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Yu.Ts.Oganessian

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Flerov Laboratory of Nuclear Reactions

Report to the 81st Session
of the Scientific Council of JINR
January 16—17, 1997

Dubna 1996

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The Flerov Laboratory of Nuclear Reactions carries out research in heavy ion physics in three main directions. They include experiments with ion beams of stable and radioactive isotopes on the synthesis of heavy and exotic nuclei, the study of nuclear reactions, acceleration technology, heavy ion interaction with matter and applied research. They were represented by three themes, grouped in 14 projects and were performed in a wide international collaboration using both the accelerators of the Laboratory and other scientific centers.

Unfortunately, in 1996 due to financial difficulties at the Institute, the FLNR accelerators worked about 30% of the planned time, which resulted in a considerable reduction of the programme of experimental investigations with the use of heavy ion beams of the Laboratory's accelerators.

Physics and heavy-ion accelerator techniques

During 1995-1996 the Dubna Electron Cyclotron Resonance Ion Sources- DECRIS-14 and ECR-4M were created and the systems for vertical injection from these ion sources into the center of the U-400M and U-400 accelerating chamber were designed, manufactured and installed. Potentially this complex provides production of intensive beams of highly-charged ions of all elements up to Xe-U.

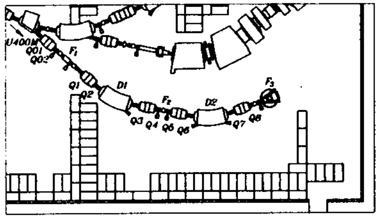
The ECR-4M ion source has been created in cooperation between the FLNR JINR and GANIL with the aim of producting intensive ion beams of ^{48}Ca (up to $5{\cdot}10^{12}$pps) and others at a low matter consumption of exotic and expensive isotopes. Beams of different ions, such as N, O, Ar, Kr were obtained in November-December 1996 at the U-400M+ECR-4M complex .

In 1996 both the U-400 and U-400M cyclotrons operated for the experiments for $\approx$2000 hours.

The upgrading of the magnetic structure for the optimization of the acceleration regime has been performed at the U-400M cyclotron, which resulted in increasing the ion beam intensity. Long runs at the completed FOBOS array were performed in the reactions - ^{14}N(53MeV/n) + ^{232}Th and ^{197}Au. and on the basis of several 10^5 three -fragment events results of a correlation analysis were obtained. In November-December 1996 a fragment-separator COMBAS with a complex of a control apparatus and semiconductor telescope-spectrometer was assembled, commissioned and tested at the beam line of the U-400M cyclotron.

The first stage of the high resolution beam line (spectrometer ACCULINA) with a hydrogen gas target of high pressure was completed and the whole setup was tested with a 50 MeV/n beam of ^{14}N and ^{7}Li. Radioactive beams of $^{6,8}He$, $^{8,12}B$ and others were produced and isolated. Fig(1) Thus, on the basis of the cyclotron complex U-400+ECR-4M and U-400M+DECRIS-14, a unique investigation base with modern experimental facilities (kinematic separators, 4 π-arrays of charged particles, neutrons and γ-quanta) has been developed at the FLNR.

All this opens wide possibilities for performing new experiments in the range of low and medium energies.
In 1997, the major emphasis will be put on the optimization of the U-400+ECR-4M cyclotron aiming at performing the experiments on the superheavy elements synthesis. At the U-400M+DECRIS-14 cyclotron experiments on the investigation of non-equilibrium processes at near Fermi energies (E≤ 30 ÷ 60 MeV/n) and reactions with radioactive nuclei will be performed.
Any further development (1997-1999) will be connected with production of radioactive ion beams (RIB). Within this project, the two cyclotrons U-400 and U-400M, both having vertical beam injection, can be used for production of RIB as in an ISOL-type facility (similar to the SPIRAL project at GANIL).



spectrometer ACCULINA

Fig.1

Radioactive products, obtained at the U-400M will be injected into an efficient ECR-source and after a magnetic analyzer, a low energy (E=30 keV · q) beam of radioactive nuclei can be transported and injected into the center of the second cyclotron. Fig(2)
The maximum energy of the RIB will amount to 50 MeV/n. A possibility of an inverse variant is also being considered, in which the U-400 cyclotron will serve as an injector. In this connection in 1996 using the U400M cyclotron, the production mechanism of the projectile-like fragments was investigated for understanding the nuclear reaction mechanism, and for making precise estimation of the secondary beam intensity. The production rates of fragments produced by $^{32-36}S$ ion beams with an energy of up to 20 ÷ 60 Mev/n were measured both in the FLNR and GANIL.

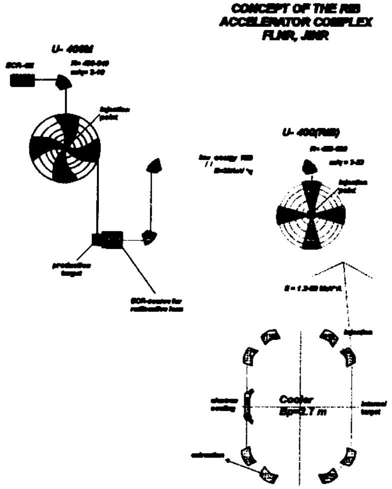


Fig.2

Heavy Elements

The theory of nuclear shell corrections put forward more than 25 years ago predicted the existence of heavy and superheavy elements. At present modern macro-microscopic theory as applied to the collective motion of heavy nuclei explains in general a number of experimental results: fission barrier configuration, shape isomerism, spontaneous fission half-lives, mass and energy distributions of fission fragments as well as many other facts which have found no explanation in the classical liquid drop model. As a result of the fission barrier emergence, determined by the nuclear structure, partial s.f. half-lives of heavy nuclei turned to be by 12-20 orders of magnitude larger than the value predicted by the classical liquid drop model. As a result of high stability of spontaneous fission, isotopes of heaviest elements undergo an α-decay with a half-life of $10^{-3} \div 10^{1}$ s. Fig(3)

Experimental investigations on the synthesis of heavy and superheavy elements 106 - 112 carried out in 1993-1996 by the FLNR-LLNL (Livermore) collaboration at the U-400 cyclotron and by the GSI-FLNR collaboration at the UNILAC accelerator, resulted in discovery of a new domain of heavy nuclei stability near the deformed shells in transactinide elements.
These investigations quantitatively confirm the predictions of the macro-microscopic theory about a significant stabilizing effect of the deformed shells in the region of heavy deformed nuclei with Z=108 and N=162, and the existence of a spherical shell with Z=114 and N≈180 may be realistic. On the basis of this theory and new experimental data for the whole region of nuclei with Z≥104 the properties of heavier nuclei up to Z=114 and N=174 have been estimated. These nuclei should have a high stability with respect to spontaneous fission and undergo an alpha-decay with a half-life of 1-10 sec.
It is expected that during the period of 1997-1998 they will be synthesized in the $^{232}Th, ^{238}U, ^{244}Pu + ^{48}Ca$ reactions. Both facilities- VASSILISSA and Dubna Gas-Filled Recoil Separator (DGFRS) will be used in these experiments. In the reaction ^{244}Pu(^{48}Ca,xn)$^{292-x}$114 at a minimum excitation energy of the compound nucleus E_x ~35 MeV the number of the emitted neutrons will amount to x=3-4, i.e. the final nuclei will be isotopes of element 114 with N=175 and N=174.

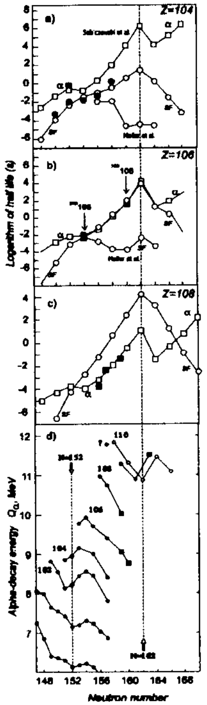


Fig.3. a,b,c) partial half-lives T_α and T_{sf} for even-even isotopes with Z = 104, 106 and 108. Solid lines and open points – calculations. Black points – experiment.
d) $Q_\alpha(N,Z)$. Black points – experiment values, open points – calculations for isotopes with Z = 110.

The expected luminosity of this experiment corresponds to the cross section of ≈1 pb or even less. Preparatory work for the forthcoming experiments on the synthesis of superheavy nuclei has been made on the DGFRS and the first stage in modernization of the separator's detection system has been completed. Partial upgrading of the electronic and detector system of the separator VASSILISSA has been made too. In the beginning of 1997 it is planned to continue the upgrading and reconstruction of the VASSILISSA and DGFRS as well as modernization of its detection system.

Simultaneously with this, in future it is planned to continue the synthesis and study of new isotopes of elements 104÷108 in the fusion reactions with $^{20,22}Ne$, $^{24,26}Mg$, ^{31}P, $^{32,34}S$ and ^{48}Ti ions.

Chemistry of Transactinides

Investigation of the chemical properties of the new elements is one of the traditional research programs of the FLNR. A series of collaborative experiments was conducted in the FLNR in February-March 1996, with the participation of sixteen scientists from PSI Villigen (Switzerland) , GSI Darmstadt, Rc Dresden (Germany) and INP Cracow (Poland). The experiments were performed at the KHIPTI setup using some equipment brought from PSI (OLGA 3) and RC. Interesting results on the properties of element 104 were obtained. A new setup KIT (a system of 8 ionization chambers with a transporting tape) has been completely constructed. Planned for 1997 is the on-line chemical identification of the element with Z=106 by means of detection of the α-decay and spontaneous fission of the "long lived" isotopes $^{265,266}106$ using the KIT ionization chambers.

Nuclear Fission

In the framework of the collaboration of several groups from Vanderbilt Univ.(Nashville), INPN(Catania), ISN(Grenoble), Univ.(Brussels), Univ.(Texas), IP(Bratislava), INP(Alma-Ata)) influence of the nuclear structure on the fission dynamic has been studied. In the experiments on spontaneous and induced fission performed recently, strong experimental proof of the fission mode phenomenon has been obtained.

For the first time multiparameter correlations (mass-energy-angle for fission fragment in coincidence with neutrons and γ-quanta) have been measured at subbarrier energies in the reactions $^{204,208}Pb(^{16}O,f)$ and $^{208}Pb(^{18}O,f)$. Fig(4)

The range of excitation energies at the saddle point for the compound $^{220,224,226}Th$ nuclei was E^*_{sp}=16÷40 MeV. At low excitation energies two different fission modes (symmetric and asymmetric) have been observed and the time -scale of nuclear collective motion for these modes have been estimated. The experimental characteristics of fission modes are proved to be in good agreement with the predictions of macro-microscopic theory.

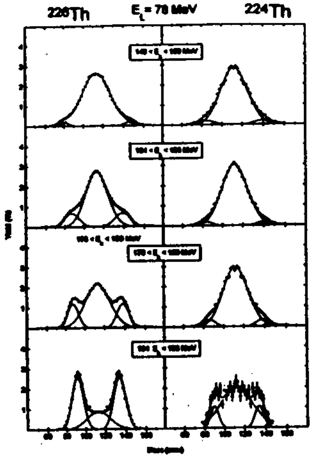


Fig.4

At present, until February 1997 a multidetector set-up "Corset + Demon" (large angle fission fragment detectors and a 4π neutron array) has been used for the measurement of the spontaneous fission of ^{248}Cm with the aim of studying the phenomenon of cold compact and cold deformed fragmentation and searching cluster decay modes.

Cluster decay and spontaneous fission of ^{232}Th have been measured by the polyethyleneterephtalate track detectors in the Gran Sasso underground laboratory. The lower limit of the partial half-life for the most probable ^{26}Ne cluster decay was found: $T_{1/2cl}>5\cdot10^{21}$ yr (a 90% confidence level). Spontaneous fission with the partial half-life $T_{1/2sf}=(1.2^{+0.5}_{-0.3})\cdot10^{21}$ yr was recorded.

Fusion and fission cross section of a $^{226,224}Th$ compound nucleus in the reaction $^{16,18}O$ + ^{208}Pb deep below the fusion barrier have been studied and interesting information on the limitation of deep subbarrier fusion - evaporation was obtained. Fig(5)

Influence of the shell structure at the entrance channel in deep subbarrier as well as over Coulomb barrier region for the reactions ^{86}Kr + $^{130,136}Xe$ was experimentally studied at the UNILAC in the framework of the FLNR-GSI collaboration.

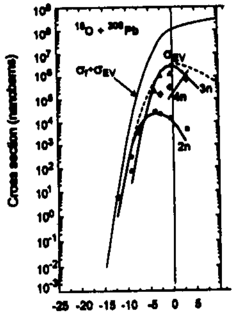


Fig.5

The measurements were performed in the excitation energy range of 10÷70 MeV and formation cross sections of the evaporation residues were obtained for the xn- evaporation channel range 1÷7 , see Fig(6)

In 1997 measurements of subbarrier fusion-fission in the Pb+(^{48}Ca,^{58}Fe,^{64}Ni) reactions and the analysis of low energy fission dynamic will be continued. Will be continued also the investigation of the cluster decay of $^{235,238}U$; ^{242}Cm; ^{114}Ba and ^{118}Ce, using nuclear reactions the protons and ions.

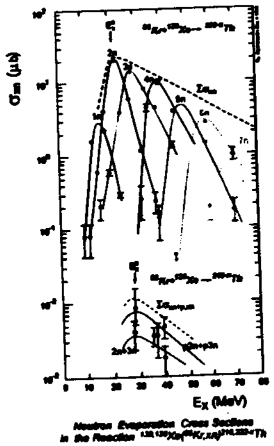


Fig.6

Nuclear Reactions with the Isomeric $^{178}Hf^{m2}$ Target

In 1996 a mass separated ^{178}Hf target containing $1.5\cdot10^{14}$ atoms of $^{178}Hf^{m2}$ was prepared at IPN(Orsay), and first experiments on the γ-spectroscopic studies in the reactions (n,γ) and (α, α'γ) were performed at the Grenoble high-flux reactor and the Orsay Tandem. The detecting systems and background conditions were tested. The results on the isomeric-to-ground state ratios in the reactions with a low-spin ground state and high-spin $^{178}Hf^{m2}$ and $^{180}Ta^{m}$ targets were analyzed and intensive K-mixing in excited nuclei was deduced. At present a very large collaboration is working, including 27 institutes of Europe and the

USA. A series of experiments was performed for studying the nuclear and electromagnetic interactions with the nuclei in a high spin state.

Nuclear Reactions at Intermediate Energies.
The FOBOS Set-Up

The data analysis of two- and three -body decay of the heavy compound-like nuclear system produced in incomplete fusion reactions ^{7}Li(43 MeV/n) + ^{232}Th and ^{14}N(34MeV/n) + ^{197}Au has been completed and published. A multi-mode mechanism has been observed for the ternary (light IMF-accompanied) hot system fission. IMF emission from the compound nucleus before the beginning of the fission process, from a strongly deformed system during the descent from the saddle to the scission point, and from the neck region near scission have been distinguished by analyzing the velocity distribution of the IMF with respect to the fissioning system.

The FOBOS set-up was further upgraded with a forward array of 80 phoswich counters and a new target system including an air-lock. In 1996 high-statistics runs at the completed FOBOS array were performed in the reactions- ^{14}N(53MeV/n) + ^{232}Th and ^{197}Au. On the basis of several 10^5 three-fragment events a correlation analysis has been made. Simultaneous and sequential ternary breakup are clearly distinguished in these data. It has been shown that the decay into three fragments of nearly equal mass can proceed simultaneously through a collinear intermediate configuration and can be considered as a limiting case of the neck emission mechanism.

Dynamics of a Non- Equilibrium Process.
Multi-Module Set-Up MULTI

A new set-up "MULTI" has been constructed by the FLNR - - LNP JINR - LAMPF (Los Alamos) - IPN (Rez) - PI (Yerevan) collaboration for the study of a very excited nuclear system produced by heavy ions at intermediate energies and for the investigation of exotic nuclei provided by the secondary radioactive beams. The set-up consist of 19 BGO-detectors, a multi-wire position-sensitive ionization chamber, two silicon telescopes and a 4π BGO-phoswich spectrometer. The first experiment on the study of the ^{8}B nucleus structure has been performed using this set-up at the U-400M cyclotron.

The production rates of fragments produced by beams of ^{32}S and ^{34}S ions with the energy of up to 20 MeV/n have been measured at the MSP-144 spectrometer.

The properties of very neutron-rich isotopes in the region of neutron closures N=20 were investigated according to the framework of the GANIL-FLNR collaboration. Evidence of particle instability of neutron rich ^{28}O was obtained. Fig(7) Measurement of β-decay half-life for $^{27,29}F$ and ^{30}Ne were performed. The experiment on production and identification of the new neutron rich nuclei ^{38}Mg,$^{40,41}Al$ was carried out at RIKEN in the framework of the FLNR-RIKEN collaboration. Some clues for the particle instability of ^{33}Ne were also obtained. In this experiment about 2800 events of ^{30}Ne, 90 events of ^{31}Ne and 70 events of ^{32}Ne but no events associated with ^{33}Ne were observed. Further analysis of these data sets may provide deducing the expected yield of ^{33}Ne.

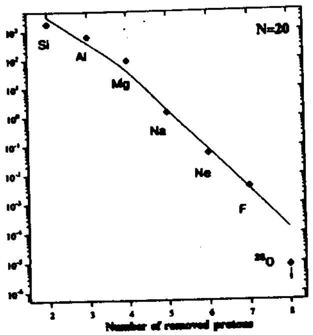


Fig.7

Investigation of the Nuclei Structure at the Boundary
of Nucleon Stability by Laser Spectroscopy

Ratios of the magnetic dipole constants for a pair of isotopes of the set lantanide and actinide elements were measured by the laser resonance fluorescence method and new data on the spatial distribution of electric currents were obtained. Among the studied isotopes, the largest difference in the ratios of the magnetic dipole constants was observed for the pair of ^{233}U-^{235}U($\approx$ 1%) A new experimental set-up for the on-line experiments using laser radiation was constructed.

Applied Research

New methods of obtaining ultra pure preparates ^{236}Pu,^{237}Np,^{97}Tc were elaborated for biomedical and ecological studies.

The new type track membranes with sterilizing properties were elaborated and certificated.

For the first time the effect of rapid radiative diffusion of contaminations in semiconductors was revealed and investigated.

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