distributions (MED) of the fragment in the reactions with ^{48}Ca projectile on a wide number of targets (Z = 62 – 96) at energies near and below the Coulomb barrier (i.e. when the influence of the shell effects on the fusion and characteristics of the decay of the composite system is considerable) have been measured [11]. ^{154}Sm, ^{168,170}Er, ^{186}W, ^{204,206,208}Pb, ^{238}U, ^{244}Pu, ^{248}Cm spectrometric layers 120-200 mkg/cm^2 in thicknesses were used as targets. They were deposited onto 20-50 mkg/cm^2 carbon backings. The pre- and post-fission neutron and γ-multiplicities as a function of the fragment mass have been studied for the transuranium elements.

The excitations of the compound-nuclei were near the same in all the cases. It was found that the quasi-fission dominates in the reactions with the transuranium elements, whereas in the reaction with double-magic ^{208}Pb the contribution of the quasi-fission process to the capture cross-section does not exceed the value of 3-4%. At the same time in the reactions with rare-earths like ^{154}Sm, ^{168,170}Er, ^{174,176}Yb the yield of quasi-fission increases again and its contribution to the capture cross-section reaches the value of ~30-40%. Obviously, such a behavior of the quasi-fission yield can be explained only by the influence of the nuclear shells. In the case of the interactions between ^{48}Ca and transuranium elements quasi-fission process is supported mostly by the formation of two spherical shells with the protons number Z ~ 82 and the neutrons number N ~ 126, when the composite system decays before it reaches equilibrium, i.e. without going into complete fusion. In the case of interactions with rare-earth elements quasi-fission is supported mostly by the formation of two spherical shells with Z ~ 50 and N ~ 82 and, probably, by the formation of spherical shells with Z ~ 28 and N ~ 50. On the other hand, during the interaction of ^{48}Ca with ^{208}Pb the spherical shells Z ~ 82 and N ~ 126 cannot be formed because it corresponds to the elastic scattering and the formation of spherical shells with Z ~ 50 and N ~ 82 corresponds to the symmetric fission with M~A_{CN}/2. Therefore in this case the quasi-fission can be supported by the formation of spherical shells with Z~28 and N~50 only, that is in a good agreement with the experimental results.

The analysis of the dependences TKE-mass and fission fragment mass yields on the excitation energies showed that the TKE and mass distributions become more symmetric with an increase in the excitation energy. The TKE values, neutron and gamma multiplicities for the fission of super-heavy compound nuclei and those for the quasi-fission process differ greatly for both processes. The strong manifestation of the shell effects in the fragment mass distributions was observed for the quasi-fission process near A≈208, corresponding to double magic ^{208}Pb. The influence of the reaction entrance channel on the mechanism of production of the compound nucleus, for two ion-target combinations ^{12}C+^{204}Pb and ^{48}Ca+^{168}Er leading to the same compound nucleus ^{216}Ra have been investigated. It was found that the contribution of the asymmetric fission mode in the former reaction is 1.5%, and it is ~30% in the case of the latter reaction. Such a sharp increase in the yield of asymmetric reaction products in the reaction with ^{48}Ca ions has been interpreted as a manifestation of the quasi-fission process [12].

Evidence of still unknown multi-cluster decay in spontaneous decay of ^{252}Cf was found in experiment performed at the modified 4π spectrometer FOBOS [13]. Such a process should be accompanied by almost isotropic emission of post-scission neutrons in the lab system of the multiplicity as high as ~10. In order to exploit this phenomenon neutrons were registered in unusual measurement mode – normally to the fission axis. Thee tail of the distribution corresponding to high-multiplicity events is connected to multi-cluster decay (Fig. 6) [14].

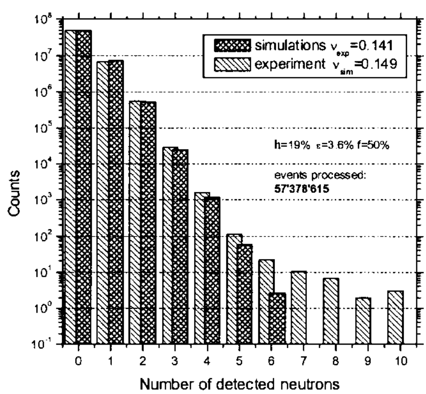

Fig. 6. Expected and measured neutron multiplicities in spontaneous fission of ^{252}Cf.

Separator VASSILISSA

As a first step in improving the identification of complete fusion reaction products, a new dipole magnet, having a deflection angle of 37°, was installed behind the separator VASSILISSA [15]. In test reactions the mass resolution better than 1.5% was achieved (Fig. 7). Using the modernized separator VASSILISSA the new neutron deficient isotope ^{249}No was produced and identified, the decay properties of ^{250}No isotope were defined more precisely in the fusion reactions ^{48}Ca + ^{204}Pb and ^{44}Ca + ^{208}Pb leading to the same compound nucleus ^{252}No* [16].

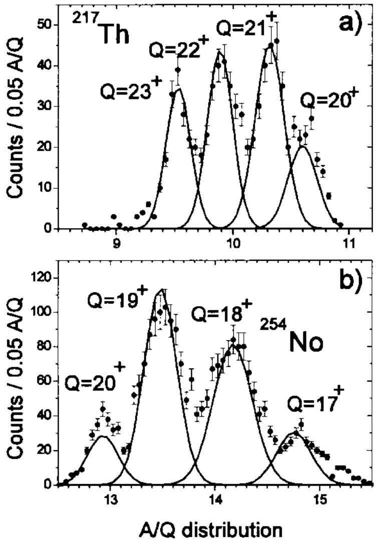

Fig. 7. A/Q distributions of the ^{217}Th and ^{254}No ER's

The upgraded separator VASSILISSA was used to confirm results of previous experiments on the synthesis of heavy isotopes of element 112 obtained in complete fusion reactions of ^{48}Ca and ^{238}U. Limits of $280 \leq A$ 286 for the atomic mass number of the observed spontaneously fissioning isotope were measured [17].

Fragment separator COMBAS

Using the in-flight fragment-separator COMBAS in the forward angle spectrometry of charged reaction products a number of experiments has been carried out devoted to the study of the reaction mechanisms in nucleus-nucleus collisions near Fermi energy and the determination of the intensity of secondary radioactive beams of neutron-rich nuclei with atomic numbers $2 \leq Z \leq 11$. The nuclear reactions ^{18}O(35·A MeV) + ^{181}Ta, ^{22}Ne(40·A MeV) + ^{9}Be and ^{40}Ar + ^{9}Be(and ^{197}Au) at 31·A MeV and 38·A MeV energies has been studied [18].

The reaction products were detected in the final focus of the separator by a silicon detector telescope ΔE_1(0,38 mm, 60×60 mm^2), ΔE_2(3,5 mm Ø60 mm), E_{res}(7,5 mm, Ø60 mm) and were identified by the nuclear charge and mass number using combination of magnetic rigidity, TOF and the (ΔE, E) method.

As an example, the forward-angle inclusive velocity distributions of isotopes with atomic numbers $2 \leq Z \leq 9$ in the reaction ^{18}O(35·A MeV) + ^{181}Ta are displayed in Figs.8a and 8b.

In the Fermi energy domain, the dominance of stripping, pick-up and exchange nuclear reactions is observed. For peripheral reactions at intermediate energy no evidence was found for any dramatic reaction mechanism change. Pickups of few protons on the projectile are realized with large cross-sections, which conflicts with the prediction of fragmentation models. The comparison of the forward-angle yields of isotopes with $2 \leq Z \leq 11$ in reactions ^{18}O(35·A MeV) + ^{181}Ta and ^{18}O(35·A MeV) + ^{9}Be show that the inclusive velocity distributions, isotopic and elements distributions are similar. The strong influence of the neutron excess $(N/Z)_t$ of the target on the production cross section of neutron-rich isotopes including drip-line nuclei was observed.

Peripheral reactions of ^{40}Ar with ^{9}Be (light target) and ^{197}Au (heavy target) at two energies 31·A MeV and 38·A MeV were used to elucidate the effect of the neutron content of the target on the production of neutron-rich isotopes of light elements.

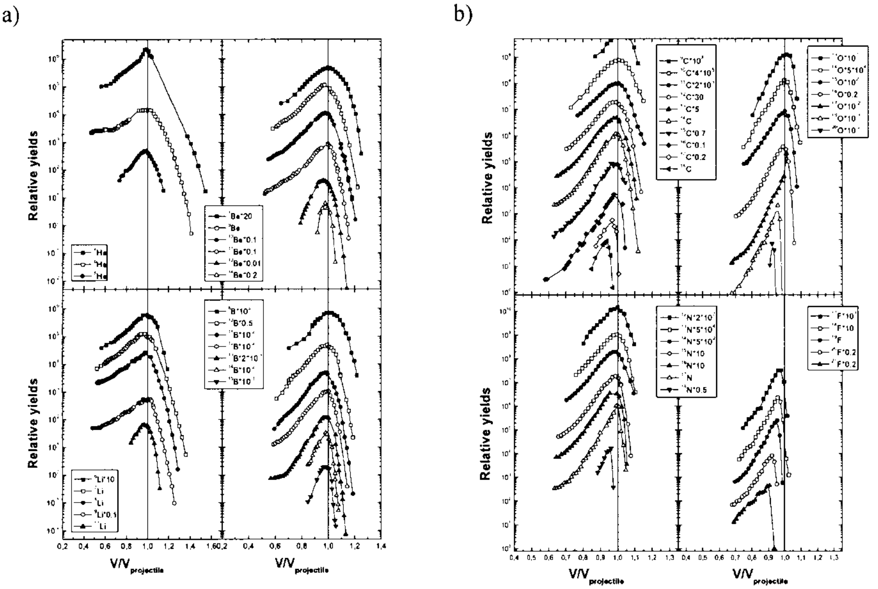

Fig. 8. Forward-angle inclusive velocity distributions of isotopes with atomic numbers $2 \leq Z \leq 9$ in the reaction ^{18}O(35·A MeV) + ^{181}Ta

Forward-angle yields of projectile-like fragments with mass numbers $15 \leq A \leq 45$ and atomic numbers $5 \leq Z \leq 20$ were measured. The bulk of experimental data which was obtained is currently under processing and analysis. The production rates of exotic nuclei which could be used as secondary radioactive beams: ^{20}N (10^3 pps), ^{21}N ($3 \cdot 10^3$ pps), ^{21}O ($3 \cdot 10^4$ pps), ^{22}O (10^4 pps), ^{23}O (10^3 pps), ^{24}O (10^2 pps), ^{23}F ($2 \cdot 10^5$ pps), ^{24}F ($3 \cdot 10^4$ pps), ^{25}F (10^3 pps), ^{26}F ($3 \cdot 10^2$ pps), ^{26}Ne ($6 \cdot 10^4$ pps), ^{27}Ne (10^4 pps), ^{28}Ne (10^3 pps) and ^{29}Ne (10^2 pps) have been determined [19].

High-resolution beam-line ACCULINNA

A series of experiments aimed at the ^{5}H nucleus produced in the ^{3}H+^{3}H reaction was carried out [20]. In the present study the protons were detected in a range of θ_{lab}=173°–155°, corresponding, in CM system, to a very backward direction branch (θ_{CM}=176°–165°). The experimental set up employed in these experiments is shown in Fig. 9. Protons were detected by an annular Si detector supplied with strips on both sides (32 sectors on one side and 32 rings on another side, each ring being 0.8 mm in width). Another such detector was used to measure the energy loss ΔE left by tritons recorded by the triton telescope in the forward direction. Three 1 mm thick annular Si detectors accomplished the energy measurements for these tritons. 49 DEMON modules installed in forward direction 2.5 m apart from the target detected neutrons originating from the ^{5}H system. By detecting triple p-t-n coincidence events it was possible to restore the complete kinematics for the ^{3}H+^{3}H→t+n+n+p reaction channel.

The cryogenic tritium target having double (2×6μ) stainless steel windows on its both sides was bombarded with 58 MeV tritons. The ACCULINNA beam line was used to obtain a high quality triton beam, which was focused in a 5 mm spot on the target window. The energy spread of this beam (the full width of the distribution) was 0.5 MeV.

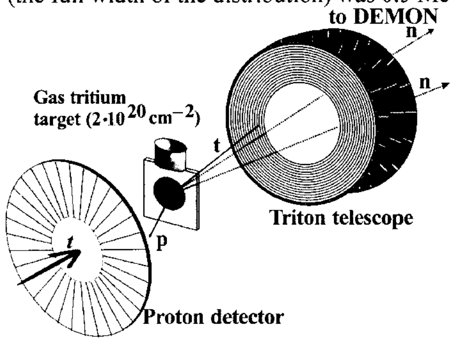

Fig. 9. Detector array and target

Except auxiliary irradiations, two main series of experiment were performed with the triton telescope installed 22.5 and 15 cm apart from the target. These two installations differ in the detection efficiency for the ^{5}H system obtained with different excitation energy. The close setting of the triton telescope well matched the ^{5}H excitation range between 3 and 5 MeV and had a reduced efficiency in the lower region of the ^{5}H energy. On the contrary, the far setting was effective for low energy ^{5}H and missed its "di-neutron" decay mode at E_{5H}>3 MeV.

The beam intensity bombarding the target was 1.5×10^7 s^{-1}, on average, and beam doses of 4.6×10^{13} and 1.3×10^{13} were collected, respectively, in the experiments made with the "far" and "close" settings.

So far, only preliminary results of analysis are obtained for the data collected in the "close" setting bombardments. Therefore conclusions about the ground-state ^{5}H resonance must await the complete analysis of the data obtained at both sets.

The ^{5}H energy spectrum obtained in the "close" setting experiments is shown in Fig. 10 by points supplied with error bars. Circles in this figure show the phase space continuum simulated taking into account the final state n-n interaction. An excess in the experimental spectrum obtained over this continuum between 2.5 and 3.5 MeV is almost entirely due to the l=2 contribution. Perhaps this implies that the excited $5/2^+$ and $3/2^+$ states of ^{5}H are responsible for this noticeable excess [21].

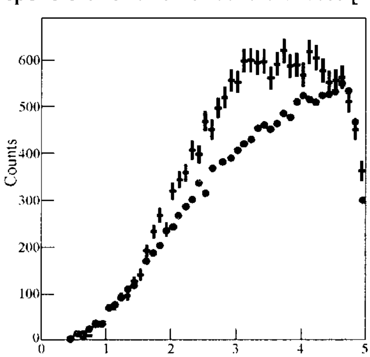

Fig. 10. ^{5}H energy spectrum obtained in "close" geometry.

Final conclusions about the ^{5}H propertied inferred from these experiments must await the complete data analysis. In particular, the analysis will be performed in terms of K-harmonics.

Reactions induced by stable and radioactive ion beams of light elements

In the framework of DRIBs experiments preparation, the elastic and inelastic scattering of ^{6}Li, being an isobar with ^{6}He, has been studied. The reaction products were detected using the magnetic analyzer MSP-144. The angular distribution in the case of the elastic scattering was considered in the framework of the optical model, and for the analysis of the inelastic scattering data the same parameters were applied. Good agreement between experiment and calculations was achieved. The derived parameters of the optical potential will be used for comparison of the data on elastic and inelastic scattering of ^{6}He, received on installation DRIBS.

In collaboration DUBNA-GANIL, experiments on the synthesis of neutron rich isotopes of fluorine, neon, sodium and magnesium were carried out. The isotopes ^{29,31}F, ^{30,32}Ne, ^{37}Na and $^{36\text{-}38}$Mg have been observed for the first time (Fig. 11). It was impossible to produce the magic nucleus ^{40}Mg. Analysis of the properties of these nuclei was performed using the self-consistent theory of finite Fermi systems. One can conclude that the known magic numbers N=20 and N=28 disappear, and that the new N=16 and N=26 magic numbers appear at the boundaries of neutron stability [23].

Z/N	17	18	19	20	21	22	23	24	25	26	27	28
12		*^{30}Mg 335*	*^{31}Mg 230*	*^{32}Mg 95ms*	*^{33}Mg 90ms*	*^{34}Mg 20ms*	*^{35}Mg 70ms*	**^{36}Mg**	**^{37}Mg**	**^{38}Mg**		**^{40}Mg**
11	*^{28}Na 30.5*	*^{29}Na 44.9*	*^{30}Na 48ms*	*^{31}Na 17.0*	*^{32}Na 12.9*	*^{33}Na 8.4ms*	*^{34}Na 5.5ms*	*^{35}Na 1.5ms*		**^{37}Na**		
10	*^{27}Ne 32ms*	*^{28}Ne 18ms*	*^{29}Ne 15.6*	**^{30}Ne** 7.5ms	*^{31}Ne 3.4ms*	**^{32}Ne** 3.5ms		**^{34}Ne**				
9	*^{26}F 10.2*	*^{27}F 6.5ms*		**^{29}F** 2.9ms		**^{31}F**						
8		**^{26}O***		**^{28}O***								

Fig. 11. Chart of the neutron rich O-Mg nuclides. Nuclei observed for the first time are written in bold, nucleon instable oxygen nuclei are marked (*).

With the purpose of preparation of a technique of laser spectroscopy of fission fragments (within the framework of project DRIBS-2) on laser spectrometer LNR-JINR, experiments on laser spectroscopy of stable isotopes have been carried out with the purpose of definition of their root-mean-square charging radius, magnetic dipole and electric quadrupole of the moments of nucleus.

Yields of Kr and Xe isotopes were independently measured in the photofission of heavy nuclei ^{232}Th, ^{238}U and ^{244}Pu at the FLNR MT-25 microtron bremsstrahlung [24].

Using resonance laser spectrometry, measurements were carried out of the hyperfine optical line splitting in the atomic spectra of rare-earth elements Nd, Sm, Eu, Gd and Lu. The magnetic dipole and electric quadrupole splitting constants were determined for isotopes of the indicated elements and for $^{90,91,92,94,96}Zr$. The measurements with heavier isotopes $^{96\text{-}102}Zr$ have been performed on a cyclotron of the Yuvaskyula university. The charge radii of argon isotopes between two closed neutron shells N=20 and N=28 were measured. The obtained results are an essential contribution to the charge radii systematics for the region of Z=20 and $20 \leq N \leq 28$, in which it is expected that the nuclear structure undergoes inversion and shell numbers change.

Theoretical and computational physics

Detailed analysis of reaction dynamics of superheavy nucleus formation and decay at beam energies near the Coulomb barrier has been performed [9]. Main attention was paid to the dynamics of formation of very heavy compound nuclei taking place in strong competition with the process of fast fission (quasi-fission). The choice of collective degrees of freedom playing a principal role, finding the multi-dimensional driving potential and the corresponding dynamic equation regulating the whole process have been studied. Thorough theoretical analysis of available experimental data on the "cold" and "hot" fusion-fission reactions has been performed and the perspectives of future experiments have been reviewed along with additional theoretical studies in this field needed for deeper understanding of the fusion-fission processes of very heavy nuclear systems.

Langevin equations combined with statistical model for neutron evaporation have been successfully used for analysis of the fusion-fission reactions leading to formation of superheavy nuclei [25]. Mass distribution of fission and quasi-fission fragments was calculated and a reasonable agreement with experimental data was obtained. It was found that probability for neutron evaporation on reaction stage before CN formation is negligibly small. This fact is very important for applicability of statistical model for description of decay of low excited compound nucleus.

From the analysis of appropriate experimental data within a simple theoretical model it was clearly shown for the first time that the neutron transfer channels with positive Q-values really enhance the fusion cross section at sub-barrier energies [26]. In the process of "sequential fusion" an intermediate neutron transfer to the states with Q>0 is, in a certain sense, an "energy lift" for the two interacting nuclei. The effect was found to be very large especially for fusion of weakly bound nuclei. New experiments have been proposed, in which the effect will be clearly distinguished.

Applied research

Investigation of radiation damage physics of alloys, monocrystals and polymers at their bombardment with heavy ions

To develop the method of forming monodisperse quantum-dimensional extractions of high volumetric density in solids (Patent of the Russian Federation No 2193080 of 20.08.02), experiments have been conducted to study the influence of the radiation dose by 17-40 keV helium ions on forming a superlattice of helium nanopores in aluminium, molybdenum, nickel and stainless steel. The investigations have shown that the threshold dose of irradiation to form a superlattice of helium nanopores is higher than $3 \cdot 10^{17}$ cm^{-2}, temperature

of irradiation - not more 1000 degrees C. The nanopore size is 2-4 nm, superlattice parameter - 4-7 nm. Research on the influence of the superlattice of helium nanopores on the hardening of metals has been conducted. Preliminary work is in progress on irradiation of samples of aluminium and molybdenum with the superlattice of helium nanopores on the ECR source by Fe ions in order to form Fe nanoextractions. Samples of aluminium, molybdenum and silicon with a sprayed Ni layer for irradiation on ECR by helium ions have been prepared to study the opportunity of forming nickel nanoextractions at the simultaneous process of forming a superlattice of nanopores and their ballistic filling by nickel atoms.
Experiments were conducted to study the opportunity of using high energy heavy ions for ionic - track lithography on polymeric materials. It is supposed to study a role of elastic scattering of ions on materials of immersing masks, when forming the boundaries of the irradiated and unirradiated surfaces and realizing the requirements on minimization of the ionic action zones down to micron sizes.

Obtaining of data on modification of polymers exposed to heavy ions

Opportunities of modification of a contour of the surface of polyimide (PI) and polyethylene terephthalate (PET) films were explored with the purpose of improving the adhesion of superimposed metal layers. Depth of the contour was varied by changing the energy of bombarding ions, angles of entering the ions in the polymer and requirements on chemical treatment after ion irradiation. The strength and longevity of the obtained compounds polymer / metal were investigated. Determined were optimal values of the process of ion modification of polymeric surfaces. The obtained results were used in the new technology of producing pliable printed circuit boards.

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. A feasibility of production of thick "blotting" membranes and membranes of the «wells with a porous bottom» type was investigated.

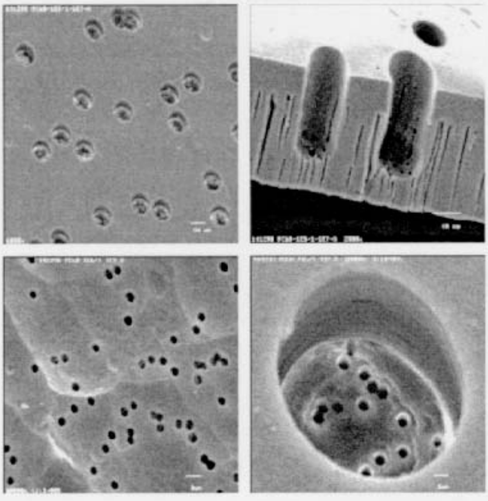

Fig. 12. Membranes with profiled pore channels - «wells with a porous bottom»

Development of methods of obtaining ultra-pure radionuclides

Results are tabulated in Table 1.

	Reaction	E (MeV)	Irradiation time	Yield, Bq
^{149}Tb	(97%)^{142}Nd (^{12}C, xn) ^{149}Dy → ^{149}Tb	120	8-10 h.	(1,5-3,0) 10^{9}
^{225}Ac	^{226}Ra (γ, n) ^{225}Ra→^{225}Ac	24	100 h. at 20 μA electron beam of MT25	10^{9}/g ^{226}Ra
^{237}U	^{238}U (γ, n) ^{237}U	24	10 h. at 15 μA electron beam of MT25	1,5$10^{6}$/15μA 10 mg^{238}U
^{235}Np	^{235}U(d, 2n) ^{235}Np	18	10 hours	3,5 10^{3}

Development of the accelerator of heavy ions and protons DC-72

The electromagnet of the DC-72 cyclotron has been manufactured. The diameter of the electromagnet's pole is equal to 2.6 m, its weight - about 330 tons (Fig. 13) The electromagnet was assembled and prepared for magnetic field topography measurements and shimming.

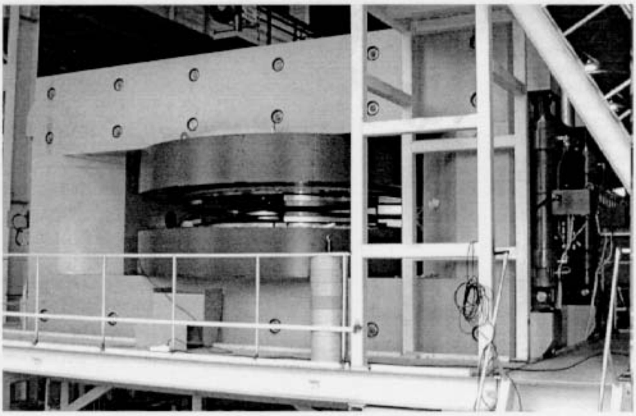

Fig. 13. Electromagnet of the DC-72 cyclotron.

Physics and heavy ion accelerator techniques

Development of the accelerator technique was focused on the realization of the project DRIBs (production of radioactive ion beams at Dubna cyclotrons) This project after its initial fast progress has slowed down due to inadequate financing. According to the schedule of stage I of the project, a complex for the generation of exotic radioactive nuclei of ^{6}He or ^{8}He in the interaction of beams of ^{7}Li or ^{11}B (produced on the U-400M cyclotron), ionization and separation of ^{6}He and ^{8}He ions was created and tested. at the ^{7}Li beam of the U-400M cyclotron. A radioactive ^{6}He beam was transported from the U-400M hall to a distance of 120 m and accelerated up to an energy of 15 MeV/A using the cyclotron U-400. The efficiency of the whole process was 1.5% (1.5$\cdot$$10^{-2}$ of the nuclei produced in the target were transformed into beams).

Systems for diagnostics of the extracted from U-400 ^{6}He and ^{8}He beams, the vacuum system for the beam lines and physical set-ups as well as control systems were developed. The experiments with accelerated ^{6}He ion beams were postponed to the end of 2004 due to the lack of financing of this part of the project.

Intensive research and design works were underway in the framework of the Project DRIBs (phase II). They included: modernization of the microtron's systems, design and testing of the target-ion source complex, design of a transport line for beams of single-charged ions – products of uranium photofission, development of the charge breeder on the basis of the ECR ion source. Unfortunately, these parts of the Project, which have already been prepared for the realization, are not provided with the financial support.

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