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FLEROV LABORATORY OF NUCLEAR REACTIONS

RESEARCH ACTIVITIES IN 2001

Report to the 91st Session
of the JINR Scientific Council
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The 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. These investigations are grouped in 15 projects within the framework of three topics and an all-Institute project:

- Synthesis of new nuclei and study of nuclear properties and heavy ion reaction mechanisms (9 projects);
- Radiation effects and modification of materials, radioanalytical and radioisotopic investigations at the FLNR accelerators (4 projects);
- Development of the FLNR cyclotron complex for producing intensive beams of accelerated ions of stable and radioactive isotopes (2 projects);
- Development of the U400+U400M+MT25 cyclotron-microtron complex for producing radioactive ion beams (DRIBs – project).

Reliable performance of the FLNR accelerators is a prerequisite for successful experiments and technical development. The first stage of DRIBs – production of light radioactive ion beams – should be realized in 2001, thus we have really to estimate, how much time we have to put to the experimental research programs and how much time has to be taken for DRIBs project.

The U400 and U400M FLNR cyclotrons running time in 2001 was close to 7000 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 2001 is shown in the tables:

Set-Up on U400	Beam-time
DGFRS	2100
VASSILISSA	500
CORSET	750
Chemistry	700
Appl. Res.	350
DRIBs	700
Others	250
Total:	5350

Set-Up on U400M	Beam-time
ACCULINNA	400
MULTI	300
COMBAS	250
FOBOS	50
DRIBs	700
Total:	1700

Synthesis of new elements

An important achievement of the Laboratory is the experimental proof of predictions of the macro-microscopic theory concerning the existence of spherical shells with $Z \approx 114$ and $N \approx 184$. This achievement inspires hope that approaching the boundaries of this unknown region where the influence of the N=184 spherical shell becomes noticeable has become a reality in fusion reactions using the heaviest isotopes of U, Pu, Cm as targets and a ^{48}Ca ion beam.

During January and April-July, 2001, we continued the experiments aimed at the synthesis of superheavy nuclei with Z=116 in the complete fusion reaction $^{248}Cm+^{48}Ca$ using the Dubna Gas-Filled Recoil Separator. The beam dose of ^{48}Ca projectiles of 1.5×10^{19} was collected.

To improve background conditions for detecting long-time decay sequences, a special measurement mode was employed. The beam was switched off after a recoil signal was detected with parameters of implantation energy and time-of-flight system expected for Z=116 evaporation residues, followed by an α-like signal with an energy of $10.0 \le E_\alpha(\mathrm{MeV}) \le 11.5$, in the same strip, within a position window Δy=2 mm and time intervals of up to 5 s. The duration of the pause was determined from the observed pattern of out-of-beam α-decays and varied from 2 to 60 minutes. Thus, all the expected sequential decays of the daughter nuclides with Z≤114 could be observed in the absence of beam-associated background.

During these irradiations two more similar identical decay sequences of genetically linked events were observed, each consisting of an implanted heavy atom, three subsequent α-decays, and terminated by spontaneous fission. These three decay chains (including the first one observed in 2000, see fig.1) can be assigned to the implantation and decay of the heavy nuclide with Z=116. The energies and decay times of the descendant nuclei are in agreement with those observed in the decay chains of even-even isotope $^{288}114$ produced in the $^{244}Pu+^{48}Ca$ reaction. Thus, the primary α-decays in chains should be attributed to the parent nuclide $^{292}116$, produced via evaporation of four neutrons. $^{292}116$, $^{288}114$ and $^{284}112$ are the heaviest known α-decaying even-even nuclides.

As a result of these investigations performed during 1998 – 2001 decays of the heaviest nuclei ^{277}Hs (Z=108), $^{280,281}110$, $^{283,284,285}112$, $^{287,288,289}114$ and $^{292}116$ were observed.

The experimental results are summarized in Table 1 and the decay properties of the heaviest Hs - $^{292}116$ isotopes are presented in Table 2.

Table 1.

Date	Target	Excit. energy E^* (MeV)	Beam dose ($*10^{18}$)	Nucleus detected	Num. of events	Cross sect. (pb)
March, 1998	^{238}U	31.0	3.5	$^{283}112$	2	5
Nov. – Dec., 1998	^{244}Pu	35.0	5.2	$^{289}114$	1	1
March, 1999	^{242}Pu	33.5	7.5	$^{287}114$	2	2.5
June – Oct., 1999	^{244}Pu	35.3	10	$^{288}114$	2	1
June, 2000 – May, 2001	^{248}Cm	33.1	23	$^{292}116$	3	0.5
May – July, 2001	^{248}Cm	30.4	8.0	$^{293}116$	0	< 0.5

Table 2.

Isotope	Decay mode	E_α (MeV)	TKE_{mes} (MeV)	$T_{1/2}$
^{277}Hs	SF		170	11 m
$^{280}110$	SF		210	7.6 s
$^{281}110$	α	8.83		1.1 m
$^{283}112$	SF		190	3 m
$^{284}112$	α	9.17		44.3 s
$^{285}112$	α	8.67		11 m
$^{287}114$	α	10.29		5 s
$^{288}114$	α	9.83		2.6 s
$^{289}114$	α	9.71		21 s
$^{292}116$	α	10.56		52.5 ms

What can we learn from the analysis of the whole set of the data?

In reactions with ^{48}Ca at a bombarding energy close to the Coulomb barrier a maximum yield for the 3n- and 4n-evaporation channels is expected. Evaporation channels accompanied by the emission of charged particles (protons, α-particles) are strongly suppressed.

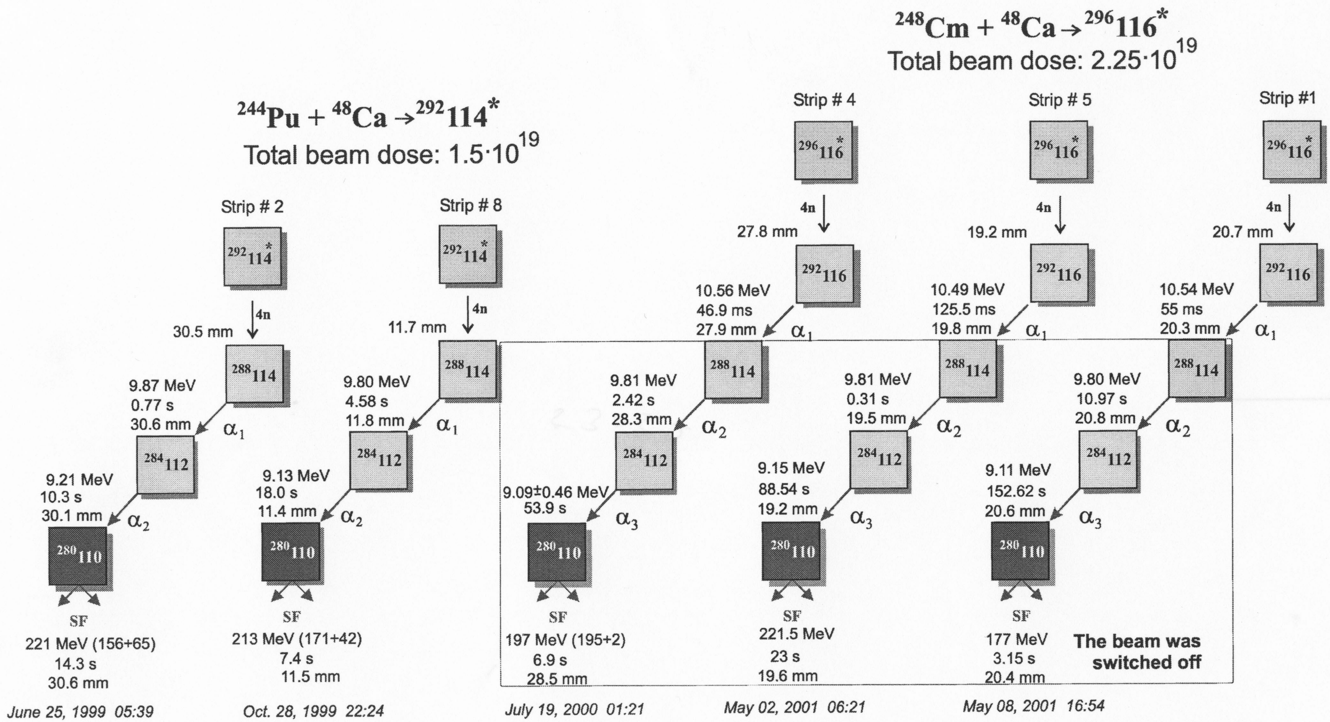

Fig. 1.Decay sequences of the nuclei observed in the reactions $^{244}Pu+^{48}Ca$ and $^{248}Cm+^{48}Ca$

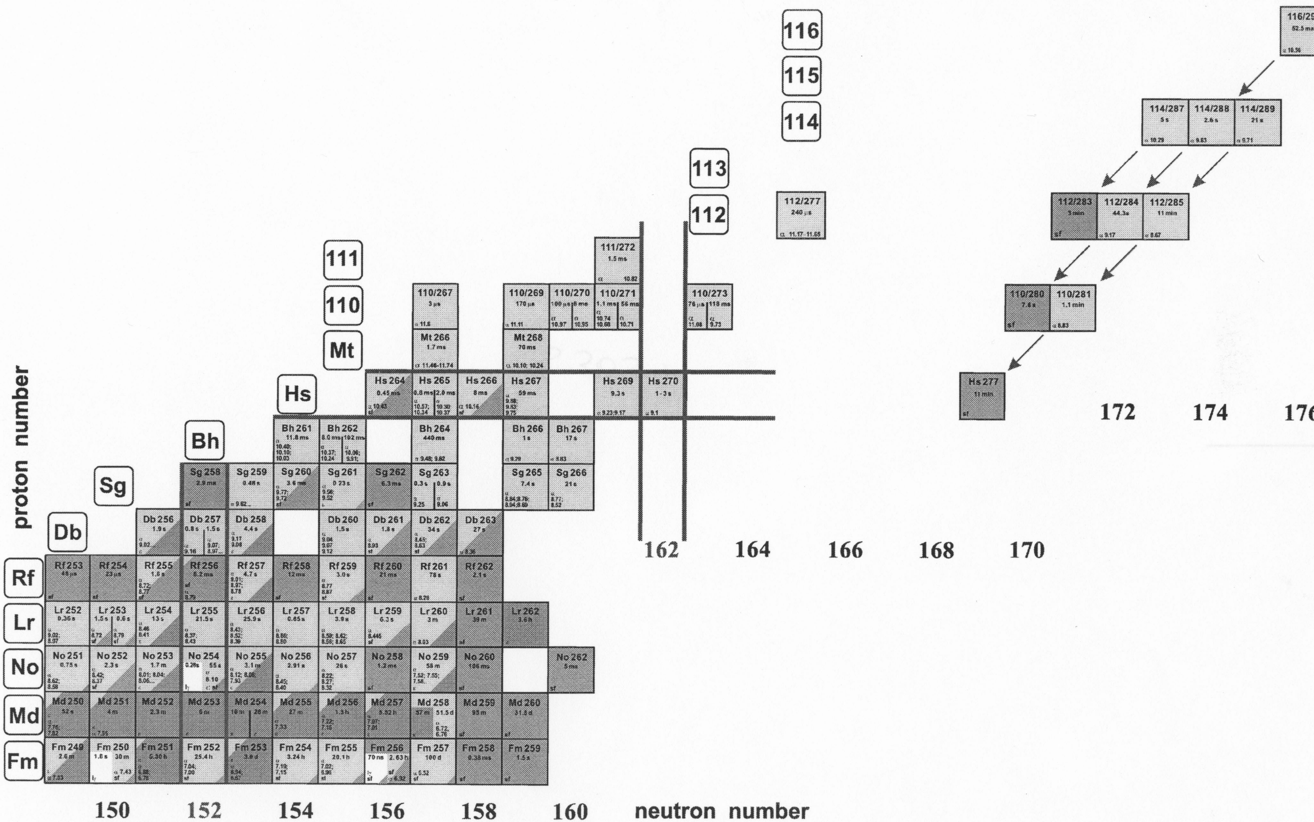

Fig. 2.Chart of the nuclides of the transfermium elements

For all events of sequential α-decays the energies and decay probabilities obey the basic rule of Geiger-Nuttall, which connects the α-decay energy Q_α and the half-life T_α and imply decays of nuclei with large atomic numbers Z=110 ÷ 116 (fig.3).

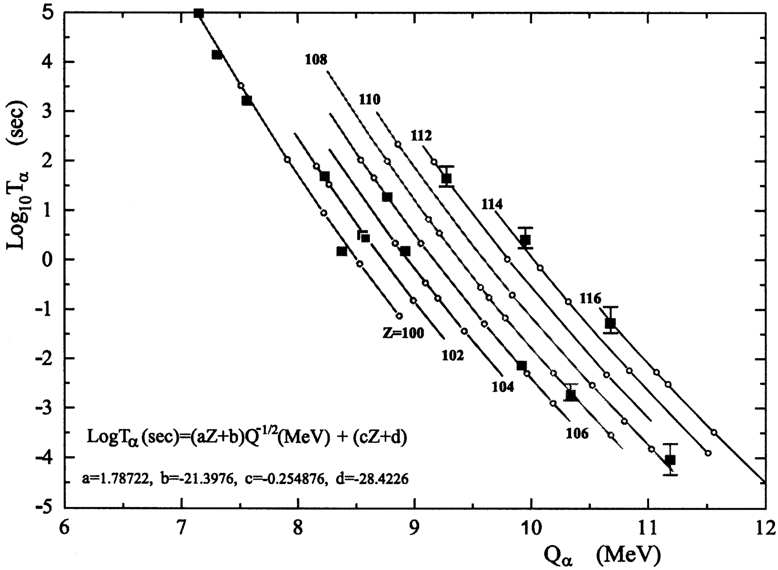

Fig.3. A plot of $LogT_\alpha$ vs Q_α (the rule of Geiger-Nuttall) for even-even nuclides with Z≥100

The spontaneous fission events with TKE ≈200 MeV are related to the decay of considerably long-lived nuclei (T_{sf} ≈10÷1000 s) with Z ≥ 106 that are «children» or "grandchildren" of heavier nuclei.

The significant increase in the lifetimes of $^{281}110$ with respect to the $^{273}110$ by a factor of $8\cdot10^5$ and of $^{285}112$ with respect to the $^{277}112$ by a factor of $2.7\cdot10^6$ can be considered as an indication on the presence of nuclear shells at higher neutron numbers (see fig. 2).

Comparing the half-life of $^{292}116$ ($T_{1/2}$=52.5 ms) and that of its daughter $^{288}114$ ($T_{1/2}$ = 2.6s, one can suppose, that Z=114 is probably a proton shell. There is also an indication, that this shell is a spherical one. In the limits of the detector energy resolution and the statistical uncertainty in the decay times, all the three α-decays of $^{288}114$ can be attributed to the decay from the ground state, which is populated after decay of the evaporation residue or after the α-decay of the parent nucleus $^{292}116$. This can be compared with the decay of $^{277}112$, which populate different levels in deformed (due to the predicted neutron shell N=162) $^{273}110$. The three observed α transition differ by 0.5 MeV.

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).

We presented for consideration by the IUPAC our results on the synthesis of superheavy nuclides with Z=112, 114 and 116 in the fusion reactions of actinide targets with ^{48}Ca ions.

During the period of 2002-2004, the investigations will be aimed at the synthesis of nuclei with Z ~115-118 in the ^{243}Am, $^{249}Cf+^{48}Ca$ reactions. Both facilities - VASSILISSA and the Gas-Filled Recoil Separator (GFRS) - will be used in these experiments in a wide international collaboration.

Chemistry of transactinides

Relatively long half-lives of the isotopes with Z=108 ÷ 114, obtained in ^{48}Ca-induced reactions, open up new opportunities for the investigation of chemical properties of superheavy elements. Quasi-on-line mass separation or chemical separation can be employed. These methods have sufficient advantages in the effective target thickness (factor of ≈10) and in the beam acceptability.

The first attempt on chemical identification of element 112 was performed at the Dubna U-400 cyclotron in January 2000. The 3-min $^{283}112$ can be produced with a cross section of about 5 pb in the reaction $^{238}U(^{48}Ca,3n)$. 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. After 10 days of irradiation with ^{48}Ca ions an integral beam dose of $6.9 \cdot 10^{17}$ was accumulated. During this bombardment, no SF events were observed. The experiment does not give an unambiguous answer about physical and chemical properties of element 112.

The next experiment on chemical isolation of element 112 was performed in November – December 2001. The detection system was extended: the ionization chamber was placed downstream after the 8 pairs of the Au-plated PIPS detectors. The chamber and the PIPS-detectors were positioned inside the neutron multiplicity counter (fig. 4). The ionization chamber was able to detect spontaneous fission of Rn-like reaction products in flowing gas during 5÷10 min depending on flow rate.

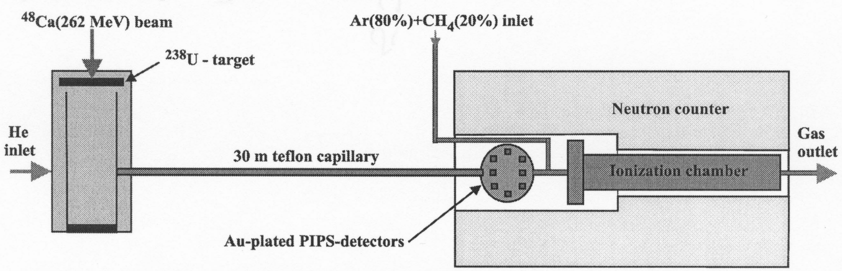

Fig. 4. Schematic view of the set-up for isolation and identification of element 112.

A 2-mg/cm^2 $^{238}U_3O_8$ target was deposited onto a 2 μm HAVAR foil and contained also 100 μg of natural Nd. Recoils were thermalized in pure helium and transported through 30 m long capillary to the detection apparatus. There were 8 detection chambers in series. The adsorption of the Hg atoms formed in reaction $Nd(^{48}Ca; xn)$ was measured through 5.65-MeV α-particles of ^{185}Hg. After the PIPS-detector chamber $Ar+CH_4$ mixture was added to the gas.

After 20 days of irradiation with ^{48}Ca ions an integral beam dose of $4 \cdot 10^{18}$ was accumulated. During this bombardment, no SF events were detected by the PIPS-detectors. Several spontaneous fission events with multiple neutrons were detected by the ionization chamber. Now control experiments and background measurements are running. The next step of this work will depend on the obtained results.

The first results on the properties of Hs (Z=108) were obtained with scientists from Switzerland, Germany and USA.

Planned for 2002 – 2004 is the on-line chemical isolation and identification of heavy isotopes and detection of the α-decay and spontaneous fission fragments in coincidence with neutrons. A series of collaborative experiments is planned for 2002 - 2004 at the FLNR together with scientists from Germany: (GSI, Darmstadt; University, München; University, Mainz), PSI (Villigen, Switzerland) and NINP (Cracow, Poland).

Separator "MASHA"

Long lifetime makes it possible to change the approach to the synthesis of superheavy nuclei. If we have a short lifetime of micro- or milliseconds we need the on-line in beam separation. All existing recoil separators have similar limitations: to keep kinematic conditions one needs thin targets approximately 0.3 mg/cm^2. But the recoil range in typical target material is much higher and one could use targets with thickness of about 2 mg/cm^2. The properties of superheavy elements are predicted to be similar to that of volatile elements Hg, Tl, Pb, Bi, Po, At or Rn, thus one can think about an off-line separator. In that case we can get the definite information about the mass of nuclides. Today we have finished the design of the separator "MASHA" (Mass Analyzer of Super Heavy Atoms, fig.5).

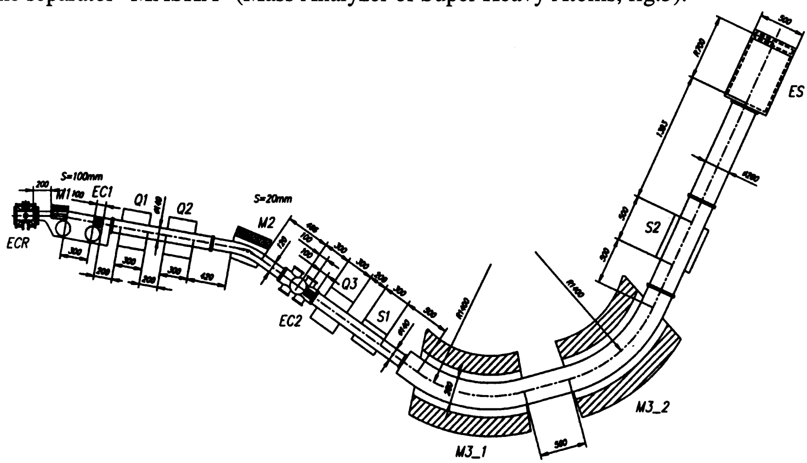

Fig. 5. Separator "MASHA".

The projectiles and recoils are stopped in catcher that has high temperature of ≈2500° C and volatile products will diffuse to the ion source. We plan to use the 2.4 GHz ECR-ion source at low He pressure of 10^{-5} mbar to get the single charged ions. After extraction from ECR the ion beam will be prepared for preseparation. In the intermediate focus masses around A≈300 are separated from masses around A≈250 (target-like transfer reaction products). After the main magnetic separator on the focal plan we expect the mass resolution of about 1000. The first experiments with this separator are planned for 2003.

Nuclear fission

In the framework of the collaboration FLNR-IReS-LPC-ULB-Texas A&M University-INFN, the mechanisms of formation and decay of heavy and superheavy 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 set-up. The experiments were carried out at the accelerators of the FLNR, Texas

A&M University and INFN. At energies close to and below the Coulomb barrier fission properties of the compound nuclei $^{216,218,220}Ra$, ^{256}No, ^{270}Sg, $^{266,271,274}Hs$, $^{286}112$, $^{292}114$, $^{290,296}116$, $^{294}118$, $^{302}120$ and $^{306}122$ were studied for the first time.

It was found, that the mass distribution of fission fragments for compound nuclei $^{216,218,220}Ra$, $^{286}112$, $^{292}114$, $^{290,296}116$, $^{302}120$ and $^{306}122$ is 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 (fig. 5,6)

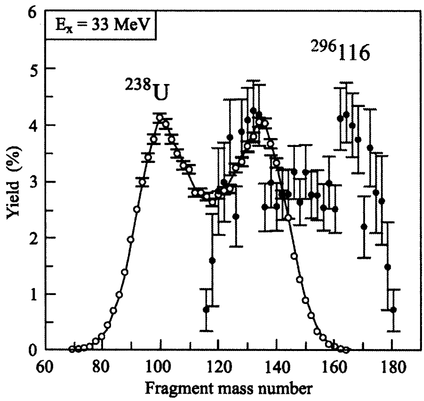

Fig. 6. Mass distribution of fission fragments of ^{238}U and $^{296}116$ compound system at low excitation energy.

For the detection of neutrons 49 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. These investigations showed that TKE, neutron and γ-ray multiplicities for fission and quasi-fission of superheavy compound nuclei are significantly different.

The dependence of the capture (σ_c) and fusion-fission (σ_{ff}) cross sections for nuclei ^{256}No, $^{266,274}Hs$, $^{286}112$, $^{292}114$, $^{296}116$, $^{294}118$ and $^{306}122$ on the excitation energy in the range 15–60 MeV has been studied. It should be emphasized that the fusion-fission cross section for the compound nuclei produced in reaction with ^{48}Ca and ^{58}Fe ions at excitation energy of $\approx$30 MeV depends only slightly on reaction partners, that is, as one goes from $^{286}112$ to $^{306}122$, the σ_{ff} changes no more than by the factor 4–5. This property seems to be of considerable importance in planning and carrying out experiments on the synthesis of superheavy nuclei with Z>114 in reaction with ^{48}Ca and ^{58}Fe ions.

In the case of the reaction $^{86}Kr+^{208}Pb$, leading to the production of the composite system $^{294}118$, contrary to reactions with ^{48}Ca and ^{58}Fe, the contribution of quasi-fission is dominant in the region of the fragment masses close to A/2

In the region of heavy nuclei $^{216,218,220}Ra$ and ^{256}No, ^{270}Sg and $^{266,271,274}Hs$ the phenomenon of multimodal fission was first observed and studied.

During 2002 – 2004 investigation of fusion-fission and quasi-fission cross sections in reactions between ^{48}Ca, ^{58}Fe and ^{64}Ni ions and ^{238}U, ^{244}Pu, ^{248}Cm and ^{249}Cf targets leading to the formation of nuclear systems with Z=112÷122 together with the study of neutron and γ-quanta multiplicities in the fission of superheavy nuclei with Z=116÷122 are planned. As first experiments with DRIBs measurements of characteristics of low energy fission of neutron-reach Th, Cm and Cf isotopes, produced in ^6He and ^8He induced reactions on ^{226}Ra, ^{244}Pu and ^{248}Cm targets will be performed. Experiments will be carried out in collaboration with GSI (Darmstadt, Germany), INPN (Catania, Italy), IReS (Strasbourg, France), ISN (Grenoble, France), University of Brussels (Belgium), University of Texas (USA), IP (Bratislava, Slovakia) and INP (Almaty, Kazakhstan).

Separator VASSILISSA

In 2001 in order to obtain the possibility to provide the mass determination of the newly synthesized superheavy nuclides the new dipole magnet with deflection angle 37^o was installed as postseparator after VASSILISSA. The new detection system consisting of TOF-detectors, the new focal plane 32 strip 60×120 mm^2 detector and corresponding data acquisition system has been developed.

Test experiments with ^{40}Ar, ^{48}Ca beams and Dy, Yb, Pb targets showed that the post-separator provided the additional suppression of unwanted reaction products by the factor of about 10 and the possibility to have the mass resolution for heavy nuclei with masses of A≈300 at the level of 2.0 %.

For the period of 2002 – 2004 it is planned to continue the experiments on the synthesis of superheavy nuclei in reactions of ^{34}S and ^{48}Ca with ^{232}Th, $^{236,238}U$ and ^{243}Am using the recoil separator VASSILISSA and magnetic mass analyzer. After the upgrade of the high voltage system of VASSILISSA to 250 kV it will be possible to investigate the influence of the shell structure in the entrance channel in the regions of deep subbarrier and above the Coulomb barrier energies for the reaction like $^{86}Kr+^{124}Sn$, ^{136}Xe, $^{136}Xe+^{124}Sn$, ^{136}Xe. As first experiment with DRIBs the fusion process and de-excitation of compound nuclei by evaporation of neutrons, protons and α's will be studied in reactions $^{6,8}He+^{40,44,48}Ca$.

The experimental work is planned to be performed in the collaboration with GSI (Darmstadt, Germany), RIKEN (Saitama, Japan), Comenius University (Bratislava, Slovakia), GANIL (Caen, France), University of Messina (Italy).

Fragment-separator COMBAS

The production of isotopes with the mass numbers $15 \le A \le 40$ and atomic numbers $6 \le Z \le 14$ induced in the inverse kinematic reaction $^{40}Ar + ^9Be$ in the Fermi energy domain (37,5A MeV) has been studied in forward-angle measurements using the fragment-separator COMBAS. No evidence was found for any dramatic change of the reaction mechanisms for peripheral reactions in comparison with the same in the low energy range. The dominant role of stripping, pick-up and exchange nuclear reactions were observed. The yields of isotopes produced in stripping reactions are well approximated with a simple exponential function of Q_{gg}.

The production rates of exotic nuclei $^{20,21}N$, $^{21\text{-}24}O$, $^{23\text{-}26}F$ and $^{26\text{-}30}Ne$ which can be used as secondary radioactive beams have been determined.

In 2002-2004, using intermediate energy projectiles the yields and cluster properties of heavy neutron reach isotopes $^{10\div14}Be$, $^{14\div17}B$, $^{16\div20}C$, $^{20\div24}O$ and $^{23\div26}F$ will be studied at the separator COMBAS in break-up reactions on targets of hydrogen isotopes. Experiments will be carried out in collaboration with the GSI (Darmstadt, Germany) and Comenius University (Bratislava, Slovakia).

High-resolution beam-line ACCULINNA

In order to install a liquid-tritium target the separator ACCULINNA was upgraded. The beam line was extended beyond the 2-meter concrete wall to a newly built hall housing the reaction chamber in which the new, improved performance particle telescopes were installed. For the detection of neutrons 41 DEMON modules were used. The beam monitoring and detector arrays were upgraded in order to fit experiments aimed at the study of ^4H and ^5H produced in reaction with a primary triton beam (fig. 7).

Even though the unstable nuclear systems ^4H and ^5H were studied over more than 40 years, the data on these nuclei remain scarce and often are controversial. To further investigate the resonance states of ^4H and ^5H we used transfer reactions occurring when a liquid tritium (deuterium) target was bombarded with tritons. For this study, an environmentally safe liquid-tritium (deuterium) target was created and installed at the secondary radioactive beam line ACCULINNA, which was used in this case to deliver to the target a 57.5-MeV triton beam accelerated by the U-400M cyclotron. This beam line was used also to cut the angular and energy divergence of the primary triton beam to FWHM values of 7 mrad and 0.3 MeV, respectively. The target cell had a material thickness of 0.4 mm for liquid tritium or deuterium.

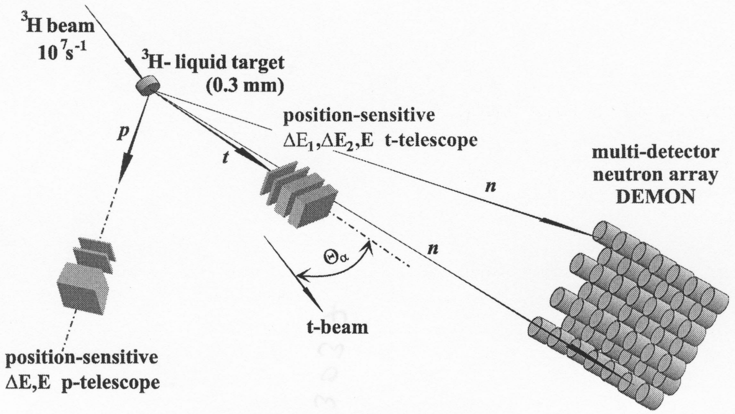

Fig. 7. Modernized detector array of ACCULINNA.

For reactions t+d→p^{4}H, t+t→p+^{5}H and t+t→d+^{4}H we detected protons/deuterons in coincidence with complementary tritons emitted from the target. Two highly granulated Si detector telescopes accomplished this detection. Neutrons emitted in the decay of unstable ^4H and ^5H could be also detected in coincidence with the charged reaction products. Typical beam intensity on the target was $2x10^7$ s^{-1}. Measurements were carried out with the triton and neutron detector arrays set at the optimum angles in a laboratory angular range of 13-33 degrees for protons and deuterons leaving the target.

A state of ^4H with $E_{res}=3.22\pm0.15$ MeV and $\Gamma_{obs}=3.33\pm0.25$ MeV was obtained in t+d reaction from the spectra of protons leaving the target at $\theta_{lab}=18°-32°$ and detected in coincidence with tritons. A valuable fraction of protons detected in t+t reaction at $\theta_{lab}=18°-32°$ in *ptn* coincidence events was attributed to the states of ^5H nucleus. At ≈2.5 MeV above the *tnn* decay threshold the ^5H spectrum shows up a narrow maximum followed by a wide structure at 4-7 MeV (fig. 8).

At the ACCULINNA beam line experiments with cryogenic $^{1,2,3}H$ targets are planned for the period of 2002 – 2004 at the beams of U400M and with DRIBs (ISTRA set-up). Elastic scattering of ^6He and ^8He on the tritium target to the backward hemisphere will be studied in order to get information about the clustering configurations of ^6He in t+t and ^8He in ^5H+t clusters.

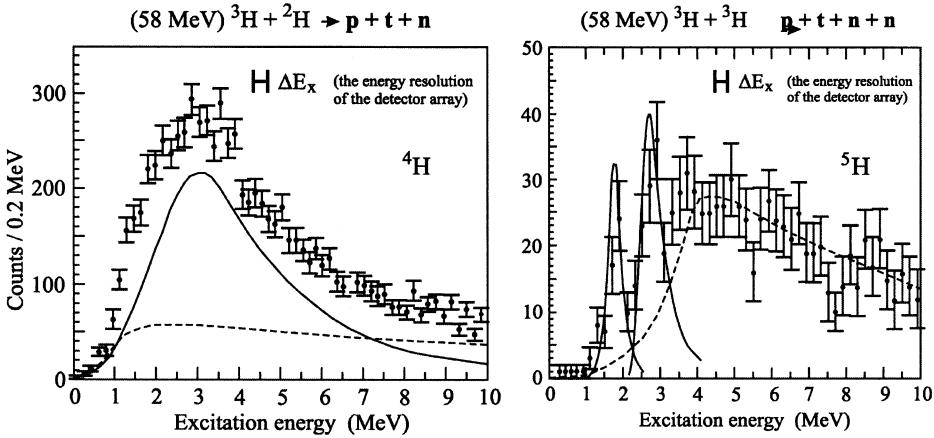

Fig. 8. ^4H and ^5H spectra.

The study of the transfer reaction will be extended to such transfers as: $^8He+^3H\rightarrow^{10}He+p$, $^9Li+^3H\rightarrow^{11}Li+p$, $^6He+^3H\rightarrow^8He+p$, aimed at the study of the halo clustering in $^{6,8}He$ and intended to the search for possible structures in the tetra-neutron system. New excited states in ^{11}Li and ^8He populated in reactions will be searched for. The work will be performed in collaboration with the groups of GSI (Darmstadt, Germany), GANIL (Caen, France), YerPhI (Yerevan, Armenia), RIKEN (Saitama, Japan), Kurcharov Institute (Moscow, Russia), Comenius University (Bratislava, Slovakia).

Reactions induced by stable and radioactive ion beams of light elements

On a secondary ^6He beam, formed with the help of a special channel (Q4DQ spectrometer) of the U-400M cyclotron experiments were carried out on measuring the excitation functions of $^6He+^{209}Bi$ fusion-fission reactions. The beam intensity was $5\cdot10^4$ pps. The excitation function was measured in the energy range 25-70 MeV. Also measured was the 4n evaporation decay channel of the ^{215}At compound nucleus produced in this reaction. A comparison of the experimental data with ALICE-MP-code calculated data showed that the values of the angular momentum and radius should be increased by 15-20% as compared to those for the ^4He+Bi reaction. New results were obtained for the energy dependence of the total reaction cross sections σ_R in the energy range 10-28 MeV/A.

In the $^{28}Si(^6He, ^4He)x$ channel reaction cross sections for α-particles emission were measured. In the range of energy of less than 17 MeV/A, the value of σ_R was observed to increase sharply. The energy spectra of the α-particles produced in the interaction of ^6He with silicon are indicative of two production mechanisms: transfer reactions and the break up of ^6He in the field of the ^{28}Si nucleus.

The independent yields of Kr and Xe isotopes were measured for the photofission of the heavy nuclei ^{232}Th, ^{238}U and ^{244}Pu at the FLNR MT-25 microtron bremsstrahlung. The fragments produced were slowed down in a gas and transported by a gas flow through a capillary to a cryostat (see fig. 9). The fragment transportation efficiency was 70% for transportation at a distance of 30 m in a time interval of 2 s (for a distance of 1m, the time was 0.1 s). The Kr and Xe isotopes condensed in the cryostat, and all other elements were absorbed by a filter at the target chamber outlet. The Xe fragments were identified by the γ-radiation spectra of their daughter products.

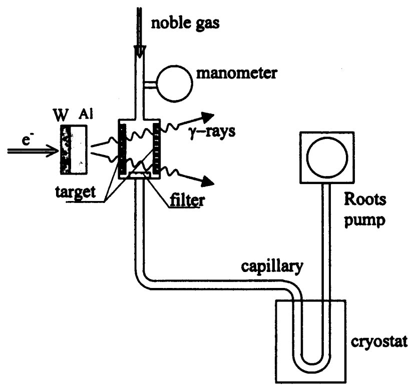

Fig. 9. Set-up for transportation of photofission fragments

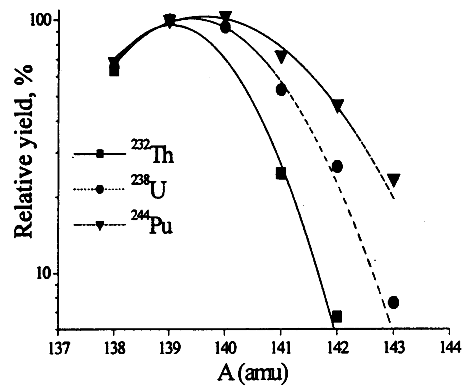

Fig. 10. Yields of Xe isotopes in photofission of ^{232}Th, ^{238}U and ^{244}Pu

The yields of 5 isotopes of Xe were determined. From the dependencies obtained, it is seen that the yields of neutron-rich isotopes increase as the atomic number of the fissioning nucleus increases. The conclusion is made that the use of photofission fragments for studying their properties and for further accelerating within the framework of the DRIBs project is promising.

The GANIL-FLNR collaborative experiments were also continued. In these experiments, research was carried out of the structure and properties of nuclei with neutron shells of N= 20÷28 ($^{30-36}$Mg, $^{26-32}$Ne, $^{22-24}$O, $^{26-29}$F) in the so-called "island of inversion". It was shown that nuclei that have a neutron shell with N close to 20 are deformed. It also follows from the data obtained that in this region there are new magic numbers (N≈16) and that the stability of nuclei with extreme neutron numbers ^{26,28}O, ^{31}F is governed by the deformation of those nuclei.

In collaboration with Jyväskylä University, the decay characteristics of the ^{228}110 compound system produced in the reaction ^{238}U+^{40}Ar at the excitation energy of ~70 MeV were studied. It was found that the fission fragment mass distributions have a structure with peaks corresponding to mass numbers A=70-80, 100 and 130, which can be accounted for by the fact that in this reaction both spherical and deformed magic nuclei (clusters) of Ni, Ge, Sn, Zr, Mo, Tl are produced.

In collaboration with teams from Manchester (England) and Jyväskylä (Finland), the charge radii of the neutron-deficient isotopes of titanium, ^{44}Ti and ^{45}Ti, were measured. The experiments were carried out at the Jyväskylä University's cyclotron. The charge radius of Ti nuclei was found to increase as the neutron number decreases. It is planned to continue these investigations.

Using resonance laser spectrometry, measurements were carried out of the hyperfine optical line splitting in the atomic spectra of the 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. An anomaly was found in the magnetic splitting, which points to the fact that the magnetic moment of those nuclei is distributed in a spatial way.

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. 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 (together with IPC, Moscow, and TRCRE, Takasaki, Japan). It allows creation of "intelligent" membranes with controlled properties.

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 (in cooperation with NPI, Rez, and HMI, Berlin). 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). 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.

In cooperation with the Oak Ridge Laboratory (USA) and the Institute of transuranium elements (Karlsruhe, Germany), 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 500-1000C, 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

1. Methods of production of radioisotopes $^{99m}Tc(^{99}Mo)$, ^{225}Ac and some others employing the (γ,n) reaction at the microtron MT25 were developed.
2. A technique of radiochemical extraction of ^{149}Tb was developed. The dependence of the ^{149}Tb yield in reaction $^{142}Nd(^{12}C, xn)^{149}Dy$ 4,1 min. → ^{149}Tb (x=5÷7) on the ^{12}C ion energy was determined.
3. A combined effect of radionuclides and chemical pollution in Saratov region was estimated. Natural radionuclides were determined; the geochemistry of microelements in seismically active regions (France, Tadjikistan, Krasnodar) was investigated.

Physics and heavy ion accelerator techniques

In 2001, the emphasis was made on the further optimization of the U-400 and U400M cyclotrons and of the ion sources in view of performing experiments on the superheavy element synthesis and of experiments on production of light exotic nuclei.

The main efforts in the development of the accelerator technique were concentrated on the realization of the project DRIBs (production of radioactive ion beams at Dubna cyclotrons).

In March 2001, according to the schedule of realization of the stage I of the project a complex for the generation, ionization and separation of ^{6}He and ^{8}He ions was created and tested at the ^{11}B beam of the U-400M cyclotron. Assembling, adjusting and a long term testing of the system providing transport of RIB from the U-400M cyclotron hall to a distance of 120 m have been realized since July 2001.

In October the transport of ions was realized along the 1/4 of the transport line length. In October and November it is planned to transport the beam into the U-400 hall. In December 2001 the beam of ^{6}He will be accelerated up to the energy of 12 MeV/n using the U-400 cyclotron. The extraction of the ^{6}He beam from the U-400 and delivery to a physical target is planned for June 2002, and the first experiments are scheduled for the second half of 2002.

Using the experiments with the RI-beams we suppose to study during 2002-2004:

- elastic and inelastic scattering of $^{6,8}He$ on the $^{40÷48}Ca$ and Pb targets for testing the parameters of the optical model for halo nuclei (MSP-144 and VASSILISSA),
- fission and fusion reactions induced by ^{6}He, the probability of the full momentum transfer, fission modes of the heaviest Pu÷Cf isotopes (CORSET+DEMON),
- neutron correlations in extra neutron reach H and He isotopes beyond the drip-line (ISTRA).

To realize all the capabilities of the DRIBs we need the further modernization of our experimental set-ups.

We need a more dedicated tritium target. Such a target is now ordered and it will be tested on the U400M to really understand what resolution can we get having monochromatic tritium beam and thin target. The new reaction chamber is also in preparation. These are the main parts of the ISTRA set-up. We will have two extraction lines from U400. One is in the direction where our main experimental set-ups are located, another one will be in an opposite way where we want to put the CORSET for fusion-fission studies and the ISTRA set-up together with DEMON-modules (fig. 11).

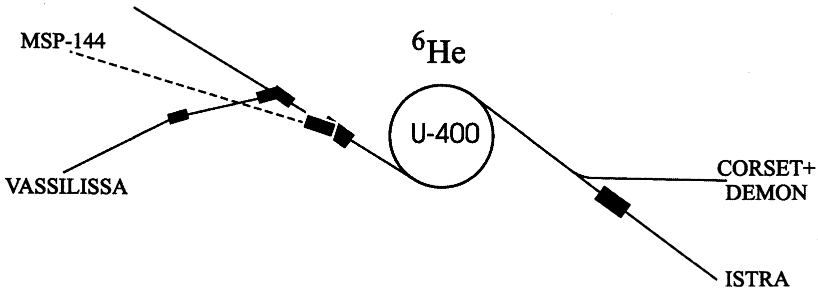

Fig. 11. Beam lines for RI in the U400 experimental hall

We plan also to look for reactions with heavy targets like Cm and Cf in view to come to very heavy isotopes of known elements up to Fm and to study their fission using the neutron multiplicity detectors.

The upgraded VASSILISSA has now the modified time-of-flight detector and also a magnetic analyzer, which allowed obtaining the mass by direct measurements with the accuracy of about 1.2% for superheavy elements. For light nuclei the mass will be defined quite precise. Thus we can get the look for different scenario of interactions of hallo nuclei with "normal" ones.

For the second stage of the DRIBs project the yields of Xe isotopes with A = 137-143 were measured in the photofission of ^{232}Th, ^{238}U and ^{244}Pu. The results point to the fact that photofission reactions are promising for the production of neutron-rich Xe isotopes intended for further acceleration at the cyclotron. In January 2002, it is planned to work out assignments for R&D and manufacturing of the uranium target complex, ion source and separators in the framework of Project DRIBs (stage II). The second stage – acceleration of fission fragments – should be realized in 2002.

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