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PERSPECTIVES OF STUDIES WITH HEAVY ION BEAMS AT DUBNA

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An overview of all the avenues of research with heavy ion beams currently underway at Dubna is hardly possible and not the goal of this talk. Moreover, an attempt to confront prospects of these studies to the main trends of the development of heavy ion physics looks unjustifiable. Frankly speaking, I am restrained from doing so first of all because the recent appearance of the 7-volume Treatise on Heavy Ion Science edited by D.A.Bromley /1/ has demonstrated the enormous amount of work accomplished in heavy ion physics. The mere account of the most interesting results which constitute the milestones of the 30-year history of this field of science shows its fruitfulness and versatility, giving grounds for comparing it to the horn of plenty (see fig. 1).

The synthesis of transuranium elements remains one of the principal problems being solved with the help of heavy ion beams. The initial experiments along this line of research were begun as early as in the mid-50's, shortly after the discovery of mendelevium, the element with atomic number 101 (ref. /2/). The discovery of mendelevium completed a series of brilliant studies on the synthesis of transuranium elements in the neutron and light charged-particle capture reactions, carried out under the leadership of G.T.Seaborg at Berkeley, U.S. The production of new elements with atomic numbers greater than 101 did not seem feasible in those reactions because there was no sufficient amount of suitable target nuclei with $Z > 98$. The hopes of American physicists and chemists to synthesize new elements in superintense pulsed neutron fluxes produced by nuclear explosions were not justified either (see ref. /3/). Later it became clear that the possibilities of this method are limited by short lifetimes of the heavy isotopes of fermium ($A > 257$) with respect to spontaneous fission and, first of all, by the fact that the nuclei involved in the α-decay chains of the neutron-rich isotopes of uranium undergo delayed fission, the radioactive decay mode discovered at Dubna /4/.

In the mid-50s the first attempts to synthesize new elements by using heavy ion beams were made simultaneously at the three laboratories: in the U.S.S.R, Sweden, and in the U.S. At that time heavy ion physics was in its infancy. As nowadays, the essential aspects of this field of science developed owing to the efforts made to synthesize new elements. In particular, the solution to this

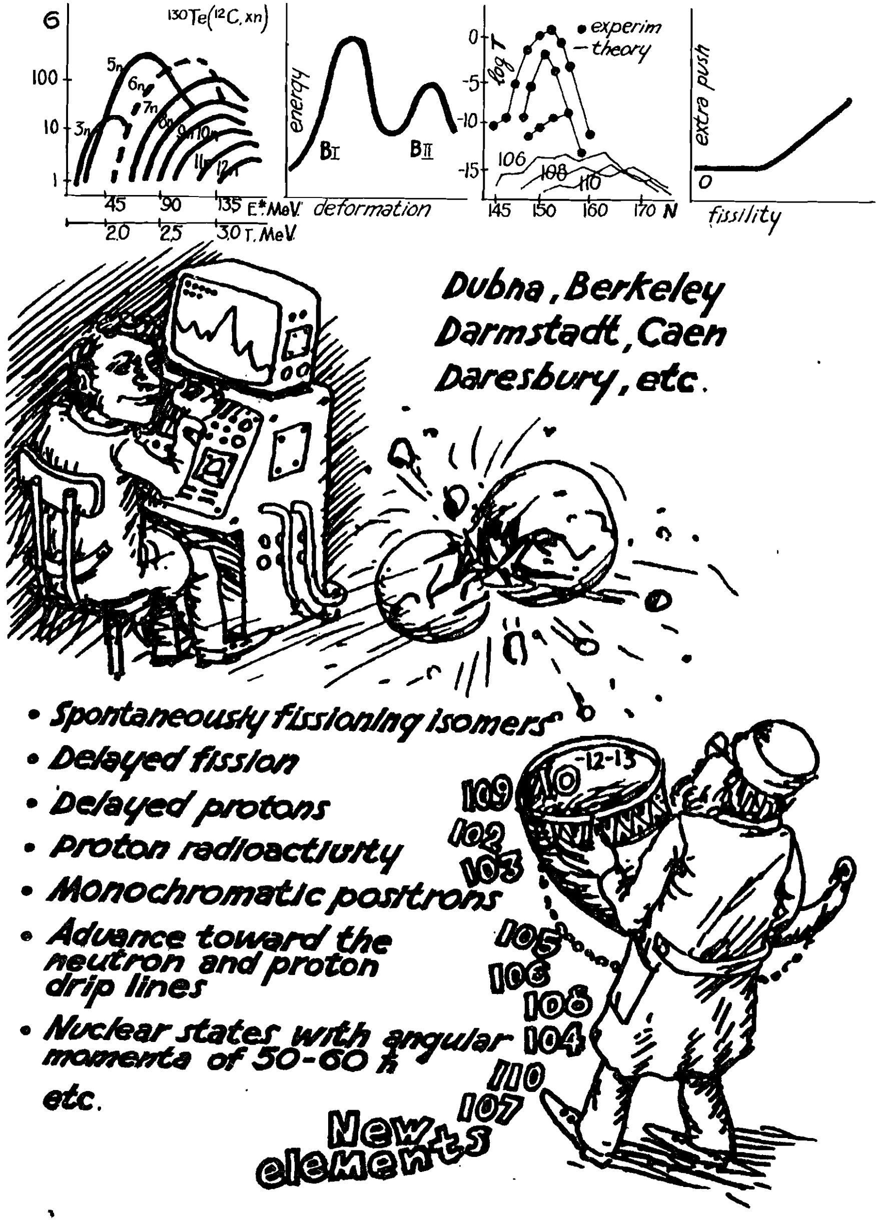


Fig. 1.

problem required the development of facilities for producing intense heavy ion beams. By 1955 considerable achievements were made in the development of powerful sources of high charge state ions at the 150-cm cyclotron of the I.V.Kurchatov Atomic Energy Institute in Moscow /69/, which allowed us to produce ion beams of carbon, nitrogen and oxygen with intensities high enough for performing the first experiments to synthesize element 102 /9,10/. Then we had at our disposal only a small amount of ^{241}Pu which contained considerable admixtures of lighter isotopes. The mixture of plutonium isotopes was bombarded with ^{16}O ions.

However, already the initial experiments had revealed some difficulties which made the detection of element 102 nuclei very complicated. These difficulties remained over the whole 33-year period of work on the synthesis of new elements, and they grew as the atomic number of the nuclei being synthesized increased. In going from the observation of reaction products to their unambiguous assignment to a hypothetical new element one should solve some problems the complexity of which is conditioned by short lifetimes which make the use of traditional chemistry impossible. The identification of the sought nuclei of new elements presents an extremely difficult problem since the low cross section (10^{-32}-10^{-35} cm^2) of reactions leading to the formation of nuclei of new elements makes up the 10^{-8}th - 10^{-11}th fraction of the total reaction cross section. In addition, the identification should be performed against the dense background due to the products of reactions occurring on the nuclei of admixtures (for example, lead and bismuth) contained in the target. Because of these difficulties the results of a number of experiments designed to synthesize element 102 which had been carried out in the late 1950's in Stockholm /5,6/, at Berkeley /7,8/ and in Moscow /9,10/ turned out to be erroneous.

It was necessary to widen the range of the heavy ions being accelerated, to enhance beam intensity, to develop methods for the unambiguous identification of single short-lived nuclei of new elements, to prepare monoisotopic targets from U, Pu, Am, Cm, and Cf, as well as to control the level of admixtures in them so that it could not be higher than the 10^{-6}th part of the target weight. The beams of ^{12,13}C, ^{14,15}N, ^{16,18}O and ^{20,22}Ne ions of sufficiently high intensity were produced at the cyclotron U-300 at Dubna in 1960 (see fig. 2).

Until the mid-70's the JINR cyclotron U-300 and the linear accelerator HILAC constructed at Berkeley (U.S.) in 1958 and some-

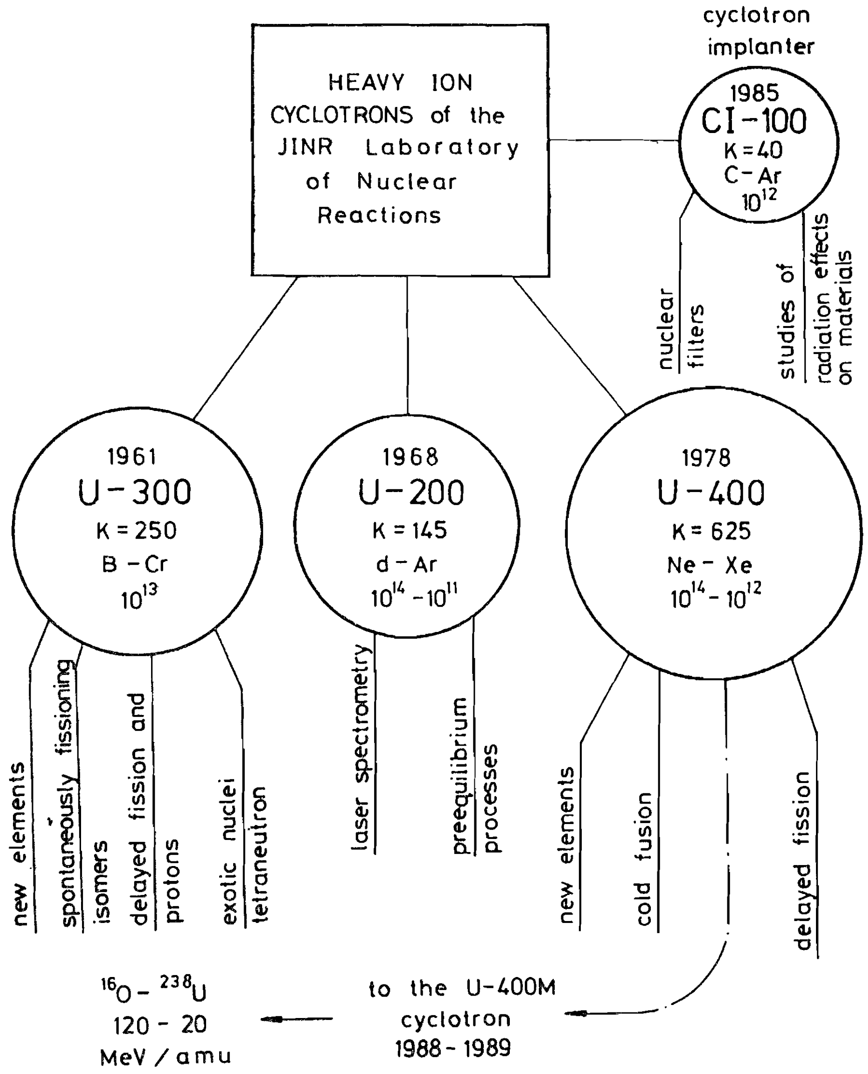


Fig. 2

what later rebuilt into the SuperHILAC for a wider range of heavy ions were the only accelerators suitable for experiments on the synthesis of new elements. In 1976 at GSI (Darmstadt, F.R.G.) the linear accelerator UNILAC was put into operation which produced all heavy ions up to uranium. In 1978 the isochronous heavy ion cyclotron U-400 started to operate at Dubna. It has produced the most intense heavy ion beams ranging from oxygen to krypton (see fig. 2).

The above-mentioned accelerators were used to carry out the principal experiments which led to the discovery of elements with atomic numbers ranging from 102 to 109.

The experimental facilities built for the studies aimed at the synthesis of new elements, as well as the effective methods of separation and identification of rare exotic nuclides and their decay products, developed for this purpose, enabled other studies to be performed. These studies have yielded results which can be regarded as major achievements of heavy ion physics. Some of these results have been obtained at Dubna (see fig. 1).

Having paid considerable attention to the spontaneous-fission studies of heavy nuclei and to the search for new spontaneously fissioning nuclides we have succeeded in discovering spontaneously fissioning isomers (see ref. /11/) and delayed fission /4/. The studies of these phenomena have ultimately led to new conceptions of the double-humped structure of the nuclear fission barrier and of the stabilizing effect of nuclear shells /12,13/. The systematics of spontaneous-fission half-lives for transfermium elements are of great importance for the quantitative evaluation of the spontaneous-fission probabilities of heavy nuclides including nuclei of the as yet unknown elements.

One of the peculiar features of these systematics, namely a noticeable slowing down of the rate of decrease (with increasing atomic number) in the spontaneous-fission half-lives in the region of $Z \gtrsim 104$ is of special interest. As a result, all the nuclei with $Z \gtrsim 105$ including the even-even nuclei $^{260}106$ /14-16/ and $^{264}108$ /17,18/ undergo mainly α decay rather than spontaneous fission. This fact makes one hopeful that the predicted island of stability of atomic nuclei really exists with its summit around $Z \simeq 114$ and $N \simeq 184$ or 178.

Of the other results of studies with heavy ion beams from the Dubna cyclotron U-300, one should mention the detection of ^{212m}Po, the first high-spin α-radioactive isomer, the discovery of the emission of delayed protons in β decay, the synthesis of the neutron-rich nuclei of light elements, and the detection of deep inelastic interactions between complex nuclei.

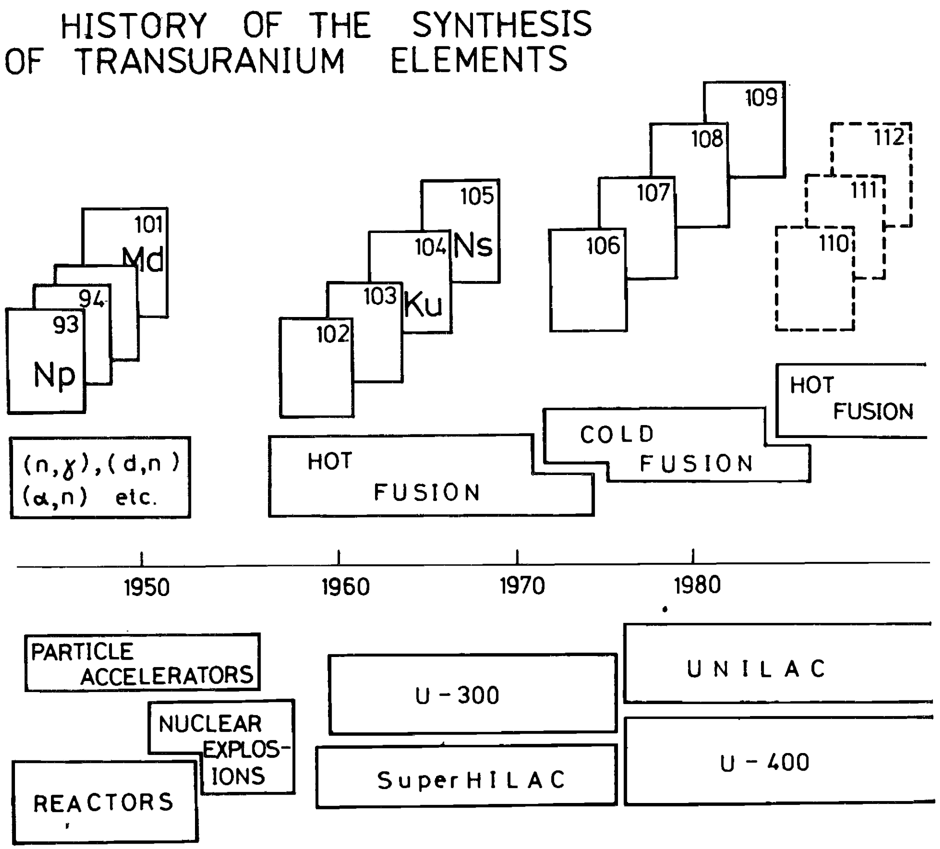


Fig. 3.

The experimental studies aimed at synthesizing heavy elements can be divided into three phases (see fig. 3).

The first phase lasted from the late 50's until the mid-70's. The complete-fusion reactions between the actinide target nuclei ^{238}U, ^{242}Pu, and ^{243}Am and ^{20,22}Ne, ^{16,18}O, ^{14,15}N and other projectiles were used to synthesize the nuclei of new elements with Z ≥ 102.

The elements with atomic numbers 102 and 103 were discovered at Dubna as a result of the series of experiments completed in 1966 (element 102 /19-27/) and in 1968 (element 103 /28-30/). In these experiments correct data on the properties of the five isotopes $^{252-256}$102 and ^{256}103 were obtained for the first time. The identification of the new elements nuclei was performed by measuring the energies of the α decay main lines, by establishing the genetic relationship with the α decay of daughter nuclei, as well as on the basis of the data obtained from (HI,xn) excitation function measurements and from cross reaction studies.

In 1964-70 experiments were carried out at Dubna which have led to the discovery of element 104, the first transactinide. In those experiments we chose spontaneous fission detection as the principal method of observing new nuclei. Now we can say that this choice has proved successful. First, the registration of spontaneous fission simplified the task of detecting the new nuclides which had been produced in nuclear reactions having cross sections as small as 10^{-34} - 10^{-32} cm^2. Second, it is just spontaneous fission studies of the isotopes of element 104 that have yielded the most interesting results. On the other hand, the physical identification of the element 104 nuclei by detecting their spontaneous fission was difficult because, in the reaction ^{242}Pu + ^{22}Ne /31/ used, nuclei with atomic numbers smaller than 104 could (and actually did) occur and these nuclei underwent spontaneous (shape isomers) or delayed fission. It is worth remembering that spontaneously fissioning isomers and delayed fission fragment emitters were discovered by us in the process of studying the background interfering the observation of element 104.

Bearing in mind all the difficulties associated with these new phenomena we decided to perform experiments on the chemical identification of element 104. For this purpose Zvara et al./32,33/ developed and used a basically new approach to investigating the chemistry of single atoms which underwent radioactive decay for few seconds.

The authors of the discovery of element 104 /31-33/ proposed to christen it kurchatovium to memorize the name of I.V.Kurchatov whose classical, pioneering work has laid the foundations for a number of important trends of nuclear physics, namely the studies of nuclear isomerism, nuclear physics, fission physics, and many others.

Element 105 was discovered at Dubna /34/ and identified /35-39/ by physical and chemical methods. The authors of the discovery of element 105 proposed to name this element nielsbohrium to pay homage to the enormous contribution of N.Bohr to the physics of the 20th century.

The second phase of work on the synthesis of new elements is associated with the use of cold-fusion reactions. The studies have been carried out during a period of more than 10 years and resulted in the discovery of several elements. They will be presented in the talks to be given by Oganessian, Armbruster and Münzenberg at this School-Seminar.

In the early 70's there were serious doubts about the possibility of inducing the so-called cold-fusion reactions. However the studies carried out by Oganessian et al. /40,41/ have refuted these doubts and proved that these reactions have certain advantages for the synthesis of elements with $Z > 100$. At Dubna a source of the high-charge state ions of Ti, V, Cr, Mn, Fe and Ni has been developed which has made it possible to carry out at the U-300 cyclotron experiments to synthesize the nuclei of elements 104-107. Since 1981 experiments at Dubna have been undertaken at the cyclotron U-400. The Darmstadt group has begun its work in the field of new element synthesis at nearly the same time. I would like to specially mention the close collaboration between the two groups. The natural competition between Dubna and Darmstadt in no way impeded the information exchange which allowed, with lesser efforts, to carry out the studies which were complementary to one another.

The time of triumphs was followed by a difficult period due to a dramatic decrease in cold-fusion reaction cross sections with the increasing atomic number of the compound nucleus. In the experiments aimed at synthesizing elements 108 and 109 one could observe only one nucleus during 3-10 days though maximum-intensity (about $10^{13} s^{-1}$) ion beams were used. The long-term experiments on the synthesis of element 110 using Ni and Co beams carried out at both Laboratories have been unsuccessful (see fig. 4).

Bearing all these negative results in mind it is natural to put the question as to whether it is not time to stop and abandon the dream of producing nuclei close to the hypothetical summit of the island of stability of superheavy elements ($Z \simeq 114$).

In our view, however, attempts to produce new elements with $Z \gtrsim 110$ can and must be pursued. A natural reason why the use of cold-fusion reactions has been unsuccessful is the action of strong Coulomb forces between the nuclei involved in the collision. But a qualitative consideration shows that complete-fusion reactions between uranium group target nuclei and projectiles lying between neon and chromium may prove the most successful to synthesize elements with $Z \gtrsim 110$. Therefore attention was drawn to reactions of the type Th+Ca, U+Ar, and others in our report at the 1983 Conference in Florence /42/.

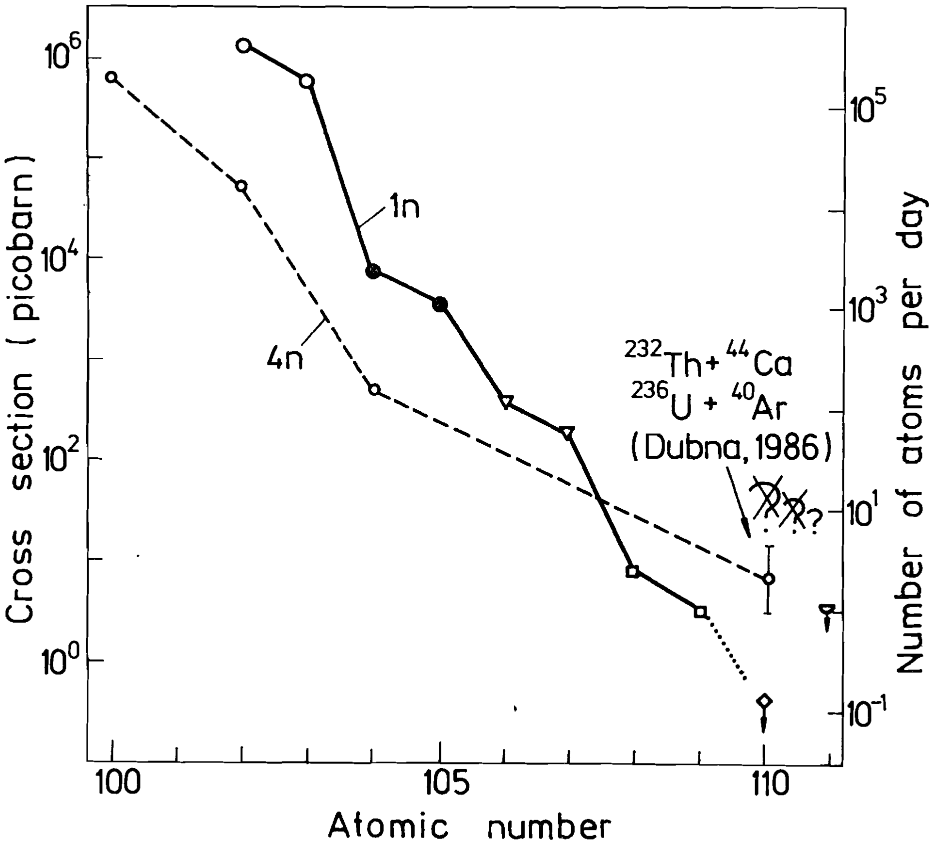


Fig. 4.

Cross sections of cold-fusion reactions (HI,1n) on Pb and Bi target nuclei, and those of hot-fusion reactions (HI,4n) on uranium target nuclei, which lead to the synthesis of transfermium nuclei. The spontaneously fissioning short-lived ($T_{1/2} \simeq 8$ ms) product formed in the reactions ^{232}Th + ^{44}Ca and ^{236}U + ^{40}Ar has been detected by Oganessian et al. The data obtained for the dependence of this product yield on bombarding ion energy and the results of the thorough investigation of background sources suggest that element 110 has been synthesized in these experiments. There will be no questions after the kinematics of the spontaneously fissioning short-lived product will have been studied and experiments will have been performed to observe the activity using two independent techniques.

The choice of these reactions has been motivated by the following considerations. First, these reactions are characterized by greater asymmetry and weaker Coulomb repulsive forces acting between the target nuclei and the projectile, compared with reactions occurring on lead and bismuth targets. Second, the macroscopic properties of the colliding nuclei, namely static and dynamical deformations, the possibility of neck formation, etc, can facilitate the formation of a relatively slightly excited, if not cold, compound nucleus in the case of a thorium or uranium target.

The probability of formation of slightly excited compound nuclei in the reactions Th+Ca or U+Ar depends on the dynamics of the transition of the nuclear system from the entrance channel to the saddle point of the compound nucleus. The coupling between collective and single-particle motion which occurs in the process of this transition leads to the heating of the nuclear system and to the appearance of a dynamical barrier which prevents fusion. The dynamical barrier is the subject of great attention for both theoreticians and experimentalists and, apparently, it will continue to be of considerable interest for a long time to come. However, as for the role of the dynamical barrier in hindering the fusion of thorium-uranium with argon-calcium nuclei and for the possible synthesis of element 110, these problems should be solved only in direct experiments. In any case the quantitative results of theoretical estimates have no predictive significance since we deal here with a very weak reaction channel (10^{-34} - 10^{-36} cm^2).

Recently the corresponding experiments have been carried out at Dubna and at Darmstadt. The results will be reported by the authors at this School-Seminar. Therefore I shall only touch upon them briefly.

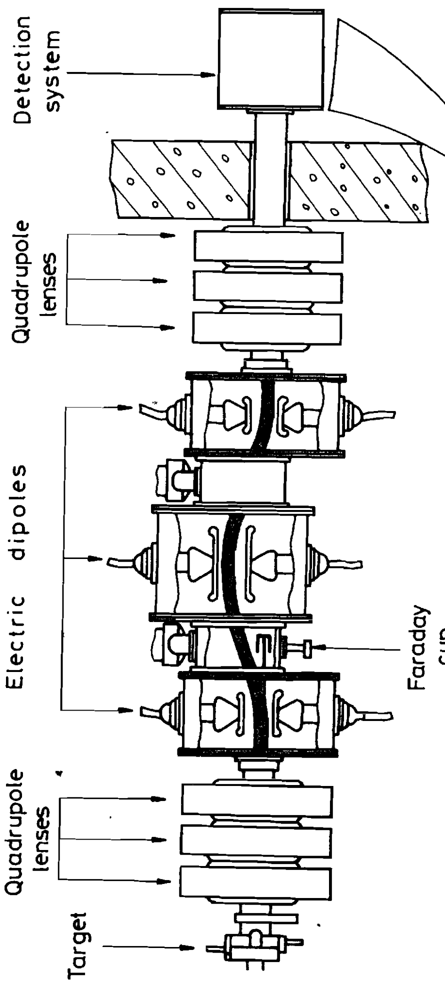
Oganessian et al. observed, in the reactions ^{232}Th + ^{44}Ca and ^{236}U + ^{40}Ar, a spontaneously fissioning product with a short half-life, which is very likely to be an isotope of element 110. The obtained dependence of the product yield upon the bombarding energy and the results of the thorough studies of different background sources support this assumption.

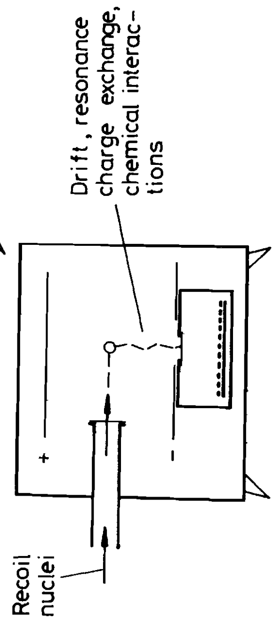
On the other hand, no nuclei of element 110 have been detected in the reaction ^{235}U + ^{40}Ar at Darmstadt. Armbruster et al. /43/ present arguments in favour of the assumption that the cross sections of the reactions leading to the synthesis of element 110, U+Ar and Th+Ca, are expected to be very small, several hundreds of times smaller than the value observed by Oganessian et al. at Dubna.

Final conclusions cannot be drawn until control experiments have been carried out. A high confidence level will evidently be achieved provided that these experiments are carried out by two independent methods. One method is associated with a continuation of the experiments of Oganessian et al., namely with the thorough investigation of the kinematical properties of the recoil nuclei occurring in the reactions Th+Ca and U+Ar, and with the performance of cross reactions. The other method will involve the use of an electrostatic separator of complete-fusion reaction products, VASSILISSA, which has recently been put into operation on a beam from the cyclotron U-400 /44/ (see fig. 5). The capability of the technique based on this separator, to record the α decay and spontaneous fission of the short-lived (up to several microseconds) nuclei formed in reactions having cross sections of several picobarns will offer essential possibilities for studying the spontaneously fissioning product observed in the reactions ^{232}Th+^{44}Ca and ^{236}U+^{40}Ar, as well as for searches for shorter-lived isotopes of elements with Z $\geq$ 110, including α radioactive isotopes.

In general, the separator VASSILISSA is similar to the SHIP facility used by the Darmstadt group in experiments aimed at synthesizing new elements. Therefore a detection system similar to that operated at Darmstadt will be installed at the VASSILISSA. At the same time we are trying to improve the methods of detecting and investigating the separated products of nuclear reactions. For example, one can retard these products in the working gas of an ionization chamber and, by using their drifting in the electric field, to enhance noticeably the detection efficiency for α particles. By filling the chamber with various gases it is possible to convert it into a reaction one (in chemical sense) and to study the various interactions between the atoms of new elements and the filling gas atoms, processes such as drifting, charge exchange, chemical interactions, sorption, etc. (see fig. 5). In all likelihood, such chemical studies can be carried out with atoms having lifetimes of several or tens of milliseconds.

Our knowledge of heavy-ion reactions allows us to conclude that these reactions are unlikely to permit an approach to the summit of the island of stability of superheavy nuclei (Z=110, N=184) predicted about 20 years ago /47-50/. True, later the masses of the superheavy nuclei were calculated using more precise model parameters and, as a result, the predicted summit was displaced toward Z=178 and the half-life of the longest-lived nucleus was





	SHIP	VASSILISSA
Ion flux (c^{-1})	10^{13}	10^{13}
$\Delta\Omega$ (mster)	25	10
$M/\Delta M$	20	20

THE RECOIL SEPARATOR VASSILISSA

Fig. 5

calculated to be $T_{1/2} \simeq 1$ year [51]. All this drastically decreases the probability for detecting superheavy elements in nature.

The history of searches for superheavy elements is very dramatic (see review articles [45,46]). Several research groups made attempts to find these elements in nature and observed some effects which, due to insufficient sensitivity or inadequacy of the experimental technique, were erroneously considered as evidence for the discovery of superheavy elements.

We at Dubna carried out searches for superheavy elements in galactic cosmic rays during several years [68]. Ten tracks of anomalous length (about 360 μm) were revealed in crystals of olivine taken from some iron-stony meteorites. These tracks might have been produced by stopped relativistic superheavy nuclei. The anomalous tracks form a separate group in the distribution of the tracks in length. No one track has been found between this group of tracks and the nearest group of tracks with a maximum at about 200 μm (which, we believe, had been produced by thorium-uranium nuclei). This kind of distribution of track lengths could be expected for superheavy nuclei separated from uranium and adjacent elements by a large region of short-lived nuclei which cannot be present in cosmic rays.

However, despite the above arguments and other indirect considerations, the assumption that the anomalous tracks detected belong to the cosmic-ray nuclei of superheavy elements remains unproved in view of the fact that the dependence of the track length on the atomic number of the relativistic nuclei which had stopped in the olivine crystal volume has not been established experimentally. Such a calibration requires a bombardment of olivine crystals with gold and uranium nuclei at an energy of above 100 MeV/amu.

In other experiments, we at Dubna investigated, with a very high sensitivity, spontaneous fission activity in some stony meteorites and in chemical fractions obtained from processing hot brines taken in the regions of abyssal fractures of the earth's crust of the Central Asia and Baikal rift zones. Rare spontaneous fission events have been detected in those samples, which cannot be explained as being due to the decay of known nuclides. There is a great temptation to admit that the observation of these events is indicative of the existence of a spontaneously fissioning superheavy element in nature. However, the average number of spontaneous fission neutrons ($\bar{\nu}$) turned out rather small, close to the $\bar{\nu}$ value observed in the fission of actinide nuclei. Therefore, it cannot be excluded that the spontaneously fissioning nuclide observed is an isotope of a radioactive element heavier than bismuth, but which has been produced in an unusual state in the process of natural nucleosynthesis.

In our view, the phenomenon detected should be investigated thoroughly. Unfortunately this is associated with great difficulties since the count rate of spontaneous fission events in meteoritic samples and in hot brines is extremely small. For example, in the Allende meteorite kindly provided to us by Dr. R.Clarke of the Smithsonian Institution (Washington, U.S.A.), the count rate was as low as one event per 50 days per one kilogram of meteorite. In the case of hot brines the count rate turned out to be still lower.

In order to investigate the properties of the new nuclide and identify it we consider it necessary to carry out chemical experiments for the purpose of obtaining fractions weighing several grams and producing count rates of about 10 fissions per day.

Such experiments can be performed with hot brines as initial material. Therefore, the boring of special holes has been begun in the region of the rift zones mentioned above (see fig. 6). It would be interesting to obtain considerable amounts (several tons) of meteoritic substance. The material available in the world's collections is a very small part of meteoritic bodies that have fallen down on the earth during the last 100-200 years. Fortunately, as it seems to us, there are other possibilities for obtaining large amounts of meteoritic substance.

One possibility is associated with the search for meteorites on the ocean bottom. According to an estimate /52/, about 3000 meteorites more than 10 kg in weight each fall on the earth's surface 1000 km^2 in area for one million years. Of these, about 250 belong to carbonaceous chondrites. Modern technical facilities permit the lifting of a considerable part of these unique natural objects from the ocean bottom. Meteorites that have fallen during the last 10 million years are accessible for transportation to the surface in the regions of deep-sea hollows where the rate of sediments accumulation does not exceed one mm for million years. Thus, the deep-sea hollows present fertile plantations for collecting meteorites.

Another possibility of obtaining meteoritic substance is, in our opinion, the study of sedimentary rocks formed during a short interval of time (about 1000 years) 65 million years ago. Geochemists have concluded that these rocks contain a considerable

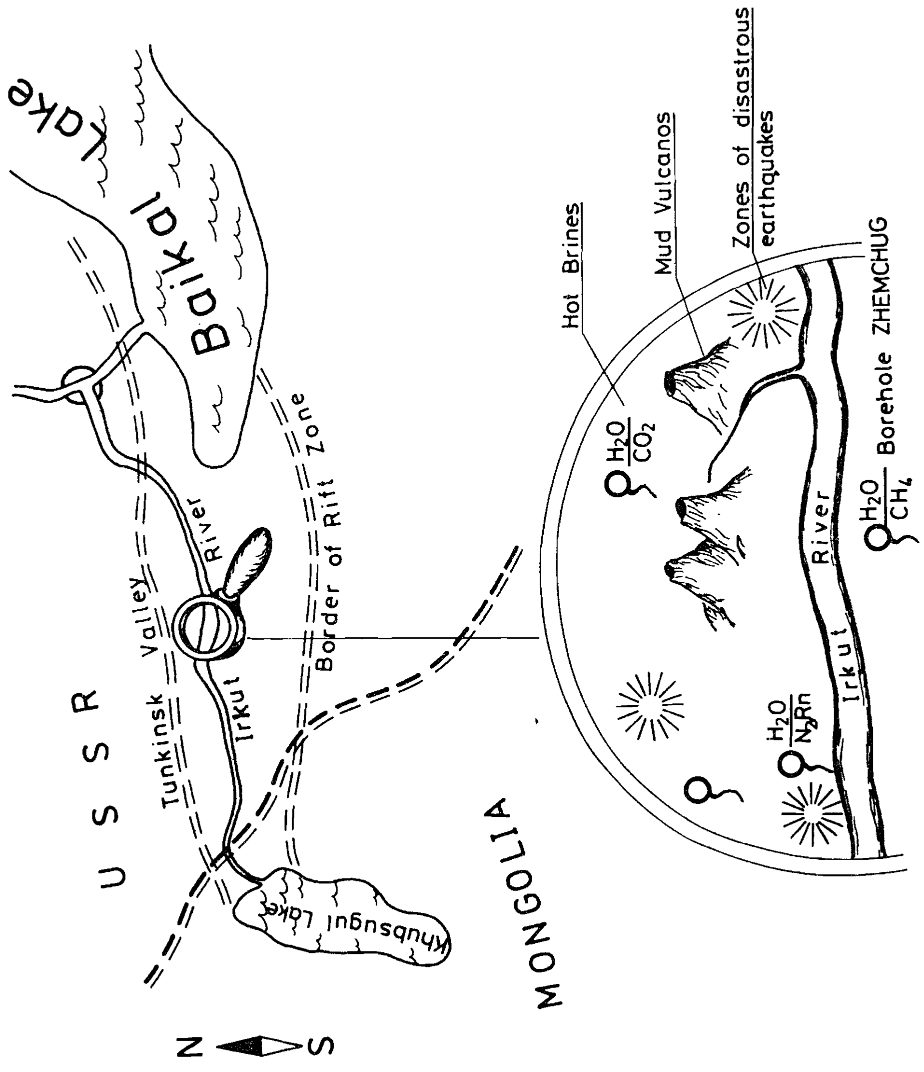


Fig. 6

amount of meteoritic dust produced as a result of the sputtering of a hypothetical cosmic body that had undergone a collision with the earth. Now we have at our disposal large amounts of such rocks which contain, according to estimates, up to 5% of meteoritic dust /53/.

Intense heavy ion beams produced at the Dubna cyclotrons enable us to conduct research along other lines which are not directly related to the synthesis of and search for heavy elements. For example, interactions between complex nuclei at energies up to 20 MeV/amu are under study at the Laboratory. These include the processes of fusion, deep inelastic interactions and fission which can be accompanied by tne emission of light particles, nuclear clusters and γ rays. We conduct the investigations of short-lived nuclei using laser spectroscopy. The studies of the chemistry of heavy elements, especially of kurchatovium, play a significant role in the research program of the Laboratory.

Recently a lively interest has been shown in the properties of the superheavy isotopes of the lightest elements. This interest is caused by the possibility of the verification of predictions for the properties of few-nucleon systems on the basis of various models including those taking into account the quark structure of the nucleon. It has turned out that intense heavy ion beams open up great possibilities in this respect. The experimental studies carried out at our Laboratory will be reviewed in a talk to be given by Penionzhkevich. In these studies reactions yielding two products in the exit channel are used and the correlation between the energy spectrum of one product and the binding energy of its partner is investigated.

In the studies of few-nucleon systems the possible existence of neutron drops, in particular, the systems consisting of four neutrons -- the tetraneutron -- is of special interest. Searches for the tetraneutron in the reaction ^{7}Li(^{11}B,^{14}O)4n have been underway at Dubna. Although the data obtained do not provide sufficient information for making an unequivocal conclusion about the existence of the tetraneutron, they open up new vistas for further experiments. In particular, we intend to use the simplest reaction $T + T \rightarrow 2p+4n$ which may prove more suitable for the tetraneutron studies.

It is supposed to conduct searches for bound and quasibound states in exotic systems such as the nuclear-stable ^{13}Li, ^{8}n, ^{7}H, ^{10}He, ^{12}He, etc., by using other types of reactions, e.g. ^{14}C+^{18}O, ^{14}C+^{22}Ne, and others.

Interactions of heavy ions with substance considerably differ from those of light particles. The specific ionization produced by heavy ions as they pass through substance is several thousand times greater compared with protons, and their damaging effect exceeds by several tens of thousands of times the effect produced by fast neutrons. Therefore it is natural to use heavy ion beams for tests of various structure materials /63/. Because the activation of the samples irradiated is low or even absent at all, it is possible to carry out the studies of materials properties using most precise techniques /54,64/ immediately after or during a heavy ion bombardment.

In investigating radiation damages in materials one observes the overall effect of heavy ion beam on the sample as a whole, without isolating separate tracks. However, the study of radiation damages in the region of an individual ion track is of great interest. Changes in the chemical properties of material in a heavy ion track are employed to produce nuclear filters. The initial diameters of heavy ion tracks are several tens of Å. The number of tracks produced per second can reach 10^{12} s^{-1} at a track density of 10^{12} m^{-2}.

The filters produced are not active because the ion bombarding energy is below the Coulomb barrier. The filters are widely used in solving various problems /55,56/, e.g. gas separation /57,59,60,65/, purification of gases from dust and bacteria /58,61/, filtration of liquids /62,66/, concentration of vaccines /67/, and others. Nuclear filters are ideal matrices for manufacturing metallic structures, for example, metallic filters or cold cathodes /56/.

It cannot be excluded that along with the evident applications of nuclear filters, their further studies can facilitate the solution to global ecological problems such as the purification of large volumes of water and air contaminated as a result of man's activities and, as an ultimate goal, water desalination.

I hope that I have succeeded in demonstrating the exceptional prospects and applications of heavy ions in basic and applied research. The development of more powerful heavy ion accelerators and more sophisticated research facilities will apparently promote the realization of those prospects, especially in solving problems which are inaccessible to other techniques.

References

1. Bromley D.A. (Ed.) Treatise on Heavy-Ion Science. Plenum Press, New-York and London, 1985, vol. 1-7.

2. Ghiorso A. et al. Phys. Rev., 1955, vol.98, p.1518.
3. Hoff R.W. In: Weak and Electromagnetic Interactions. Proc. Int. Symp., Heidelberg, 1986. H.V.Klapdor (Ed.), Springer-Verlag, Berlin, 1986, p.207.
4. Kuznetsov V.I., Skobelev N.K., Flerov G.N. Yad.Fiz., 1966, v.4, p.279.
5. Fields P.R. et al. Phys. Rev., 1957, vol.107, p.1460.
6. Fields P.R. et al. Arkiv. Fys., 1959, vol.15, p.225.
7. Ghiorso A. et al. Phys. Rev. Lett., 1958, vol.1, p.18.
8. Ghiorso A. et al. Phys. Rev. Lett., 1961, vol.6, p.473.
9. Flerov G.N. et al. Doklady AN SSSR, 1958, v.120, p.73.
10. Flerov G.N. et al. ZhETF, 1960, v.38, p.82.
11. Flerov G.N. and Druin V.A. "Structure of Complex Nuclei", (in Russian) Ed. N.N.Bogolubov, Moscow, Atomizdat, 1966, p.249.
12. Strutinsky V.M. Yad. Fiz., 1966, v.3, p.614.
13. Strutinsky V.M. Nucl. Phys., 1967, vol.A95, p.420.
14. Demin A.G. et al. Z. Phys., 1984, vol.A315, p.197.
15. Armbruster P. GSI-Preprint 84-47, Darmstadt, 1984.
16. Münzenberg G. et al. Z. Phys.,1985, vol.A322, p.227.
17. Oganessian Yu.Ts. et al. Z. Phys., 1984, vol.A319, p.215.
18. Hofmann S. et al. In: Weak and Electromagnetic Interactions. Proc. Int. Symp., Heidelberg, 1986, H.V.Klapdor (Ed.), Springer-Verlag, Berlin, 1986, p.179.
19. Donets E.D., Shchegolev V.A., Ermakov V.A. At. En., 1964, v.16, p.195.
20. Zager B.A. et al. At. En., 1966, v.20, p.230.
21. Akapiev G.N. et al. At. En., 1966, v.21, p.243.
22. Flerov G.N. et al. Yad. Fiz., 1967, v.5, p.1186.
23. Mikheev V.L. et al. At. En., 1967, v.22, p.90.
24. Druin V.A. et al. At. En., 1967, v.22, p.127.
25. Donets E.D., Shchegolev V.A., Ermakov V.A. At. En., 1966, v.20, p.223.
26. Flerov G.N. Proc. of the Int. Conference on Heavy Ion Physics, Dubna, 1966, JINR D7-3548, Dubna 1966, issue 2, p.3.
27. Flerov G.N. Ann. Phys., 1967, vol.2, p.311.
28. Donets E.D., Shchegolev V.A., Ermakov V.A. At. En., 1965, v.19, p.109.
29. Flerov G.N. et al. Nucl. Phys., 1967, vol.A106, p.476.
30. Flerov G.N. et al. Yad. Fiz., 1968, v.7, p.977.
31. Flerov G.N. et al. At. En., 1964, v.17, p.310.
32. Zvara I. et al. At. En., 1966, v.21, p.83.
33. Zvara I. et al. Radiokhimiya, 1969, v.11, p.163.

34. Flerov G.N. et al. JINR P7-4932, Dubna 1970.
35. Flerov G.N. et al. JINR P7-5108, Dubna 1970.
36. Flerov G.N. et al. At. En., 1970, v.29, p.243.
37. Druin V.A. et al. JINR P7-5161, Dubna, 1970.
38. Druin V.A. et al. Yad. Fiz., 1971, v.13, p.251.
39. Zvara I. et al. JINR P12-5120 Dubna, 1970.
40. Oganessian Yu.Ts. et al. Nucl. Phys., 1975, v.A239, p.353.
41. Oganessian Yu.Ts. et al. Lect.Notes Phys., 1974, v.33, p.221.
42. Flerov G.N. In: Proc. Int. Conf. on Nuclear Physics, Florence, 1983. P.Blasi and R.A.Ricci (Eds.), Tipografia Compositori, Bologna, 1984, vol.2, p.365.
43. Armbruster P. et al. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986, p.52.
44. Yeremin A.V. et al. JINR P15-85-786, Dubna, 1985.
45. Flerov G.N., Ter-Akopian G.M. Rep. Prog. Phys., 1983, v.43,p.817.
46. Flerov G.N., Ter-Akopian G.M. In: Treatise on Heavy-Ion Science, v.4. Extreme Nuclear States. D.A.Bromley (Ed.), Plenum Press, New York and London, 1985, p.333.
47. Nilsson S.G. et al. Nucl. Phys. 1968, v.A115, p.545.
48. Nilsson S.G. et al. Nucl. Phys., 1969, v.A131, p.1.
49. Fiset E.O., Nix J.R. Nucl. Phys. 1972, v.A193, p.647.
50. Brack M. et al. Rev. Mod. Phys., 1972, v.44, p.320.
51. Möller P., Leander G.A., Nix J.R. Z. Phys. 1986, v.A323, p.41.
52. Halliday J., Blackwell A., Griffin A. Science, 1984, v.223,
53. Nazarov M.A. et al. The 20th All-Union Meteoritic Conference, Abstracts of Papers, Tallin, AN SSSR, 1987, p.6.
54. Havancsak K. et al. Proc. of the Meeting on the Uses of Nuclear Filters, Dubna, 1985. JINR P18-86-110, Dubna, 1986, p.77.
55. Flerov G.N. Vestnik AN SSSR, 1984, No. 4, p.35.
56. Fischer B.E., Spohr R. Rev. Mod. Phys., 1983, v.55, p.907.
57. Schaupert K., Armbruster P., Spohr R. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986, p.255.
58. Spurny K.P. et al. Environm.Sci.Tech., 1969, vol.3, p.464.
59. Khan H.A. et al. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986, p. 262.
60. S.Nguyen Nhu et al. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986, p.265.
61. Dersch R. et al. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986. p.266.
62. Sial A. et al. GSI Scientific Report 1985, GSI 86-1, Darmstadt, 1986. p.263.

63. Vorobyev E.D. Proc. of the 4th Meeting on the Uses of New Nuclear-Physical Methods, Dubna 1981, JINR P18-82-117, Dubna, 1982, p.93.
64. Afanasiev V.D. Proc. of the Meeting on the Uses of Nuclear Filters, Dubna, 1985, JINR P18-86-110, Dubna, 1986, p.88.
65. Apel P.Yu. et al. Proc. of the Meeting on the Uses of Nuclear Filters, Dubna, 1985, JINR P18-86-110, Dubna, 1986, p.68.
66. Lopukhin Yu.M., Zakharchenko V.N. Proc. of the 4th Meeting on the Uses of Nuclear-Physical Methods, Dubna 1981, JINR P18-82-117, Dubna, 1982, p.145.
67. Mchedlishvili B.V. and Kolikov V.M. Proc. of the 4th Meeting on the Uses of Nuclear-Physical Methods, Dubna 1981, JINR P18-82-117, Dubna, 1982, p.138.
68. Perelygin V.P., Stetsenko S.G., Flerov G.N. JINR E7-85-245, Dubna, 1985.
69. Morozov P.M., Makov B.P., Ioffe M.S. At. En., v.2, 1957, p.272.

Note added in proof

In the caption to fig. 4 the author would like to refer to the recent paper by Yu.Ts.Oganessian et al. (JINR Preprint D7-87-392, Dubna, 1987) in which the unambiguous conclusion that the 10 ms activity observed in the reaction ^{236}U + ^{40}Ar belongs to element 110 has been confirmed.

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Флеров Г.Н. **E7-87-512**

Перспективы исследований на пучках тяжелых ионов в Дубне

В реакциях горячего и холодного слияния ядер на пучках тяжелых ионов были синтезированы элементы с атомными номерами 102-109. Их идентификация проводилась, в основном, ядернофизическими методами за исключением элементов с Z = = 104 — курчатовия, и Z = 105 — нильсбория, которые были идентифицированы в Дубне по химическим реакциям, протекающим в газовой фазе. Резкое падение величины поперечного сечения реакций холодного слияния с увеличением атомного номера компаунд-ядра вызвало необходимость применения для синтеза ядер с $Z > 110$ реакций горячего слияния. В экспериментах по синтезу 110-го элемента в реакциях ^{232}Th + ^{44}Ca и ^{236}U + ^{40}Ar в Дубне получены первые положительные результаты. Синтез новых элементов дал существенную информацию о свойствах их ядер, в частности, позволил установить высокую стабильность тяжелых ядер по отношению к спонтанному делению — явление, обусловленное влиянием оболочечных эффектов в ядрах. Кратко рассматриваются другие направления работ на пучках тяжелых ионов в Дубне.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Flerov G.N. **E7-87-512**

Perspectives of Studies with Heavy Ion Beams at Dubna

The elements with atomic numbers 102-109 have been synthesized in hot-fusion and cold-fusion reactions induced by heavy ions. All of them, except for kurchatovium, the element with atomic number 104, and nielsbohrium, the element with atomic number 105, were identified mostly by using nuclear-physical methods. Elements 104 and 105 were identified by means of chemical reactions in a gaseous phase. A sharp decrease in the cross section of cold-fusion reactions with increasing atomic number of the compound nucleus necessitated the use of hot-fusion reactions for the synthesis of nuclei with $Z > 110$. The Dubna experiments aimed at synthesizing element 110 by the reactions ^{232}Th + ^{44}Ca and ^{236}U + ^{40}Ar have yielded the first positive results. The synthesis of new elements has provided essential information about their nuclear properties. In particular, the experiments have allowed one to establish the high spontaneous-fission stability of heavy nuclei — the phenomenon due to shell effects in nuclei. Other directions of research with heavy ion beams, at Dubna are briefly reviewed.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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