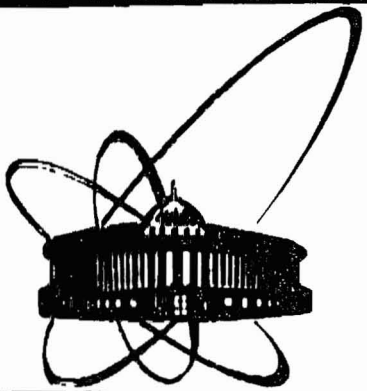

объединенный
институт
ядерных
исследований
дубна

E7-87-167

G.N.Flerov, G.M.Ter-Akopian

SYNTHESIS AND STUDY OF ATOMIC NUCLEI WITH Z > 100

Submitted to "Progress in Particle and Nuclear Physics"

1987

INTRODUCTION

The synthesis and investigation of the properties of the heaviest atomic nuclei is a very interesting and dynamically developing field of nuclear physics. According to the present-day terminology, it can be related to the studies of nuclei far from stability, the so-called exotic nuclei. This field, however, is characterized by specific features which distinguish the problems it tackles from the diversity of important problems being solved in the process of extending the chart of known nuclides. Here, the main attention is paid not only to the mere production of new nuclides, but also to synthesis of the atomic nuclei of new chemical elements. For over 40 years the scientific community witnessed the steady increase in the number of known elements: 17 man-made elements have been added to the series of 92 chemical elements ending in natural uranium. Leaving aside the problems of application of these elements we note the tremendous scientific and social importance of their discovery, as well as the great possibilities of co-operation between scientists of different countries in their attempts to advance toward the limits of the Periodic System.

The first transuranium element, neptunium, was synthesized by MacMillan and Abelson (1940) in a neutron-capture reaction. During the following 15 years another 8 transuranium elements were discovered. Those exclusively fine and now classical studies were carried out by the group of physicists and chemists, led by G.T.Seaborg. Their results were summarized in a number of reviews and monographs (see, e.g., Seaborg, 1963, 1967, 1968; Hyde, Perlman and Seaborg, 1964). The new elements were produced in reactions induced by light charged particles (p,d,α) and in neutron-capture reactions. The synthesis of the following element required a target nucleus with Z smaller by one or two units. Such target nuclei could be accumulated in sufficient amounts in a nuclear reactor.

For the identification of the new elements the chromatographic separation method was used according to the actinide hypothesis advanced by G.T.Seaborg. This hypothesis suggests that the transuranium elements through element 103, together with Ac, Th, Pa, and U, form the actinides series analogous to the lanthanides series which includes lanthanum and another 14 elements lying after lanthanum in the Periodic System of Elements.

The initial stage of work at synthesizing the transuranium elements was completed by the discovery of element 101. It was named by the authors after D.I.Mendeleev, the creator of the Periodic System which had served as a guide in discovering a whole number of new chemical elements. Already in work aimed to synthesize mendelevium (Ghiorso and others, 1955) the authors came across the difficulty of identifying the new element by using "one atom at a time"

techniques. The yield of the new element from the nuclear reaction ^{253}Es $(\alpha,n)^{256}Md$ was about 1 atom/hour because of the very small amount of the target material ($\sim 5\times10^{-7}$ μg ^{253}Es) bombarded by α particles. In the first experiments a total of 17 atoms of mendelevium were produced, which allowed one to obtain only a rough estimate of the ^{256}Md half-life, $T_{1/2}$=30 min. This estimate was changed by a factor of three in a later study (Phillips and others, 1958).

The use of the traditional method of synthesizing elements with Z >101 was impossible because of the absence of target material which could be bombarded by light charged particles to produce the atomic nuclei of new elements. The time came to make a choice between two feasible methods, one of which could be based on using extremely intense pulsed neutron fluxes produced by thermonuclear explosions, and the other using heavy ion reactions.

At first nuclear chemists in the US gave preference to thermonuclear explosions. As a matter of fact, einsteinium and fermium were first produced by this method. The subsequent experiments continued until 1969 (see Hoff, 1986). In those experiments one succeeded in producing the long-lived isotope ^{257}Fm as a result of the capture of 19 neutrons by the ^{238}U nucleus, followed by a β-decay chain. However, attempts to produce the heavier nuclides of the Z > 100 elements were unsuccessful. Later it became evident that the method of synthesizing nuclei in thermonuclear explosions, as well as in high-flux nuclear reactors, has some limitations because of the short spontaneous fission half-life of heavy fermium isotopes (A > 257) and as a result of the fact that the nuclei involved in the β-decay of the far neutron-rich isotopes of uranium undergo delayed fission - the radioactive decay discovered at Dubna (Kuznetsov, Skobelev and Flerov, 1966).

The studies relevant to the synthesis of new elements with heavy-ion beams were started in the mid'50s in the USSR, Sweden and the USA. That was the outset: the newly born science - heavy ion physics - picked up speed for many years to come. Since then, the essential aspects of this science developed under the strong influence of the problem of new element synthesis. This problem has stimulated the development of the heavy-ion acceleration techniques.

During a rather long period of time, for about 15 years, the studies were underway by using the heavy-ion beams of carbon, nitrogen, oxygen and neon. Such beams were first produced in cyclotrons designed for accelerating light charged particles, the biggest of which was the cyclotron of the Research Institute of Physics in Stockholm.

Owing to significant progress in the development of powerful sources of high-charge state ions, carbon, nitrogen and oxygen beams were successfully produced at the 150-cm cyclotron of the I.V.Kurchatov Atomic Energy Institute in Moscow, which surpassed in intensity the beams available at other laboratories.

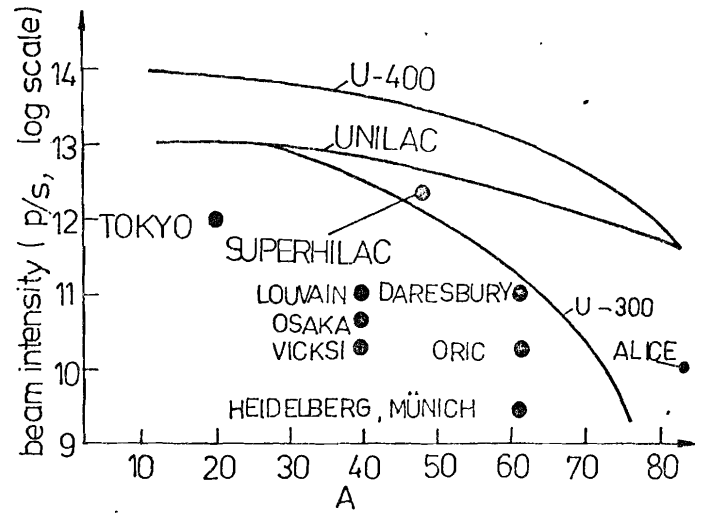

Fig. 1. Beam intensities at various heavy-ion accelerators for energies of up to 10 MeV/amu.

In 1958 the linear accelerator Hilac specially designed for heavy-ion acceleration was put into operation at Berkeley (USA). In 1960 the cyclotron U-300 with a pole diameter of 3 meters started to operate at Dubna, which was also constructed for the same purposes.

In the 1970's the number of the laboratories having at their disposal heavy-ion beams with energies of $\lesssim$10 MeV/amu increased sharply, and somewhat later the construction of heavy-ion accelerators for energies of $\gtrsim$40 MeV/amu was begun. However, only some accelerators designed for energies of $\lesssim$10 MeV/amu could provide sufficiently intense heavy-ion beams required for solving the problem of synthesizing new transfermium elements. Fig. 1 shows the beam intensities of the accelerators in operation, which produce projectiles with a wide range of atomic numbers, from carbon through uranium.

Over two decades (in the 1960's and 1970's) the studies aimed at the synthesis and investigation of the transfermium elements were carried out only in two or three laboratories: at the Joint Institute for Nuclear Research, Dubna, at the Lawrence Berkeley Laboratory, Berkeley, USA, and partially at the Oak Ridge National Laboratory, Oak Ridge, USA. In 1976 the linear accelerator UNILAC was put into operation at Gesellschaft für Schwerionenforschung at Darmstadt, FRG. At this accelerator an interesting research programme was initiated for the synthesis and investigation of the properties of the heaviest elements, including the synthesis of new elements.

The heavy-ion accelerators at Dubna provided high beam intensities at all stages of work aimed at the synthesis of transfermium elements. The cyclotron U-300 offered the best possibilities for this work until 1975. At this cyclo-

tron argon ions were first accelerated to an energy higher than the Coulomb barrier of heavy target nuclei. In 1973 considerable progress was made in the ion source techniques and, as a result, the heavy-ion beams of Ti, V, Cr, Mn, Fe and Co were produced for the first time. These beams were used for new element synthesis in cold-fusion reactions (Oganessian, 1974; Oganessian and others, 1975a). In 1975 the U-300 cyclotron provided the production of an intense ion beam of ^{48}Ca, a very rare calcium isotope (Flerov and others, 1976). The very first experiments aimed to synthesize superheavy elements were carried out at the U-300 cyclotron (see Flerov and Ter-Akopian, 1983, 1985). In 1978 the four-meter cyclotron U-400 was constructed at Dubna. The ion beams from this cyclotron, ranging from carbon to krypton, have all the parameters required for the synthesis and investigation of the properties of atomic nuclei with $Z > 100$.

The linear accelerator UNILAC, Darmstadt, also provides the experimentalists with intense beams of all heavy ions required for such studies. This accelerator is capable of producing the beams of ions of all elements including uranium.

The synthesis and study of the atomic nuclei with $Z > 100$ and, moreover, the synthesis of new elements involve a great variety of complicated problems. Moreover, experiments in this field are very expensive and time-consuming. The difficulties are due to, first of all, the extremely small cross sections of the reactions leading to the formation of new element nuclei. Their magnitudes range from some fractions of a microbarn to one picobarn ($10^{-36}cm^2$) that is to a minuscule cross section still accessible to experimental studies. The yield of the nuclides sought is often as small as several events and sometimes even less than one event per day. The large number of channels along which heavy-ion reactions proceed with total cross sections exceeding one barn substantially complicates the identification of the rare nuclei being sought. Therefore, the predictions relevant to the choice of the optimal reactions leading to the synthesis of new elements, as well as those for the bombarding energy corresponding to a maximum cross section, and for the height of this maximum, are of special importance.

At the initial stage new transfermium elements were produced by using heavy-ion beams with mass $A \geq 22$ and targets made of the isotopes of Pu, Am, Cm, Bk and Cf. The fusion of such nuclei leads to the formation of compound nuclei with fairly high excitation energies (≥ 40 MeV), even if the bombarding energy is equal to the Coulomb barrier. Now such reactions are called hot-fusion ones. For calculating the cross sections of these reactions the approach elaborated by Jackson (1956) and Sikkeland (see Sikkeland, Maly and Lebeck, 1968; Sikkeland, Ghiorso and Nurmia, 1968) was used rather successfully. In this approach based on a statistical model, the cross section of the fusion reaction accompanied by evaporation of x neutrons at a given energy E of the bombarding nucleus is written in the form of a product:

$$\sigma_x(E) = \sigma_{CN}(E) P_x(E) \langle \Gamma_n / \Gamma_f \rangle^x, \qquad (1)$$

where $\sigma_{CN}(E)$ is the compound-nucleus cross section, $P_x(E)$ is the probability of evaporation of x neutrons, Γ_n / Γ_f is the compound-nucleus neutron-to-

fission width ratio averaged over the evaporation cascade. For strongly asymmetric target-projectile combinations, the fusion cross section constitutes a major part of the interaction cross section and can be calculated with sufficiently high accuracy by taking into account the cut-off of partial waves with angular momenta larger than some critical value. The well-known bell-shaped excitation function of the (HI,xn) reactions is described by the simple formula for $P_x(E)$ derived in a paper by Jackson (1956). The main quantity that is responsible for the very low cross section $\sigma_x(E)$ is the third factor $\langle \Gamma_n / \Gamma_f \rangle^x$, which takes into account the competition between neutron evaporation and fission in the process of compound-nucleus de-excitation. It is convenient to define the quantity Γ_n / Γ_f using the semiempirical systematics of Sikkeland (Sikkeland and others, 1968a,b) who has shown that the average ratio between the neutron emission and fission widths depends on the atomic number and mass of the compound nucleus, being weakly dependent on its excitation energy.

Calculations using the Jackson-Sikkeland approach gave a good agreement with experimental data. The results of those calculations were successfully used to predict the cross sections of reactions leading to the synthesis of new elements. The experimental data agree rather well also with other calculations in which the competition between fission and neutron evaporation is defined by the standard statistical model formulae taking into account the excitation energy dependence of the fission barrier (Orlova and others, 1979; Reisdorf, 1981; Iljinov and Cherepanov, 1984).

The second stage of work aimed at synthesizing transfermium elements began with using the cold-fusion reactions (Oganessian, 1974; Oganessian and others, 1975a) induced by bombarding the magic Pb and Bi nuclei with Ti, Cr, Fe and other heavy ions. For passing to the cold-fusion reactions leading to the formation of the $Z_{CN} \geq 106$ nuclei more thorough studies of the interaction of complex nuclei were required. In the case of $Z_{CN} \leq 105$ and a comparatively light projectile ($A \leq 22$), the contact between the surfaces of the two nuclei that undergo a head-on collision at an energy close to the Coulomb barrier leads to their fusion and to compound-nucleus formation almost with 100% probability. In moving toward the heavier and/or more symmetric systems the situation changes, and the energy dependence of the fusion cross section becomes very complicated because of the effects of nuclear matter viscosity, compound-nucleus fissility and the presence of the additional degrees of freedom: single-particle and collective excitations of the colliding nuclei, nucleon exchange, neck formation and other deformations. This situation is just typical of the experiments resulting in the synthesis of the heaviest elements nuclei and of the experiments aimed to produce new elements with $Z \geq 110$. The formation of the sought nuclei from this region is observed with the fusion cross section making up a very small (10^{-8}th - 10^{-4}th) fraction of the total interaction cross section. Despite the great progress made in the theoretical consideration of fusion of two complex nuclei taking into account the potential energy surface and friction (Swiatecki, 1980,1981; Bjørnholm and Swiatecki, 1982; Błocki, Feldmeier and Swiatecki, 1986; Sierk and Nix 1974; Nix and Sierk, 1976,1977,1985,1986;

Davies, Sierk and Nix, 1983), it is so far impossible to make more or less reliable predictions for the cross sections of reactions leading to the formation of the nuclei of the nearest as yet unknown elements.

The estimates of the half-lives of the sought nuclei with respect to different modes of their radioactive decay are also important. Unfortunately, this kind of predictions were often far from the truth and sometimes even caused a delay in research because of their pessimism making the experimentalists hesitant. For example, that was the case with the predictions of very short spontaneous fission half-lives for the isotopes of element 102 (Juhansson, 1962) and element 104 (Ghiorso, 1969).

The prediction of the spontaneous fission half-lives of unknown nuclides remains a complicated problem which can be solved only on the basis of the clear notions of nuclear fission barriers and of the roles that different fission modes play, as well as with the knowledge of fission dynamics. One can say that in this respect the experiment more often than not, was ahead of theory by yielding results which required the substantial reexamination and development of the fundamentals of nuclear fission physics. This is well exemplified by the discovery of the spontaneously fissioning isomers made at Dubna (see Flerov and Druin, 1966) in the process of work aimed at synthesizing kurchatovium, the element with atomic number Z=104. This discovery has ultimately led to the revelation of the two-humped structure of the fission barrier and to the formulation of Strutinsky's shell-correction method used for calculating the potential energy of nuclear deformation (Strutinsky, 1966,1967). For two decades the Strutinsky method has been widely used in estimating the fission barriers and half-lives of the new heavy and superheavy elements (see, e.g., the latest predictions by Ćwiok and others, 1983; Lojewski and Baran, 1985; Möller, Leander and Nix, 1986; Möller, Nix and Swiatecki, 1986 a,b). We, however, note that theoretical predictions should be used with great caution in designing new experiments. Indeed, the standard deviation of the calculated half-lives from the available experimental values is no smaller than three orders of magnitude. Theory could not predict experimental evidence such as an abrupt change in the systematics of spontaneous fission half-lives in going from Z=102 to kurchatovium isotopes (Oganessian and others, 1975b), the relative stability against spontaneous fission of the even-even isotopes of elements 106 and 108 (Demin and others, 1984; Oganessian and others, 1984a; Armbruster, 1984; Münzenberg and others, 1985; Münzenberg and others, 1986a; Hofmann and others, 1986), the bimodal symmetric fission of several heavy isotopes of fermium, mendelevium and element 102 (Hulet and others, 1986).

The α-decay half-lives can be predicted with considerably greater confidence since the α-decay energy is calculated as the mass difference between the parent and daughter nuclei and the half-life can be determined by one of the known formulae (Taagapega, and Nurmia, 1961; Kolesnikov and Demin, 1975). As there is no much risk of a great error in the mass difference of close nuclei, one can practically use any mass formula (e.g. Kolesnikov and Vymiatnin, 1975; Möller and Nix, 1981 a,b).

The use of heavy-ion beams permitted the synthesis of new chemical elements starting with element 102, and the production of about 80 new isotopes of transuranium elements. Those studies have substantially contributed to the development of nuclear physics and nuclear chemistry and play an important role in related fields of science such as astrophysics and atomic physics. The results obtained at separate stages of work relevant to new elements synthesis using heavy-ion beams were reported in several review papers (see, e.g. Seaborg, 1967,1968; Flerov, Druin and Pleve, 1970; Flerov and Druin, 1971; Flerov and Zvara, 1971; Oganessian and Lazarev, 1981; Seaborg and Loveland, 1985; Armbruster 1985).

At present, we have reached the point at which the possibilities of cold-fusion reactions for the synthesis of new elements are practically exhausted. The still heavier elements should be synthesized by the new type of reactions - the complete fusion of target nuclei from thorium to californium with the $A > 20$ projectiles (Flerov, 1984). This is a very complicated problem since the new nuclei have to be synthesized in an extensive and so far unexplored class of nuclear reactions. Therefore, one should be prepared for cross sections as small as several picobarns or even a few fractions of a picobarn. Moreover, the properties of the nuclei being sought are difficult to predict. There is no doubt that the use of the techniques developed in the element synthesis studies and all information accumulated in these studies using heavy-ion beams will facilitate the solution to this problem. In this connection it is appropriate to summarize the results of all those studies in one review. We also hope that the present review article will contribute to a better understanding of the history of the discoveries of the transfermium elements.

HOT FUSION, THE INITIAL STAGE OF ELEMENT SYNTHESIS ON HEAVY-ION BEAMS

Element 102 and 103, the Last Elements of the Actinide Series

The studies aimed at synthesizing new elements on heavy-ion beams started with element 102 in the second half of the 1950's. At that time much was unclear in that work. With the then available intensity of heavy-ion beams, the yield of element 102 could be expected to be only several atoms per day. By extrapolating the half-life data for the $Z \leq 101$ nuclei one could conclude that the short lifetimes of the nuclei to be synthesized would make the chemical identification of the new element very difficult or even impossible at all. At the same time, one could not always foresee the serious difficulties due to the background from the radioactive decay of the numerous products of reactions proceeding with large cross sections on the target nuclei or on thallium, lead and bismuth admixtures.

These difficulties manifested themselves completely and prevented obtaining correct and positive data on the nuclear properties of elements 102 and 103 for nearly a decade. In fact, the results of a number of the experiments

carried out during that period of time turned out to be erroneous or too inaccurate to claim the discovery of new elements. For example, erroneous results were obtained by Fields and others (1957,1959), Ghiorso and others (1958,1961), Ghiorso (1959), and Flerov and others (1958,1960), who reported the discoveries of element 102, as well as in papers by Ghiorso and others (1958,1961) which contained some information about the synthesis of element 103. Those erroneous results were caused by the use of inadequate methods for the identification and detection of the new atomic nuclei, by the absence of monoisotopic targets, as well as by the fact that the experimentalists were unaware of or underestimated the background mentioned above.

Element 102 was discovered at Dubna as a result of the experimental research program completed in 1966 (Flerov and others, 1966; Flerov, 1967). That series of experiments led to the correct determination of the main radioactive decay properties of the five isotopes, $^{252-256}102$, synthesized in complete-fusion reactions between ^{238}U, ^{239}Pu and ^{243}Am targets and ^{15}N, ^{16}O, ^{18}O, ^{20}Ne and ^{22}Ne projectiles.

TABLE 1. Some data on the α-decay properties of the isotopes of element 102, obtained at Dubna by the end of 1966 (see Flerov et al.,1966, Flerov,1967)

Mass number	Half-life (s)	α energy (MeV)	Nuclear reaction	References	Table data (Lederer and Shirley 1978) Half-life (s)	α energy (MeV)
252	4.5±1.5	8.41±0.03	$^{239}Pu(^{18}O,5n)$	Mikheev and others, 1967	2.3	8.415(75%)
	3	8.41	$^{239}Pu(^{18}O,5n)$	Druin and others, 1967		8.372(25%)
253	95±10	8.01±0.03	$^{242}Pu(^{16}O,5n)$	Mikheev and others, 1967	105	8.01
	95±20	8.02±0.03	$^{239}Pu(^{18}O,4n)$			
254	50±10		$^{243}Am(^{15}N,4n)$; $^{238}U(^{22}Ne,6n)$	Donets and others, 1966	55	8.10 or 8.11
	20-50	8.10±0.05	$^{243}Am(^{15}N,4n)$	Zager and others, 1966		
	75±15	8.11±0.03	$^{242}Pu(^{16}O,4n)$	Mikheev and others, 1967		
255	180	8.08±0.03	$^{238}U(^{22}Ne,5n)$	Druin and others, 1967	198	8.121 (95.5%)*
	180±40	8.09±0.03	$^{242}Pu(^{18}O,5n)$	Flerov and others, 1967a		
256	8±3		$^{238}U(^{22}Ne,4n)$	Donets and others, 1964	3.2	8.43 or 8.41
	6±2	8.41±0.03	$^{238}U(^{22}Ne,4n)$	Druin and others, 1967		
	9±3	8.42±0.03	$^{242}Pu(^{18}O,4n)$	Flerov and others, 1967a		

*There are 10 known α lines for the isotope $^{255}102$. The 8.121 MeV line is the most intensive.

Table 1 presents some data on the isotopes $^{252-256}102$ produced at Dubna before 1967, in comparison with the presently accepted values of half-lives and α-decay energies (Lederer and Shirley, 1978).

Element 103 was discovered at Dubna in the studies carried out during 1965-68 (Donets and others, 1965; Flerov and others, 1967b,1968). Table 2 presents some data on the two isotopes, $^{255}103$ and $^{256}103$, which were produced at Dubna before 1970, and a comparison is made of these data with the table of isotopes of Lederer and Shirley (1978).

Figs. 2 and 3 show schematically the experimental setups which were used in the Dubna experiments. The nuclei produced were identified by using a combination of different methods: by establishing the genetic relationship of primary (HI,xn) reaction products with the known daughter products of their α decay, by studying the excitation functions of these reactions and by performing cross bombardments.

TABLE 2. The Dubna data on the α-decay properties of the isotopes of element 103, obtained before 1969

Mass number	Half-life (s)	α energy (MeV)	Nuclear reaction	References	Table data (Lederer and Shirley 1978) Half-life(s)	α energy (MeV)
255	20	8.38±0.03	$^{243}Am(^{16}O,4n)$	Zvara 1969, Druin 1970	22	8.429(40%);
256	45±10		$^{243}Am(^{18}O,5n)$	Donets and others, 1965	25.9	A composite spectrum is in the range of 8.33-8.64 MeV. The main line lies at 8.43 MeV.
	35±10	A composite α spectrum is in the range of 8.35-8.60 MeV. The main line lies at 8.42 MeV.	$^{243}Am(^{18}O,5n)$	Flerov and others, 1967b Flerov and others, 1968		

The experiments performed have shown that the cross sections of the reactions leading to the synthesis of the elements 102 and 103 nuclei lie between $10^{-32}cm^2$ and $10^{-30}cm^2$ and constitute the 10^{-8}-10^{-6}th fraction of the total cross section of the projectile-target interaction. Therefore, the necessary condition for the synthesis of new elements to be successful was the use of adequate methods for separating and identifying the nuclides sought, and for suppressing the enormous background from the radioactive decay of the numerous heavy-ion reaction products. That was possible to a great extent owing to the use of new techniques, namely Si-Au surface-barrier detectors and the gas-jet technique proposed by Macfarlane and Griffioen (1963) and immediately employed in the experiments designed to synthesize transuranium elements (Mikheev, 1966; Akapiev and others, 1966).

The use of uranium, plutonium and americium monoisotopic targets facilitated the unambiguous identification of the nuclei of elements 102 and 103. It was

difficult to meet the necessary requirement that the target has to be decontaminated from the admixtures of lead and other adjacent elements. The level of these admixtures could not exceed one nanogram (the 10^{-7}th fraction of the total target weight) since the interactions of heavy ions with Tl, Pb and Bi nuclei having cross sections of about 10^{-24}cm^2 might lead to the appearance of the background from a great number of the α-radioactive nuclei with $Z \geq 84$, characterized by the α-decay properties similar to those of the nuclei of elements 102 and 103.

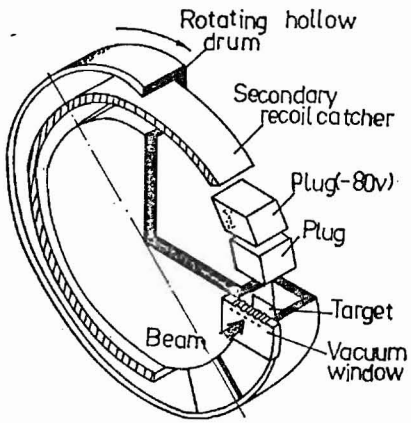

Fig. 2. Identification of the nuclei of elements 102 and 103, and half-life determination using the double-recoil technique. The projectile beam passes through the vacuum window and hits the target. Recoil nuclei escaping from the target are retarded in the gas of the chamber volume and diffuse, during ~1 s, to the inside walls of a rotating hollow drum. In the case of decay of primary reaction products the recoiling daughter atoms may leave the drum surface in ionized state and be accumulated on the secondary recoil catcher by electric field. Long-lived daughter nuclei are identified chemically, as well as on the basis of known half-lives and α-particle energies. The distribution of these nuclei on the second catcher permits half-life determination for primary reaction products.

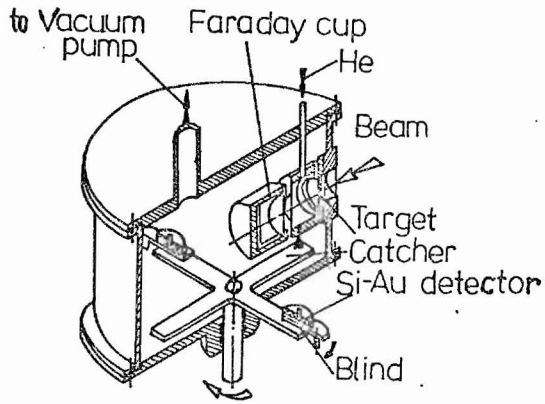

Fig. 3. Apparatus for the direct observation of the α decay of new nuclei. Atoms transported by the gas jet are collected on the shoulder of a cruciform catcher. The catcher rotates periodically through 90° and transports reaction products to α-particle detectors. In case α decay of the sought nuclide has been detected, the detector is covered by a blind to record the α decay of the atoms which have struck its surface after recoiling in the decay of the parent nucleus. In this way the genetic relationship between the sought nucleus and its known daughter is established.

Elements 104 and 105, the First Transactinide Elements

In the late 1950's-early 1960's, although there was no positive evidence for the properties of the nuclei of element 102, spontaneous fission could be expected to be a more probable process than α decay for the even-even nuclei of element 104. Therefore, when starting the experiments aimed at synthesizing element 104 we chose spontaneous fission detection as the main method for observing the new nuclei. Assessing this choice in retrospect one can say that it has proved to be successful. First, the recording of spontaneous fission has ultimately simplified the problem of detecting the nuclides produced by nuclear reactions having cross sections in the range 10^{-34}–10^{-32}cm^2, that is a factor of 10^3 smaller than in the case of the synthesis of elements 102 and 103. Second, it is just the spontaneous fission studies for the isotopes of element 104 that have provided the most interesting results.

The experiments initiated in 1962 were carried out as follows. A ^{242}Pu target was bombarded by ^{22}Ne ions, the recoil nuclei were retarded in a rotating

disk placed directly behind the target, and transported to fission fragment detectors. At the initial stage of the experiments fission fragments were detected using gas-filled proportional counters. Subsequently the counters were replaced by solid-state track detectors (mica, glass, or plastic). Already the first experiments resulted in the observation of a new spontaneously fissioning activity ($T_{1/2} \simeq 14$ ms) which attracted our attention. Cross bombardments and excitation function measurements showed that this activity was not due to an element 104 isotope. Shortly after that it was established that the spontaneous fission was due to the ^{242}Am nucleus which was formed in a surprising isomeric state (see Flerov and Druin, 1966). That indicated the discovery of the new phenomenon, shape isomers decaying by spontaneous fission with half-lives more than 20 orders of magnitude shorter than their ground state half-lives (see a review article by Bjørnholm and Lynn, 1980).

In addition to the important conclusions ensuing from the discovery of the spontaneously fissioning isomers, it was essential that those isomers had produced the background which had to be eliminated in the experiments designed to synthesize element 104. Therefore, subsequently the recoil transportation was performed using, instead of a rotating disk, a long conveyer belt along which a great number of solid-state track detectors were placed, thus allowing to cover a wide range of lifetimes (from 10 ms to 10 s). The experiments resulted in the detection of three spontaneously fissioning products from the ^{242}Pu + ^{22}Ne reaction. One of them, the known ^{242f}Am, had a half-life of 14 ms, while the half-lives of the other two were estimated to be equal to ~0.3 s and several seconds. On the basis of the data obtained in cross bombardments and of the shape of the excitation functions, taking into account the expected forbiddenness for the spontaneous fission of the odd-mass isotopes, the authors (Flerov and others, 1964) assumed that the spontaneously fissioning nuclide with a half-life of ~0.3 s was the element 104 isotope with mass number 260. However, bearing in mind the experimental difficulties, in particular, the presence of the background due to the spontaneous fission of the $Z < 104$ nuclei, the authors of that work decided to carry out chemical experiments to identify element 104 and to study its chemical properties.

For this purpose Zvara and others (1966) developed and employed a basically novel approach to the study of the chemical properties of single atoms undergoing radioactive decay in times of the order of one second. This approach, which can be called radiochemistry in the gaseous phase, was thoroughly elaborated later (see Zvara 1981) and is presently viewed upon as one of the main and promising trends in the study of the chemistry of heavy actinide and first transactinide elements (see Keller, 1984).

As the ^{22}Ne-ion bombardment of ^{242}Pu could yield only the $Z \leq 104$ elements, and because spontaneous fission is not typical for the preactinide ($Z < 89$) elements, the chemical identification of the spontaneously fissioning nuclide required, in the first place, its separation from the actinides. This was achieved by employing the great difference in volatility between the higher chlorides of the light homologs of element 104 and actinides, hafnium and

lanthanides respectively. For example, the pressure of $HfCl_4$ vapour reaches 1 atm at a temperature of 330°C whereas $EuCl_2$ and $LuCl_3$ have such a pressure at >1500°C.

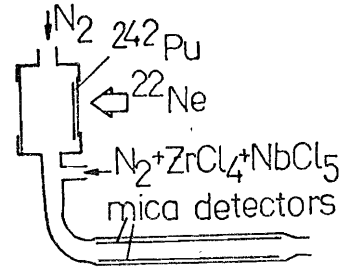

Fig. 4. Set-up for the rapid separation of gaseous chloride compounds of eka Hf (element 104) from analogous compounds of actinide elements. The recoil nuclei synthesized in the ^{242}Pu+^{22}Ne reaction are thermalized in a nitrogen stream saturated with $ZrCl_4$ and $NbCl_5$ vapors. The stream transports to mica detectors the chlorides of the elements formed as reaction products. All the system is heated to the temperature which corresponds to volatile state of eka Hf chlorides and to involatile state of actinides chlorides. Under these conditions the atoms of the $Z \leq 103$ elements can not pass to the mica detectors recording the spontaneous fission of the sought nuclei of element 104.

A schematic view of the experiments carried out in 1966 (Zvara and others, 1966,1969) is shown in fig. 4. The authors of this study have shown unambiguously that the spontaneously fissioning nuclide produced by the ^{242}Pu + ^{22}Ne reaction leads, under certain conditions, to the formation of chlorides which, as the chlorous compounds of hafnium, can be separated from the chlorides of lanthanides and actinides, owing to a great difference in volatility. So it was established that the atoms of element 104 were synthesized in the ^{242}Pu + ^{22}Ne reaction.

In view of the unambiguity of the chemical identification of element 104 the authors (Flerov and others, 1964; Zvara and others, 1966,1969) suggested that the new element should be named kurchatovium to pay tribute to the memory of I.V.Kurchatov whose classical and pioneering works have formed the basis for a number of important trends of nuclear physics, such as the studies of nuclear isomerism, neutron physics, nuclear fission physics and others.

As an extension of the studies of the chemical properties of kurchatovium and neighbouring actinides, Chuburkov and others (1967,1969) investigated the behavior of the chlorides of elements 102 and 103 in a gas stream. That investigation confirmed the identification of kurchatovium and yielded the first data on the chemistry of elements 102 and 103. Subsequently some experiments were carried out to investigate the chemical properties of kurchatovium in the gaseous phase (Zvara and others, 1970a, 1971), which fully confirmed the earlier conclusions and allowed one to determine the sublimation temperature of $KuCl_4$ more accurately and to establish the conditions under which this compound is absorbed by chemically active filters. The separation of kurchatovium and hafnium chlorides is illustrated in fig.5.

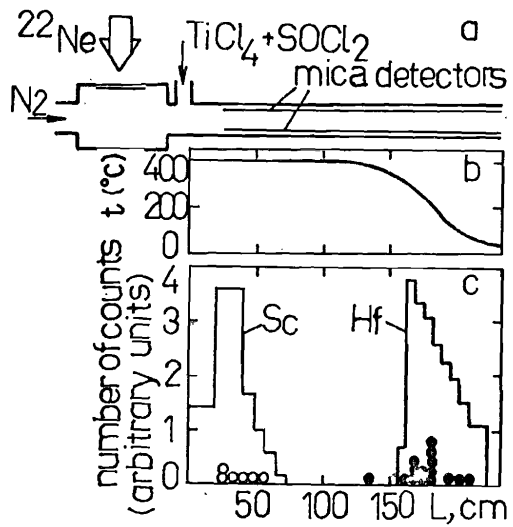

Fig. 5. (a) Schematic diagram of the set-up for the chemical separation of kurchatovium. The principle of operation is similar to that of the arrangement shown in fig. 4. Gaseous nitrogen stream is saturated with $TiCl_4$ and $SOCl_2$ vapours and then reaches the tube which acts as a thermochromatographic column. The tracks of spontaneous-fission fragments are recorded in mica placed inside the tube.
(b) Temperature regime of the chromatographic column.
(c) The distribution of fission fragment tracks (filled and open circles) along the column, compared with the distribution of ^{44m}Sc and $^{170,171}Hf$ (under these experimental conditions scandium and hafnium are the homologs of actinides and kurchatovium, respectively).

The radioactive decay of ^{257}Ku, ^{258}Ku and ^{259}Ku was investigated by Ghiorso and others (1969). Later (Flerov and others, 1971a; Druin and others, 1973; Bemis and others, 1981; Somerville and others, 1985) a 7% spontaneous fission branch was detected for the α-active isotope ^{259}Ku having a half-life of 3 s. It is presently undoubted that the spontaneous fission of this isotope has been observed in the initial experiments designed to synthesize kurchatovium (Flerov and others, 1964) and in the experiments aimed at identifying kurchatovium (Zvara and others, 1966,1969) and investigating its chemical properties (Zvara and others, 1970a, 1971).

The problem of the ^{260}Ku properties, albeit disputed for a long time because of some disagreement in lifetimes obtained by different authors, has ultimately not played an essential role either in the history of the kurchatovium discovery or in the systematics of the properties of the transfermium nuclides.

Element 105 was discovered in the nuclear reaction $^{243}Am + ^{22}Ne$ late in 1969 at Dubna (Flerov and others, 1970a). The newly detected nuclide underwent spontaneous fission with a half-life of 1.8 s. Its atomic number (Z=105) was established by measuring the angular distributions of the recoil nuclei and the excitation functions, which made it possible to determine its mass number, A=261 (Flerov and others, 1970b,c, 1971b). The experiments aimed at observing the α-decay of products from the $^{243}Am + ^{22}Ne$ reaction (Druin and others, 1970, 1971) confirmed the detection of $^{261}105$ ($T_{1/2}=1.4^{+0.6}_{-0.3}$ s, E_α= 8.9-9.1 MeV, the α-decay branch of 75%, the spontaneous-fission branch of 25%) by establishing its genetic link with $^{257}103$. Finally, the chemical identification of the new element was carried out (Zvara and others, 1970b) by using a technique similar to the one employed for the chemical identification of kurchatovium (see fig. 4). Paying homage to the great contribution of Niels Bohr to physics of the twentieth century the discoverers of element 105 proposed to name it nielsbohrium.

Choice of a Further Route in Element Synthesis. Element 106.

It is evident that element synthesis on the beams of heavy ions with atomic numbers ≤ 10 has strict limitations because the heaviest target materials available to the experimentalists are berkelium, californium (Z=97 and 98) and, possibly, einsteinium (Z=99). In the late 1960's the choice of a further route in the synthesis of new elements became topical in connection with the prediction of an island of nuclear stability in the region of the magic numbers, Z=114 and N=184 (see reviews by Flerov and Ter-Akopian, 1983, 1985). With a view of synthesizing superheavy nuclei, various reactions induced by ions heavier than argon were considered. Naturally it was interesting to use similar reactions to synthesize element 106. On the other hand, one could go the traditional way of using hot-fusion reactions. Therefore it is not surprising that the two laboratories at Dubna and at Berkeley have chosen different ways.

At Dubna, the synthesis of element 106 was carried out by using the new type of reactions, the cold fusion $^{207,208}Pb + ^{54}Cr$ (Oganessian and others, 1974; Demin and others, 1984).

The Berkeley group proceeded by using the hot-fusion reactions. Ghiorso and others (1974) produced the $^{263}106$ isotope by the $^{249}Cf(^{18}O,4n)$ reaction and identified this nuclide by establishing the correlation between its α decay ($T_{1/2}=0.9\pm0.2$ s, E_α =9.06 and 9.25 MeV) and the α decay of the daughter (^{259}Ku) and granddaughter ($^{255}102$) nuclei.

COLD FUSION

The cold-fusion reaction is now the generally accepted term for reactions in which the nuclei of transfermium elements are formed as a result of the complete fusion of magic target nuclei (Tl, Pb, Bi) with the projectile nuclei with $A \geq 40$. A number of experiments, with heavy ion beams from ^{40}Ar to ^{76}Ge, carried out before 1973, have not resulted in the observation of any products of complete-fusion reactions with $Z > 84$ (see Flerov and others, 1974). After some qualitative considerations the absence of heavy products of the complete-fusion reactions induced by the $A \geq 40$ ions was explained by the high fissility of the compound nucleus (Swiatecki and Bjørnholm, 1972; Tsang, 1974).

In 1973, some experiments were carried out (Oganessian and others, 1975a) in order to estimate the extent to which these limitations actually influence the possibility of forming compound nuclei with atomic numbers around 100. The purpose of those experiments was to search, at the highest possible sensitivity, for evaporation residues from the compound nucleus produced in the Pb + ^{40}Ar reaction. In the case of detecting such products the experimentalists intended to clarify to what extent the high binding energy of the magic lead nuclei would affect the production of moderately excited compound nuclei in this reaction.

The results of the experiments surpassed all expectations. The isotopes ^{244}Fm and ^{246}Fm, the (^{40}Ar,xn) reaction products, were obtained by bombarding three different isotopes of lead (^{206}Pb, ^{207}Pb, and ^{208}Pb). Instead of the usual several tens of atoms, their yield amounted to several hundreds and even thousands of atoms in a one-day experiment. The largest cross section characterized the reactions involving the evaporation of 2 and 3 neutrons from the compound nucleus rather than the reactions accompanied by the evaporation of 4-5 neutrons. The latter are typical for hot fusion. This fact is convincing evidence for that the use of the magic lead nuclei as target material should lead to the formation of slightly excited (cold) compound nuclei.

Subsequently Oganessian and co-workers carried out a series of studies to investigate the cold-fusion reactions induced by projectiles from ^{40}Ar to ^{64}Ni and the formation of the nuclei of new elements up to the element with atomic number 110. The results of these studies are summarized in several papers (Oganessian, 1977,1982,1983; Oganessian and Lazarev 1981; Oganessian and others 1984b).

In 1979, the Darmstadt group joined in and used the Wien velocity filter SHIP. The results obtained by this group in the experiments to investigate cold-fusion reactions and to synthesize new elements are summarized in several papers (see Armbruster, 1985,1986; Hofmann and others, 1986; Münzenberg and others, 1986a). The Darmstadt group was the first to establish that the reactions involving the evaporation of one neutron from the compound nuclei formed in cold fusion play a significant role (Münzenberg and others, 1981). Oganessian and others (1984b) succeeded in observing also the radiative-capture reaction $^{208}Pb(^{50}Ti,\gamma)^{258}Ku$.

The smaller number of stages of the compound-nucleus evaporation cascade leads to a substantial gain in the cross-section magnitude for cold-fusion reactions. An analysis of data on the Pb + Ar reaction (Gaeggeler and others, 1979) shows that they can be described with the help of eq. (1) without assuming a smaller cross section for the fusion of lead and argon nuclei, as compared with hot-fusion reactions. However, already the Ti (Z=22)-induced reactions exhibit entrance-channel limitations to fusion, and the cross sections of the Pb(Ti,xn) reactions turn out to be noticeably smaller than the values calculated by formula (1). In proceeding to the heavier projectiles, the entrance-channel limitations played an increasing role as the atomic number of the compound nucleus increased (Armbruster, 1985,1986). Nevertheless, the cold-fusion reactions proved very efficient in synthesizing a number of transactinide elements.

For this purpose different techniques were used at Dubna and at Darmstadt.

At Dubna (see Oganessian, 1983), internal beams from the U-400 cyclotron of $^{48-50}Ti$, ^{54}Cr, ^{55}Mn, ^{58}Fe, ^{59}Co, and ^{64}Ni with intensities in the range $5\times10^{12} - 5\times10^{13}$ s^{-1} were used to synthesize nuclei with Z=104-111. These ions bombarded Tl, Pb and Bi deposited onto the external surface of a rotating cooled drum. The entire surface of the drum, except for the part being irradiated, was surrounded with solid-state fission-fragment track detectors. This allowed one to record the decay of spontaneously fissioning short-lived reaction products with half-lives of $>10^{-4}$ s. If the nascent nuclei underwent α decay, their formation was established by observing the α decay or spontaneous fission of long-lived α-decay daughter products. In both cases no background was present even in long-time measurements (about 20 days). The experimental sensitivity was such that the observation of one spontaneous-fission or α-decay event corresponded to a reaction cross section of 3×10^{-37} cm^2.

The performance of such experiments was possible owing to the specific

features of the cold-fusion reactions. First, the target-like products of inelastic transfer reactions could not produce a spontaneous-fission background. Second, at bombarding energies ≤ 5.5 MeV/amu neutron evaporation (and γ-ray emission) is the main channel of compound-nucleus de-excitation. As seen from the data presented in table 3, the cross sections of the (HI,αxn) and (HI,pxn) reactions are very small. Therefore, having observed the long-lived final products of the α-decay chains of the nuclei formed in cold-fusion reactions one can draw some conclusions about the stability of the mother nuclei and about the cross sections of the reactions in which they have been synthesized.

TABLE 3. Some data on cold-fusion reactions between ^{208}Pb nuclei and titanium isotopes (Oganessian and others, 1984b)

Reaction	E^{max}_{lab} (MeV/amu)	Nucleus detected	Number of s.f. fragment tracks	Number of α-particles	Decay probability	Cross section ($\times 10^{-33}$ cm^2)
^{208}Pb(^{50}Ti, γ)^{258}Ku	5.45	^{246}Cf		65	α(0.13)	0.6
n)^{257}Ku		^{253}Fm		72	α(0.12)	5
2n)^{256}Ku		^{256}Ku	7440		SF(0.99)	6
		^{240}Cm		14	α(0.01)	6
3n)^{255}Ku		^{255}Ku	380		SF(0.5)	0.6
pn)^{256}103		^{252}Fm		<6	α(1.0)	<0.02
2n)^{252}102		^{240}Cm		14	α(0.73)	<0.06
^{208}Pb(^{49}Ti, n)^{256}Ku	5.53	^{256}Ku	120		SF(0.99)	0.2
2n)^{255}Ku		^{255}Ku	840		SF(0.5)	1.2
n)^{252}102		^{240}Cm		0	α(0.73)	< 0.004
p2n)^{254}103		^{242}Cm		0	α(1.0)	< 0.005
^{208}Pb(^{48}Ti, n)^{255}Ku	5.40	^{255}Ku	95		SF(0.5)	0.2
pn)^{254}103		^{246}Cf		10	α(0.94)	0.008
α)^{252}102		^{240}Cm		0	α(1.0)	< 0.003

The experimental approach used at GSI, Darmstadt implies the identification of new nuclides by observing their α decay and the correlated α decay chains of the daughter nuclei (Hofmann and others, 1984). The possibility of recording correlated α-decay chains sometimes consisting of up to 5 links is provided by separating the evaporation residues in the SHIP facility, a separator for heavy-ion reaction products (Münzenberg and others, 1979). A schematic diagram of this facility is shown in fig. 6. The combination of two electric and four magnetic dipole fields forms a pair of velocity filters. The velocity dispersion has a maximum value in the median plane of the system, where the separation of the evaporation residues from the

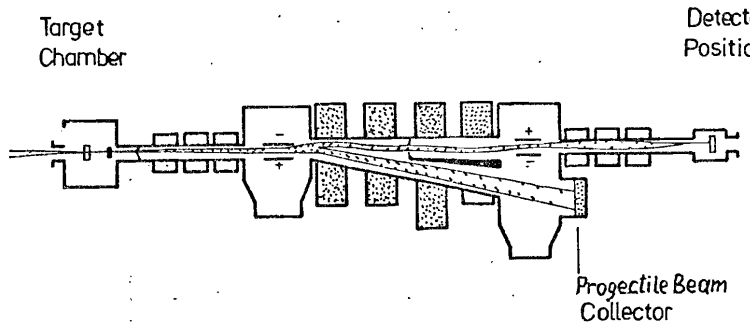

Fig. 6. Schematic diagram of the velocity filter SHIP (GSI,Darmstadt).

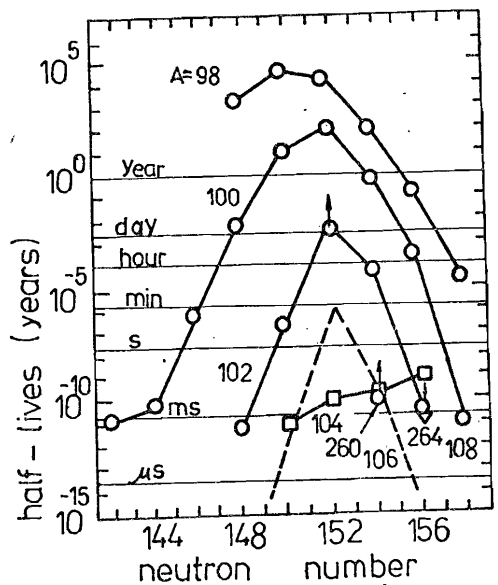

Fig. 7. Systematics of the spontaneous fission half-lives of even-even nuclei. Experimental data are shown by symbols connected by full lines. The dashed line shows the systematics of Ghiorso (1969) for the element 104 isotopes.

projectile beam occurs. The velocity dispersion is compensated for in the second part of the system. Two triplets of magnetic quadrupole lenses provide focussing of the complete-fusion products escaping the target within a 3° cone in the direction of the primary beam and having an ionic charge spread of 20%. In the case of the cold-fusion reactions leading to the forma-

tion of transfermium compound nuclei, the number of the projectiles which have passed the entire system decreased by a factor of 10^{10}-10^{13} compared with the intensity of the primary beam. This allowed one to place the detector system directly after the separator. The detector system consisted of time-of-flight detectors and position-sensitive surface-barrier detectors. The time-of-flight and energy measurements for the recoil nuclei which had stricken the surface-barrier detector permitted a rough (with 10% accuracy) estimate of the masses of these nuclei. The detection system established the time correlation between the detection and α-decay of a recoil nucleus, as well as enabled the α-decay chains of the implanted nuclei to be revealed. In this way the authors could determine the α-decay energies and the half-lives of the new nuclides and perform their unambiguous identification.

Imediately after the detection of cold fusion between lead and argon nuclei Oganessian and others (1974,1975b) began experiments to study the formation of kurchatovium isotopes in the titanium-ion bombardments of lead isotopes. These experiments yielded the new isotopes ^{255}Ku and ^{256}Ku. The data on the even-even isotope ^{256}Ku which underwent spontaneous fission with $T_{1/2} \simeq 5$ ms* were of special interest. This isotope with the closed N=152 subshell has a spontaneous fission half-life a factor of 10^6 shorter than that of the neighbouring even-even isotope ^{254}102 which also has the closed N=152 subshell. Moreover, the half-life $T_{1/2} \simeq 5$ ms is approximately 10^4 times smaller than the value predicted by the empirical systematics of the half-lives of actinide nuclei (Ghiorso, 1969). As one can see (fig. 7) from the new systematics obtained by Oganessian and others (1974), in going from elements with $Z \leq 102$ to kurchatovium ($Z=104$) the character of the dependence of $T_{1/2}$ on neutron number in even-even nuclei changes drastically. In the isotopes of fermium (Z=100) and element 102 the stabilizing effect of the N=152 subshell manifests itself explicitly in the observation of a sharp maximum in the $T_{1/2}$ value for N=152. There is no such a maximum for kurchatovium isotopes. This change in the systematics was explained qualitatively by Oganessian and others (1975b) who paid attention to the fact that in the region of interest the second maximum of the double-humped fission barrier has the largest value at N=152. The height of the second barrier decreases rapidly with increasing Z, as well as in moving farther from N=152 in the direction of a greater or a smaller number of neutrons, whereas the first barrier height remains almost unchanged (see, e.g., Brack and others, 1972). Oganessian and others (1975b) assumed that the second maximum of the fission barrier should lie below the nuclear ground state starting with kurchatovium isotopes (i.e. for $Z \geq 104$). Therefore, the spontaneous-fission lifetimes of these nuclides should depend on the neutron number weakly. From this explanation it is also possible to conclude (Oganessian and others, 1975b) that the

*Later, more accurate values were obtained: $T_{1/2}=7.4^{+0.9}_{-0.7}$ ms and the s.f. and α-decay branching ratios of 98% and 2%, respectively, by Münzenberg and others (1982a) and Hessberger and others (1985); and $T_{1/2}=6.7\pm0.2$ ms, the s.f. and α-decay branching ratios of 99% and 1% by Oganessian and others (1984b).

decrease in $T_{1/2}$ with growing atomic number in the vicinity of kurchatovium, which took place for the $Z \leq 102$ nuclei, should become slower for elements with $Z > 104$.

For comparison with theoretical calculations, the data on even-even isotopes presented in fig. 7 are most informative since, in contrast to odd isotopes, in this case there is no hindrance factor for spontaneous fission. The calculations performed by Randrup and others (1976) showed that the new systematics given in fig. 7 agree with the theoretical calculations using the double-humped fission barrier concept. The new systematics solved in a natural way the problem of the "anomalously high" hindrance factors ensuing from Ghiorso's systematics (Ghiorso, 1969) for the spontaneous fission of odd kurchatovium isotopes. For example, according to those systematics, the hindrance factor for the spontaneous fission of ^{257,259}Ku was 10^6-10^9 while it exceeded 10^{13} for ^{261}Ku (Ghiorso and others, 1970b). As a matter of fact, the new systematics showed that the hindrance factors for the spontaneous fission of ^{257,259,261}Ku lie in the range 10^3-10^4, which are common for even-odd nuclei.

In the last decade the two groups, at Dubna and at Darmstadt, made considerable progress in their attempts to synthesize transkurchatovium nuclei. This experimental research is one of the most complicated ones carried out on heavy-ion beams from accelerators. It required a large number of many-day runs of heavy-ion irradiations involving the use of very expensive and rare isotopes (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{48}Ca, and others). Sophisticated physical and chemical techniques and experimental facilities were operated during and after these runs. To venture performing these studies it was necessary to overcome the doubts expressed by some authors (Nitschke and others 1978; Viola and others, 1980) about the feasibility of the route taken. Therefore special mention should be made of the unanimity between the Dubna and the Darmstadt groups in performing this work. Such relations arose at the early stage when the experiments initiated at Dubna and aimed to synthesize superheavy elements in the U + Xe reaction were pursued at GSI, Darmstadt. There, deep inelastic reactions induced by uranium ions were investigated thoroughly with a view of synthesizing superheavy elements. It is pleasant to note that the inherent factor of competition between Dubna and Darmstadt in no way impeded the information exchange which allowed them with lesser efforts to carry out the studies which were complementary to one another.

With an enhanced heavy-ion beam intensity compared with that used at GSI, the Dubna group decided to determine the probabilities for the occurrence of different cold-fusion reactions and to establish the formation of new nuclides by detecting the known daughter products of their radioactive decay.

The Darmstadt group successfully used their special-purpose technique which was capable of establishing the actual existence of new nuclides and of identifying them by recording rare correlated α-decay chains.

The data obtained as a result of the synthesis of the isotopes of elements

TABLE 4. Experimental data on synthesis of the isotopes of elements 107-109

Z	A	$T_{1/2}$ (ms)	E (MeV)	Decay mode and its branching ratio	Reactions	E_{lab} (MeV)	Number of decay events detected	σ ($\times 10^{-33}$ cm^2)	Nucleus to be detected	References
107	261	$2.8^{+2.1}_{-1.1}$		SF(0.2)	$^{209}Bi(^{54}Cr,2n)$	290*	99	0.05	$^{261}107$	Oganessian and others, 1976***
					$^{208}Pb(^{55}Mn,2n)$	290*	71	0.02	$^{261}107$	
	261	$6.1^{+4.3}_{-1.8}$	10.39; 10.10; 10.10	α (>0.7)	$^{209}Bi(^{54}Cr,2n)$	269	7	0.12	$^{261}107$	Münzenberg and others, 1986 a,b
	262	$4.7^{+2.3}_{-1.6}$	10.35	α (>0.8)	$^{209}Bi(^{54}Cr,1n)$	264	16	0.2	$^{262}107$	Münzenberg and others, 1981, 1986 a,b
		5.6^{+53}_{-18}	10.23; 9.89; 9.71							
	262			α(1.0)	$^{209}Bi(^{54}Cr,1n)$	290*	86	0.2	^{258}Ns, ^{246}Cf	Oganessian 1983,
					$^{208}Pb(^{55}Mn,1n)$	310*	278	0.1		Oganessian and others, 1984 b
108	263			α (1.0)	$^{209}Bi(^{55}Mn,n)$	300*	33	0.002	^{255}Ku	Oganessian 1983; Oganessian and others, 1984 a
	264			α (1.0)	$^{207}Pb(^{58}Fe,1n)$	320*	13	0.005	^{256}Ku	Oganessian and others, 1984 a
					$^{208}Pb(^{58}Fe,2n)$	320*	7	0.002	^{256}Ku	
	264	$0.8^{+0.36}_{-0.04}$	11.0**	α (1.0)	$^{207}Pb(^{58}Fe,1n)$	292	1	0.003	$^{264}108$	Münzenberg and others, 1986 a; Hofmann and others, 1986
	265	$1.8^{+2.2}_{-0.7}$	10.36	α(1.0)	$^{208}Pb(^{58}Fe,1n)$	292	3	0.002	$^{265}108$	Münzenberg and others, 1984 a
	265			α(1.0)	$^{208}Pb(^{58}Fe,1n)$	320*	3	0.004	^{253}Es	Oganessian and others, 1984a
109	266	$3.5^{+16.6}_{-1.6}$	11.10	α(1.0)	$^{209}Bi(^{58}Fe,1n)$	299	1	$0.015^{+0.035}_{-0.012}$	$^{266}109$	Münzenberg and others, 1982 b, 1984 b
	266			α(1.0)	$^{209}Bi(^{58}Fe,1n)$	320*	7	0.003	^{246}Cf	Oganessian and others, 1984 b

*Ion energy measured at the entrance into a thick target.

**The α-decay energy estimate made according to the half-life.

***The data communicated by Oganessian at the 1985 European Conference on Nuclear Physics held in Varna are included.

107, 108 and 109 are presented in table 4. The main results of that work can be summarized as follows.

First, it has been established that the lifetimes of both odd and even-even nuclei decrease very slowly as one goes from kurchatovium to the heavier elements. There is no doubt that the liquid-drop fission barrier is virtually absent in these nuclei and their stability depends only on the barrier due to shell effects. The enhancement in stability is rather considerable. In particular, for the even-even isotopes $^{260}106$ and $^{264}108$ the spontaneous fission half-lives lie in the millisecond range, these values exceeding the liquid-drop limit by 17-18 orders of magnitude. This result strongly supports the hypothesis that superheavy nuclei should exist. Therefore it stimulated further fission-barrier calculations for these nuclei (Ćwiok and others, 1983, 1985; Möller, Leander and Nix, 1986; Möller, Nix and Swiatecki, 1986a,b).

The second conclusion from the studies carried out to synthesize the elements with atomic numbers 107-109 is that the cross sections of cold-fusion reactions tend to decrease drastically as the atomic number of the compound nucleus increases (see fig. 8). Therefore, already in the experiments aimed at synthesizing elements 108 and 109 one succeeded in observing only one nucleus during 3-10 days despite the fact that the maximum permissible

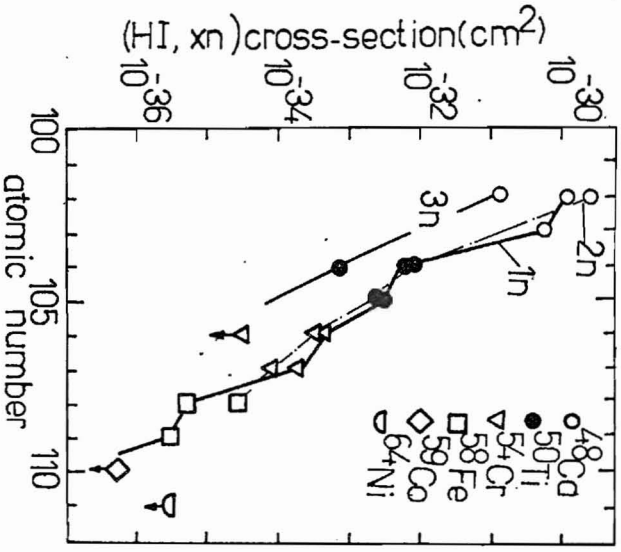

Fig. 8. Experimental cross sections of the cold-fusion reactions involving the evaporation of 1, 2 and 3 neutrons.

intensity of the heavy ion beam and effective detection methods were used. Extrapolation of the data presented in fig. 8 shows that cold-fusion reactions will give not more than one atom of element 110 during 10-100 days. Nevertheless, the appropriate experiments have been performed both at Dubna and at Darmstadt. Attempts were made to synthesize the nuclei of elements 110 and 111 in the reactions $^{209}Bi + {}^{59}Co \longrightarrow {}^{268}110^*$, $^{209}Bi + {}^{64}Ni \longrightarrow {}^{273}111^*$ (Oganessian and others, 1986) and $^{208}Pb + {}^{64}Ni \longrightarrow {}^{272}110^*$ (Münzenberg and others, 1986a,c). Unfortunately no one atom of element 110 or 111 has been detected in those experiments. The limits of the reaction cross sections are shown in fig. 8.

Recent theoretical studies (Błocki, Feldmeier and Swiatecki, 1986) also lead to the conclusion that the cold-fusion reactions have practically exhausted their possibilities for the synthesis of new elements with $Z \geq 110$.

POSSIBLE WAYS OF SYNTHESIZING STILL HEAVIER ELEMENTS ($Z \geq 110$)

Thus, the use of the cold-fusion reactions have proved inefficient in synthesizing elements with atomic numbers ≥ 110. The $^{248}Cm + {}^{48}Ca$ reaction employed in attempts to produce superheavy nuclei close to the magic ones with the proton number Z=114 and the neutron number N=184 gave no positive results either (see Flerov and Ter-Akopian, 1983,1985 and Armbruster and others,1985). The attempts to synthesize superheavy nuclei by the deep inelastic transfer reactions $^{238}U + {}^{238}U$ and $^{248}Cm + {}^{238}U$ have also failed (see Kratz and others, 1986). The heaviest atomic nuclei produced by these reactions belong to mendelevium isotopes (Z=101) (Schädel and others, 1982). With all these discouraging results and pessimistic conclusions in mind we should ask the natural question: is it not time to stop and give up the dream of producing atomic nuclei with proton number 110 and larger, including the superheavy elements ($Z \simeq 114$) close to the hypothetical summit of the island of stability? However, all those who are engaged in this field of research believe that, in addition to the studies directed to an expansion of the region of the $Z < 110$ nuclei investigated, it is possible and necessary to make further attempts to produce new elements with $Z \geq 110$. In this context we shall consider the features of the reactions so far used to synthesize new elements, as well as the reactions which, in our view, can lead to the synthesis of the still heavier elements with $Z \geq 110$. Table 5 gives the different target-projectile combinations which were used at the first and second stages of the studies relevant to the synthesis of new elements, namely, in hot- and cold-fusion reactions.

Owing to the large asymmetry in the masses of the colliding nuclei and to the presence of a low, though finite in height, liquid-drop fission barrier for compound nuclei with $Z \lesssim 106$, the formation of the latter in hot-fusion reactions was characterized by a cross section comparable to the interaction cross section. Despite the high fissility of compound nuclei with excitation energies of 40-50 MeV, they could survive in a relatively small number of cases after the evaporation of 4-6 neutrons. However, the synthesis of the

TABLE 5. Some typical hot-fusion and cold-fusion reactions and the reactions on actinide targets, which are likely to produce elements with $Z \geq 110$

Z	Hot fusion	Cold fusion
102	$^{238}_{92}U(^{22}_{10}Ne,4n)^{256}102$; $^{243}_{95}Am(^{15}_{7}N,4n)^{254}102$ $^{242}_{94}Pu(^{18}_{8}O,5n)^{255}102$; $^{246}_{96}Cm(^{12}_{6}C,5n)^{253}102$	$^{206}_{82}Pb(^{48}_{20}Ca,2n)^{252}102$
103	$^{243}_{95}Am(^{18}_{8}O,5n)^{256}103$; $^{243}_{95}Am(^{16}_{8}O,4n)^{255}103$	
104	$^{242}_{94}Pu(^{22}_{10}Ne,5n)^{259}_{104}Ku$; $^{249}_{97}Bk(^{15}_{7}N,4n)^{260}_{104}Ku$	$^{208}_{82}Pb(^{50}_{22}Ti,2n)^{256}Ku$
105	$^{243}_{95}Am(^{22}_{10}Ne,4n)^{261}_{105}Ns$; $^{249}_{98}Cf(^{15}_{7}N,4n)^{260}_{105}Ns$	$^{209}_{83}Bi(^{50}_{22}Ti,1n)^{258}Ns$; $^{209}_{83}Bi(^{50}_{22}Ti,2n)^{257}_{105}Ns$
106	$^{249}_{98}Cf(^{18}_{8}O,4n)^{263}106$	$^{208}_{82}Pb(^{54}_{24}Cr,1n)^{261}106$; $^{208}_{82}Pb(^{54}_{24}Cr,2n)^{260}106$
107		$^{209}_{83}Bi(^{54}_{24}Cr,1n)^{262}107$; $^{209}_{83}Bi(^{54}_{24}Cr,2n)^{261}107$
108		$^{209}_{83}Bi(^{55}_{25}Mn,1n)^{263}108$; $^{207}_{82}Pb(^{58}_{26}Fe,1n)^{264}108$ $^{208}_{82}Pb(^{58}_{26}Fe,1n)^{265}108$
109		$^{209}_{83}Bi(^{58}_{26}Fe,1n)^{266}109$

Fusion reactions based on actinide targets

110	$^{232}_{90}Th + {}^{48}_{20}Ca \longrightarrow {}^{280}110^*$; $^{232}_{90}Th + {}^{44}_{20}Ca \longrightarrow {}^{276}108^*$; $^{236}_{92}U + {}^{40}_{18}Ar \longrightarrow {}^{276}110^*$; $^{238}_{92}U + {}^{40}_{18}Ar \longrightarrow {}^{278}110^*$; $^{242}_{94}Pu + {}^{36}_{16}S \longrightarrow {}^{278}110^*$ $^{242}_{94}Pu + {}^{34}_{16}S \longrightarrow {}^{276}110^*$; $^{244}_{94}Pu + {}^{36}_{16}S \longrightarrow {}^{280}110^*$; $^{248}_{96}Cm + {}^{30}_{14}Si \longrightarrow {}^{278}110^*$ $^{249}_{98}Cf + {}^{26}_{12}Mg \longrightarrow {}^{275}110^*$
111	$^{231}_{91}Pa + {}^{48}_{20}Ca \longrightarrow {}^{279}111^*$; $^{231}_{91}Pa + {}^{44}_{20}Ca \longrightarrow {}^{275}111^*$ $^{236}_{92}U + {}^{41}_{19}K \longrightarrow {}^{277}111^*$; $^{238}_{92}U + {}^{41}_{19}K \longrightarrow {}^{279}111^*$; $^{237}_{93}Np + {}^{40}_{18}Ar \longrightarrow {}^{277}111^*$ $^{242}_{94}Pu + {}^{37}_{17}Cl \longrightarrow {}^{279}111^*$; $^{244}_{94}Pu + {}^{37}_{17}Cl \longrightarrow {}^{281}111^*$; $^{243}_{95}Am + {}^{36}_{16}S \longrightarrow {}^{279}111^*$; $^{249}_{97}Bk + {}^{30}_{14}Si \longrightarrow {}^{279}111^*$

still heavier elements by this kind of reactions seems to be problematic in view of the growing fissility of the compound nucleus and because of the absence of target nuclei with atomic numbers >98. The possibility of using a few-microgram targets of the long-lived einsteinium isotope ^{254}Es (Z=99), which has appeared recently (Hulet and others, 1986), and prospects for producing ^{254}Es in large amounts (Hoffman, 1986) are of considerable interest in connection with the production of new heavy isotopes of transfermium elements, but not the $Z \geq 110$ nuclei.

By passing to cold-fusion reactions one succeeded in reducing the compound-nucleus excitation energy and in enhancing the probability of its survival. As a result, the limit of known nuclides has been advanced to the region of large atomic numbers up to Z=109. In this study it has been found that reactions, involving the emission of one neutron, (HI, 1n), play a special role. In such reactions the compound-nucleus de-excitation process is not crucial for the yield of final reaction products. A small yield of the atomic nuclei of new elements is due mainly to the fact that the fusion probability drastically decreases as the atomic number of the compound nucleus increases because of the growing symmetry in the target and projectile masses and of the ever increasing Coulomb repulsion.

In this situation the synthesis of elements with $Z \geq 110$ might be feasible in the reactions in which the effect of the unfavorable factors indicated (the high excitation energy of the compound nucleus and strong Coulomb repulsion) is not very substantial. In this connection it is worth considering reactions involving the fusion of uranium and adjacent elements nuclei with the nuclei of projectiles intermediate between chromium and neon. Some of these reactions leading to the Z=110 and 111 nuclei are listed in Table 5.

These reactions, in particular, Th + Ca, U + Ar, and others were proposed and analyzed in the talk given by Flerov (1984) at the 1983 Conference on Nuclear Physics in Florence. The choice of these reactions was motivated by the following considerations. First, these reactions are characterized by large asymmetry and by weaker Coulomb repulsive forces acting between the target and the projectile nuclei, compared with reactions on lead and bismuth targets. Second, in the case of a thorium or uranium target the macroscopic properties of the colliding nuclei, namely their static and dynamical deformations, possible neck formation, etc., might make it easier to form a slightly excited compound nucleus, if not a cold one.

The probability for slightly excited equilibrium compound nuclei to be formed in the reactions Th + Ca or U + Ar depends on the dynamics of the transition of the nuclear system formed in the entrance channel to the saddle point of the compound nucleus (see, e.g., Bjørnholm and Swiatecki, 1982; Błocki, Feldmeier and Swiatecki, 1986; Nix and Sierk, 1986). The coupling of collective and single-particle motion leads to the heating of the nuclear system and to the appearance of a dynamical barrier preventing fusion.

Because of this dynamical barrier, some authors do not share the above-mentioned view that the synthesis of the $Z \geq 110$ nuclei can be carried out by

fusion reactions occurring on actinide targets. For example, Armbruster (1986) supposes that the closed N=126 shell in Pb and Bi nuclei plays a special role thus making reactions of the Pb + Ni type preferable in the synthesis of element 110 because of their lower dynamical barrier compared with the U + Ar reactions.

Recently Möller, Nix and Swiatecki (1986b), based on their calculations of potential energy surfaces for nuclear systems having configurations resembling two touching spheres, also set out the supposition that the closed nucleon shells of colliding nuclei play a significant role in decreasing the dynamical barrier of fusion.

The reactions $^{235}U + ^{40}Ar$ leading to the synthesis of element 110 were predicted by Armbruster (1986) to have very low cross sections of $1.3 \times 10^{-39} cm^2$, i.e. a factor of 3×10^3 smaller than that of the combination $^{208}Pb + ^{64}Ni$.

However, we consider this conclusion disputable since it has been drawn from an extrapolation of data on symmetric or nearly symmetric reactions leading to the Z=80-90 nuclei (Sahm and others, 1985; Reisdorf and others, 1985; Keller and others, 1986; Quint and others, 1986). In these reactions the Coulomb and nuclear forces are balanced in a quite different way compared with the reactions U + Ar or Pb + Ni.

Evidently, the survival probability for the $Z \geq 110$ compound nucleus depends on the stabilizing effect of its nucleon shells, which can vanish in a strongly heated nuclear system.

However, bearing in mind weak exotic reaction channels (the fusion reaction cross section may be the 10^{-12}-10^{-10}th fraction of the total interaction cross section) it is possible to assume that a slightly excited compound nucleus may be produced even in the case of a significant dynamical barrier. For example, in passing from the entrance-channel configuration to the saddle point of the compound nucleus the system can emit an energetic neutron or γ ray and reach an excitation energy low enough for the stabilizing shell effects to manifest themselves. This assumption about the mechanism of compound-nucleus de-excitation agrees with the experimental data obtained by Gaeggeler and others (1979) and Hessberger and others (1985). They have shown that the high-energy tails of the excitation functions of the $^{206}Pb(^{40}Ar, 2n)$, $^{208}Pb\ (^{50}Ti, 1n)$ and $^{208}Pb(^{50}Ti, 2n)$ reactions cannot be explained in terms of the statistical model and are very likely to be due to the nonequilibrium de-excitation mechanism.

What has been said above can be summarized as follows.

Having yielded several decay events of the nuclei of elements 108 and 109, the cold-fusion reactions have practically exhausted themselves. Now only fusion reactions occurring on actinide targets can hopefully lead to the synthesis of the $Z \geq 110$ nuclei. Only direct experiments can give an answer to the question as to what extent such conclusions are justified. Therefore it was found appropriate to perform such experiments by using the very

sensitive techniques employed previously in the experiments aimed at synthesizing the nuclei of elements 107-109. Recently the Dubna and the Darmstadt groups have carried out such experiments.

At Darmstadt, the $^{235}U + ^{40}Ar \longrightarrow ^{275}110^*$ reaction was investigated at an argon ion energy close to the Coulomb barrier (Münzenberg and others, 1986a). The search was made for the α-radioactive and spontaneously fissioning products which might be assigned to the nuclei of element 110. Negative results have been obtained. The limit of cross sections for the reactions possibly producing the element 110 nuclei having lifetimes longer than several microseconds was set at a level of $< 1.4 \times 10^{-35} cm^2$.

In the Dubna experiments, the $^{232}Th + ^{48}Ca$ reaction was investigated at first (Oganessian and others, 1986). These experiments did not result in the detection of complete-fusion product nuclei with spontaneous fission half-lives of >0.5 ms. The experiments have set the upper limit for the cross section at a level of $5 \times 10^{-36} cm^2$. One of the explanations of this negative result can be that the isotopes of element 110 which might have been produced in this reaction have a very short lifetime with respect to spontaneous fission (Leander and others, 1984). Therefore the authors of this study decided to pass to the ^{44}Ca projectiles which, after fusion with ^{232}Th, could yield the isotopes of element 110 with the neutron number $N \lesssim 164$, which are calculated to have enhanced stability against spontaneous fission (Ćwiok and others, 1983; Leander and others, 1984; Möller, Leander and Nix, 1986). Two spontaneously fissioning products with half-lives of $0.82^{+0.31}_{-0.23}$ms and $8.6^{+4.0}_{-2.4}$ms were observed in the $^{232}Th + ^{44}Ca$ reaction. The yields of these products as functions of bombarding energy are shown in fig. 9. The short-lived activity was identified as the spontaneously fissioning isomer ^{240f}Am ($T_{1/2}=0.9\pm0.1$ms). This conclusion was drawn from the coincidence of the half-life values, as well as from measurements of the ^{240}Ar and ^{242}Cm yields compared with known isomeric ratios. The ~8 ms spontaneous fission activity has an excitation function resembling that expected for a complete-fusion reaction. A spontaneously fissioning product with a half-life of about 8 ms was also produced in the $^{236}U + ^{40}Ar$ reaction at an Ar ion energy of 210 MeV in the laboratory system. No activity with such a half-life was observed in the $^{231}Pa + ^{40}Ar$ reaction. Thus, the observation of the spontaneously fissioning nucleus with $T_{1/2}$ ~8 ms could be considered as evidence for the formation of the isotopes of element 110 in the $^{232}Th + ^{44}Ca$ and $^{236}U + ^{40}Ar$ reactions.

Hence a question arises as to in what way one can verify this tentative conclusion and recognize element 110 as an actual member of the "elemental community". For this purpose the electrostatic reaction-product separator VASSILISSA was recently put into operation on a heavy ion beam at Dubna (Eremin and others, 1985). The separator provides a high purification factor ($10^{11} - 10^{12}$) in separating complete-fusion products from the beam particles. It also performs focussing of about 20-30% of the evaporation residues onto a device capable of isolating these recoil nuclei according to their times of flight and energies. The identification of the nuclei synthesized is done by observing correlated α-decay chains. The kinetic energy and mass

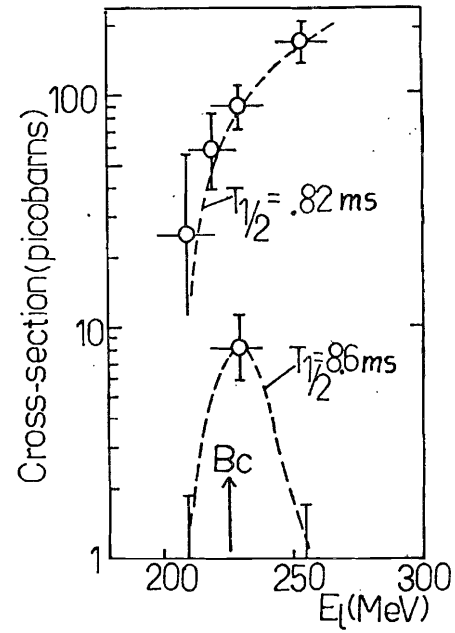

Fig. 9. Excitation functions of the reactions leading to the formation of ^{240f}Am and the spontaneously fissioning product with a half-life of 8.6 ms. A ^{232}Th target was bombarded by ^{44}Ca ions. The dashed lines are drawn arbitrarily. The Coulomb barrier is indicated by an arrow.

asymmetry of the fission fragments can be determined for spontaneously fissioning nuclei. If this separator makes it possible to confirm the results obtained for the $^{232}Th + ^{44}Ca$ and $^{236}U + ^{40}Ar$ reactions, except for the discovery of element 110, all the arguments advanced in favour of fusion reactions on actinide targets would prove correct. This would switch on "green light" for the studies of a great number of reactions possibly leading to the synthesis of atomic nuclei with $Z \geq 110$. Some of these reactions are listed in Table 5. The VASSILISSA separator offers considerable possibilities for performing such studies since it is capable of detecting the α decay and spontaneous fission of the short-lived (up to several microseconds) nuclei produced by nuclear reactions with cross sections of about $10^{-36} cm^2$.

On the other hand, half-life estimates for α decay and spontaneous fission (Möller, Leander and Nix, 1986; Möller, Nix and Swiatecki, 1986 a,b) show that the $Z \geq 110$ nuclei with half-lives of up to 0.1 s may exist. Basing on experience in developing and using rapid chemical methods for studying kurchatovium and nielsbohrium properties, one can work at improving them to use

them effectively in investigating reaction products having lifetimes from several tens to a few milliseconds.

A gas-filled separator (Ghiorso and others, 1982; Armbruster, 1985) and, perhaps, a mass separator combined with an IGISOL-type ion source (Ärje and others, 1986) may have some advantages for the synthesis and study of new elements.

CONCLUSION

The 30-year studies of transfermium elements with heavy-ion beams have resulted in the synthesis of eight new elements, namely elements 102 through 109. The radioactive properties of over 40 isotopes of these elements have been investigated.

The results obtained in the spontaneous fission studies provide experimental evidence for the crucial role played by shell effects for the stability of heavy elements. Moreover, as a result of the shell-effect fission barrier, a very slight decrease in half-lives is observed as the atomic number increases around $Z > 104$. This gives us hopes that the nuclei of superheavy elements ($Z \simeq 114$, $N \simeq 178$ or 184) may have long lifetimes with respect to spontaneous fission.

The history of the studies relevant to new element synthesis can be divided into two stages. The first stage was associated with the use of hot-fusion reactions in which the nuclei of uranium or transuranium elements were bombarded with the heavy ions of carbon, nitrogen, oxygen or neon. At the second stage, use was made of cold-fusion reactions produced by bombarding the magic lead or bismuth nuclei with chromium, manganese or iron heavy ions.

Unfortunately the probability for cold-fusion reactions to occur greatly decreases as the atomic number of the compound nucleus increases. For example, in the case of elements 108 and 109 one did not succeed in obtaining more than one atom during several days. The origin of this limitation of cold-fusion reactions can now be understood only in general and this fact stimulates further research into the fusion process between complex nuclei. At the same time, the presently available information about this process makes us hopeful for the possible synthesis of new elements with $Z \geq 110$ by fusion reactions on actinide targets. The first evidence for the possible formation of the element 110 nuclei in the $^{232}Th + ^{44}Ca$ and $^{236}U + ^{40}Ar$ reactions has been obtained. In the near future control experiments will be performed which should either confirm the discovery of element 110, or demonstrate that nature has erected insuperable obstacles before us and we should for long stop the race for new elements and be satisfied with the expansion of the nuclidic chart in the range $100 \leq Z \leq 109$. If, however, it becomes clear that element 110 has in fact been produced, a wide scope will open up for the studies associated with the synthesis of increasingly heavy elements. The purpose of the studies would be the investigation of the properties of a great number of nuclei from the long-predicted but so far inaccessible new island of stability and further research into the mechanisms which govern the fusion of complex nuclei.

REFERENCES

Akapiev, G. N., A. G. Demin, V. A. Druin, E. G. Imaev, I. V. Kolesov, Yu. V. Lobanov, and L. P. Pashchenko (1966). Atomnaya Energiya, 21, 243-246.

Ärje, J., J. Äystö, H. Hyvönen, P. Taskinen, V. Koronen, J. Honkanen, K. Valli, A. Hautojärvi, and K. Vierinen (1986). Nucl. Instr. Meth., A247, 431-437.

Armbruster, P. (1984). GSI - Preprint 84-47, Darmstadt.

Armbruster, P. (1985). Ann. Rev. Nucl. Part. Sci., 35, 135-194.

Armbruster, P. (1986). In Int. School-Seminar on Heavy Ion Physics, Dubna, 1986, Abstracts. JINR D7-86-434, Dubna, p.16.

Armbruster, P., Y. K. Agarval, W. Brüchle, M. Brügger, J. P. Dufour, H. Gäggeler, F. P. Hessberger, S. Hofmann, P. Lemmertz, G. Münzenberg, K. Poppenzieker, W. Reisdorf, M. Schädel, K. - H. Schmidt, J. H. R. Schneider, W. F. W. Schneider, K. Sümmerer, D. Fermeulen, G. Wirth, A. Ghiorso, K. E. Gregorich, D. Lee, M. Leino, K. J. Moody, G. T. Seaborg, R. W. Welch, P. Wilmarth, S. Yashita, C. Frink, N. Greulich, G. Herrmann, U. Hickmann, N. Hillenbrand, H. R. von Gunten, and H. Dornhöfer (1985). Phys. Rev. Lett., 54, 406-409.

Bemis, C. E., Jr., P. F. Dittner, R. L. Fergusson, D. C. Hensley, F. Plasil, and F. Pleasonton (1981). Phys. Rev., C23, 555-562.

Bjørnholm, S. and J. E. Lynn (1980). Rev. Mod. Phys., 52, 725-931.

Bjørnholm, S. and W. J. Swiatecki (1982). Nucl. Phys., A391, 471-504.

Błocki, J. P., H. Feldmeier, and W. J. Swiatecki (1986). Nucl. Phys., A459, 145-172.

Brack, M., J. Damgaard, A. S. Jensen, H. - C. Pauli, V. M. Strutinsky, and C. Y. Wong (1972). Rev. Mod. Phys., 44, 320-405.

Chuburkov, Yu. T., R. Caletka, M. R. Shalaevsky, and I. Zvara (1967). Radiochimiya, 9, 637-642.

Chuburkov, Yu. T., V. Z. Belov, R. Caletka, M. R. Shalaevsky, and I. Zvara (1969). Radiochimiya, 11, 394-399; J. Inorg. Nucl. Chem., 31, 3113-3118.

Ćwiok, S., V. V. Pashkevich, J. Dudek, and W. Nazarewicz (1983). Nucl. Phys., A410, 254-270.

Ćwiok, S., Z. Lojewski, and V. V. Pashkevich (1985). Nucl. Phys., A444, 1-12.

Davies, K. T. R., A. J. Sierk, and J. R. Nix (1983). Phys. Rev., C28, 679-691.

Demin, A. G., S. P. Tretyakova, V. K. Utyonkov, and I. V. Shirokovsky (1984). Z. Phys., A315, 197-200.

Donets, E. D., V. A. Shchegolev, and V. A. Ermakov (1964). Atomnaya Energiya, 16, 195-207.

Donets, E. D., V. A. Shchegolev, and V. A. Ermakov (1965). Atomnaya Energiya, 19, 109-113.
Donets, E. D., V. A. Shchegolev, and V. A. Ermakov (1966). Atomnaya Energiya, 20, 223-230.
Druin, V. A. (1970). Yad. Fiz., 12, 268-271.
Druin, V. A., G. N. Akapiev, A. G. Demin, Yu. V. Lobanov, B. V. Fefilov, G. N. Flerov, and L. P. Chelnokov (1967). Atomnaya Energiya, 22, 127-128.
Druin, V. A.,A. G. Demin, Yu. P. Kharitonov, G. N. Akapiev, V. I. Rud', G. Ya. Sun Tsinyang, L. P. Chelnokov, and K. A. Gavrilov (1970). JINR R7-5161, Dubna.
Druin, V. A., A. G. Demin, Yu. P. Kharitonov, G. N. Akapiev, V. I. Rud', G. Ya. Sun Tsinyang, L. P. Chelnokov, and K. A. Gavrilov (1971). Yad. Fiz., 13, 251-255.
Druin, V. A., Yu. V. Lobanov, D. M. Nadkarni, Yu. P. Kharitonov, Yu. S. Korotkin, S. P. Tretyakova, and V. I. Krashonkin (1973). Atomnaya Energiya, 35, 279-280.
Eremin, A. V., V. A. Tarabrin, S. V. Stepantsov, Yu. L. Obukhov, and G. M. Ter-Akopian (1985). JINR R15-85-786, Dubna.
Fields, P. R., A. M. Friedman, J. Milsted, H. Atterling, W. Forsling, L. W. Holm, and B. Astrom (1957). Phys. Rev., 107, 1460-1462.
Fields, P. R., A. M. Friedman, J. Milsted, H. Atterling, W. Forsling, L. W. Holm, and B. Astrom (1959). Arkiv Fys., 15, 225-236.
Flerov, G. N. (1967). Ann. Phys., 2, 311-323.
Flerov, G. N. (1984). In P. Blasi and R. A. Ricci (Eds.), Proc. Int. Conf. on Nuclear Physics, Florence, 1983. Tipografia Compositori, Bologna. vol. 2, pp. 365-383.
Flerov, G. N. and V. A. Druin (1966). In N. N. Bogolubov (Ed.), Structure of Complex Nuclei (in Russian). Atomizdat, Moscow. pp. 249-271.
Flerov, G. N. and V. A. Druin (1971). Atomic Energy Rev., 8, 255-326.
Flerov, G. N. and I. Zvara (1971). JINR D7-6013, Dubna.
Flerov, G. N. and G. M. Ter-Akopian (1983). Rep. Prog. Phys., 46, 817-875.
Flerov, G. N. and G. M. Ter-Akopian (1985). In D. A. Bromley (Ed.), Treatise on Heavy-Ion Science, vol.4, Extreme Nuclear States. Pergamon, New York. pp. 333-399.
Flerov, G. N., V. A. Druin, and A. A. Pleve (1970). Usp. Fiz. Nauk. 100, 45-92.
Flerov, G. N., S. M. Polikanov, A. S. Karamian, A. S. Pasjuk, D. M. Parfanovich, N. I. Tarantin, V. A. Karnaukhov, V. A. Druin, V. V. Volkov, A. M. Semchinova, Yu. Ts. Oganessian, V. I. Khalizev, and G. I. Khlebnikov (1958). Doklady Akad. Nauk SSSR, 120, 73-75.
Flerov, G. N., S. M. Polikanov, A. S. Karamian, A. S. Pasjuk, D. M. Parfanovich, N. I. Tarantin, V. A. Karnaukhov, V. A. Druin, V. V. Volkov, A. M. Semchinova, Yu. Ts. Oganessian, V. I. Khalizev, G. I. Khlebnikov, B. F. Mjasoyedov, and K. A. Gavrilov (1960). Zh. Eksp. Teor. Fiz., 38, 82-94.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, V. I. Kuznetsov V. A. Druin, V. P. Perelygin, K. A. Gavrilov, S. P. Tretyakova, V. M. Plotko (1964). Atomnaya Energiya, 17, 310-312.

Flerov, G. N., E. D. Donets, V. A. Druin, Yu. V. Lobanov, V. L. Mikheev, S. M. Polikanov, and V. A. Shchegolev (1966). In Proc. Int. Conf. on Heavy Ion Physics, Dubna 1966, Part 2. JINR D7-3548, Dubna. pp. 3-8.
Flerov, G. N., S. M. Polikanov, V. L. Mikheev, B. I. Ilyushchenko, V. F. Kushniruk, M. B. Miller, A. M. Sukhov, and V. A. Shchegolev (1967a). Yad. Fiz., 5, 1186-1191.
Flerov, G. N., Yu. S. Korotkin, V. L. Mikheev, M. B. Miller, S. M. Polikanov, and V. A. Shchegolev (1967b). Nucl. Phys., A106, 476-480.
Flerov, G. N., G. N. Akapiev, A. G. Demin, V. A. Druin, Yu. V. Lobanov, and B. V. Fefilov (1968). Yad. Fiz., 7, 977-983.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, and Yu. A. Lazarev (1970a). JINR R7-4932, Dubna.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, Yu. A. Lazarev, V. I. Kuznetsov, and S. P. Tretyakova (1970b). JINR R7-5108, Dubna.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, Yu. A. Lazarev, S. P. Tretyakova, I. V. Kolesov, and V. M. Plotko (1970c). Atomnaya Energiya, 29, 243-250.
Flerov, G. N., Yu. A. Lazarev, Yu. V. Lobanov, and Yu. Ts. Oganessian (1971a). In Int. Conf. on Heavy Ion Physics, Dubna 1971. JINR D7-5769, Dubna. pp. 125-144.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, Yu. A. Lazarev, S. P. Tretyakova, I. V. Kolesov, and V. M. Plotko (1971b). Nucl. Phys., A160, 181-192.
Flerov, G. N., Yu. Ts. Oganessian, Yu. V. Lobanov, A. A. Pleve, G. M. Ter-Akopian, A. G. Demin, S. P. Tretyakova, V. I. Chepigin, and Yu. P. Tretyakov (1974). Yad. Fiz., 19, 492-497.
Flerov, G. N., Yu. Ts. Oganessian, A. A. Pleve, N. V. Pronin, and Yu. P. Tretyakov (1976). Nucl. Phys., A267, 359-364.
Gaeggeler, H., A. S. Iljinov, G. S. Popeko, W. Seidel, G. M. Ter-Akopian, and S. P. Tretyakova (1979). Z. Phys., A289, 415-420.
Ghiorso, A. (1959). Atomnaya Energiya, 7, 338-350.
Ghiorso, A. (1969). In Proc. R. A. Welch Found. Conf. on Chemical Res., XIII. The Transuranium Elements - The Mendeleev Centennial, 1969, Houston, Texas. p. 107-150.
Ghiorso, A., B. G. Harvey, G. R. Choppin, S. G. Thompson, and G. T. Seaborg (1955). Phys. Rev., 98, 1518-1520.
Ghiorso, A., T. Sikkeland, J. R. Walton, and G. T. Seaborg (1958). Phys. Rev. Lett., 1, 18-21.
Ghiorso, A., T. Sikkeland, A. E. Larsh, and R. M. Latimer (1961). Phys. Rev. Lett., 6, 473-475.
Ghiorso, A., M. Nurmia, J. Harris, K. Eskola, and P. Eskola (1969). Phys. Rev. Lett., 22, 1317-1320.
Ghiorso, A., M. Nurmia, K. Eskola, and P. Eskola (1970). Phys. Lett., 32B, 95-98.
Ghiorso, A., J. M. Nitschke, J. R. Alonso, C. T. Alonso, M. Nurmia, G. T. Seaborg, E. K. Hulet, and R. W. Lougheed (1974). Phys. Rev. Lett., 33, 1490-1493.
Ghiorso, A., M. E. Leino, S. Yashita, L. Frank, P. Armbruster et al (1982). LBL Report 15955, Berkeley.

Hessberger, F. P., G. Münzenberg, S. Hofmann, W. Reisdorf, K. - H. Schmidt, H. J. Schött, P. Armbruster, R. Hingmann, B. Thuma, and D. Vermeulen (1985). Z. Phys., A321, 317-327.

Hoff, R. W. (1986). In H. V. Klapdor (Ed.), Weak and Electromagnetic Interactions in Nuclei. Springer-Verlag, Berlin. pp. 207-212.

Hoffman, D. C. (1986). Nucl. Instr. Meth., A249, 13-19.

Hofmann, S., G. Münzenberg, F. P. Hessberger, and H. - J. Schött (1984). Nucl. Instr. Meth., 223, 312-318.

Hofmann, S., P. Armbruster, G. Berthes, H. Folger, U. Gollerthan, E. Hanelt, F. P. Hessberger, M. E. Leino, G. Münzenberg, K. Poppenzieker, B. Quint, W. Reisdorf, K. - H. Schmidt, H. - J. Schött, K. Sümmerer, and J. Zychor (1986). In H. V. Klapdor (Ed.), Weak and Electromagnetic Interactions in Nuclei. Springer-Verlag, Berlin. pp. 179-185.

Hulet, E. K., J. F. Wild, R. J. Dougan, R. W. Lougheed, J. H. Landrum, A. D. Dougan, M. Schädel, R. L. Hahn, P. A. Baisden, C. M. Henderson, R. J. Dupzyk, K. Sümmerer, and G. R. Bethune (1986). Phys. Rev. Lett., 56, 313-316.

Hyde, E. K., I. Perlman, and G. T. Seaborg (1964). Nuclear Properties of the Heavy Elements. Prentice-Hall, New York.

Iljinov, A. S. and E. A. Cherepanov (1984). JINR R7-84-68, Dubna.

Jackson, J. D. (1956). Canad. J. Phys., 34, 767-772.

Johansson, S. (1962). Report UCRL - 10474, Berkeley.

Keller, O. L. (1984). Radiochim. Acta, 37, 169-180.

Keller, J. G., K. - H. Schmidt, F. P. Hessberger, G. Münzenberg, W. Reisdorf, H. - G. Clerc, and C. - C. Sahm (1986). Nucl. Phys., A452, 173-204.

Kolesnikov, N. N. and A. G. Demin (1975). JINR R6-9421, Dubna.

Kolesnikov, N. N. and V. M. Vymjatnin (1975). Izv. Akad. Nauk SSSR, Ser. Fiz., 39, 637.

Kratz, J. V., W. Brüchle, H. Folger, H. Gäggeler, M. Schädel, K. Sümmerer, G. Wirth, N. Greulich, G. Herrmann, U. Hickmann, P. Peuser, N. Trautmann, E. K. Hulet, R. W. Lougheed, J. M. Nitschke, R. L. Fergusson, and R. L. Hahn (1986). Phys. Rev., C33, 504-508.

Kuznetsov, V. I., N. K. Skobelev, and G. N. Flerov (1966). Yad. Fiz., 4, 279-281.

Leander, G. A., P. Möller, J. R. Nix, and W. M. Howard (1984). In E. Roecl (Ed.), Proc. 7-th Int. Conf. on Atomic Masses and Fundamental Constants, AMCO-7, Darmstadt, 1984. TH Lehrdruckerei, Darmstadt. pp. 466-471.

Lederer, C. M. and V. S. Shirley (1978). Table of Isotopes, Seventh Ed. John Wiley & Sons, New York.

Lojewski, Z. and A. Baran (1985). Z. Phys., A322, 695-700.

Macfarlane, R. D. and R. D. Griffioen (1963). Nucl. Instr. Meth., 24, 461-464.

McMillan, E. and P. H. Abelson (1940). Phys. Rev., 57, 1185-1186.

Mikheev, V. L. (1966). Pribory i Teknika Eksperimenta, 4, 22-26.

Mikheev, V. L., V. I. Ilyushchenko, M. B. Miller, S. M. Polikanov, G. N. Flerov, and Yu. P. Kharitonov (1967). Atomnaya Energiya, 22, 90-97.

Möller, P. and J. R. Nix (1981a). Nucl. Phys., A361, 117-146.

Möller, P. and J. R. Nix (1981). At. Data Nucl. Data Tables, 26, 165-196.

Möller, P., G. A. Leander, and J. R. Nix (1986). Z. Phys., A323, 41-45.

Möller, P., J. R. Nix, and W. J. Swiatecki (1986a). Preprint LA-UR-86-3182, Los Alamos.

Möller, P., J. R. Nix, and W. J. Swiatecki (1986b). Preprint LA-UR-86-3266, Los Alamos (Submitted to Nucl. Phys. A).

Münzenberg, G., W. Faust, S. Hofmann, P. Armbruster, K. Güttner, and H. Evald (1979). Nucl. Instr. Meth., 161, 65-82.

Münzenberg, G., S. Hofmann, F. P. Hessberger, W. Reisdorf, K. - H. Schmidt, J. H. R. Schneider, P. Armbruster, C. - C. Sahm, and B. Thuma (1981). Z. Phys., A300, 107-108.

Münzenberg, G., P. Armbruster, W. Faust, K. Güttner, F. P. Hessberger, S. Hofmann, W. Reisdorf, C. - C. Sahm, K. - H. Schmidt, H. J. Schött, B. Thuma, and D. Vermeulen (1982a). In N. M. Edelstein (Ed.), Actinides in Perspective. Pergamon, Oxford and New York. pp. 223-243.

Münzenberg, G., P. Armbruster, F. P. Hessberger, S. Hofmann, K. Poppenzieker, W. Reisdorf, J. R. H. Schneider, W. F. W. Schneider, K. - H.Schmidt, C. - C. Sahm, and D. Vermeulen (1982b). Z. Phys., A309, 89-90.

Münzenberg, G., P. Armbruster, H. Folger, F. P. Hessberger, S. Hofmann, J. Keller, K. Poppenzieker, W. Reisdorf, K.-H.Schmidt, H.-J.Schött M. E. Leino, and R. Hingmann (1984a). Z. Phys., A317, 235-236.

Münzenberg, G., W. Reisdorf, S. Hofmann, Y. K. Agarval, F. P. Hessberger, K. Poppenzieker, J. R. H. Schneider, W. F. W. Schneider, K. - H. Schmidt, H. - J. Schött, P. Armbruster, C. - C. Sahm, and D. Vermeulen (1984b). Z. Phys., A315, 145-158.

Münzenberg, G., S. Hofmann, H. Folger, F. P. Hessberger, J.Keller, K. Poppenzieker, B. Quint, W. Reisdorf, K. - H. Schmidt, H. - J. Schött, P. Armbruster, M. E. Leino, and R. Hingmann (1985). Z. Phys., A322, 227-235.

Münzenberg, G., P. Armbruster, G. Berthes, H. Folger, F. P. Hessberger, S. Hofmann, K.Poppenzieker, B. Quint, W. Reisdorf, K. - H. Schmidt, H. - J. Schött, K. Sümmerer, I. Zychor, M. E. Leino, U. Gollerthan, E. Hanelt (1986a). In Int. School-Seminar on Heavy Ion Physics, Dubna, 1986, Abstracts. JINR D7-86-434, Dubna. p.17.

Münzenberg, G., S. Hofmann, F. P. Hessberger, K. - H. Schmidt, G. Berthes, H. Folger, H. Geisel, J. G. Keller, P. Lemmertz, M. Montoya, K. Poppenzieker, B. Quint, H. - J. Schött, I. Zychor, and P. Armbruster (1986b). In GSI Scientific Report 1985. GSI 86-1, Darmstadt. p.31.

Münzenberg, G., F. P. Hessberger, P. Armbruster, S. Hofmann, K. - H. Schmidt, G. Berthes, H. Folger, H. Geisel, J. G. Keller, P. Lemmertz, M. Montoya, K. Poppenzieker, B. Quint, H. - J. Schött, I. Zychor, M. E. Leino, and U. Gollerthan (1986c). In GSI Scientific Report, 1985. GSI 86-1. p. 29.

Nitschke, J. M., R. E. Leber, M. J. Nurmia, and A. Ghiorso (1978). Nucl. Phys., A313, 236-250.

Nix, J. R. and A. J. Sierk (1976). In Proc. Inst. School-Seminar on Reactions of Heavy Ions with Nuclei and Synthesis of New Elements, Dubna 1975. JINR D7-9734. pp. 101-110.

Nix, J. R. and A. J. Sierk (1977). Phys. Rev., C15, 2072-2082.

Nix, J. R. and A. J. Sierk (1985). In Proc. Int. Conf. on Nuclear Physics, Bombay, 1984. World Scientific, Singapore. pp. 365-383.

Nix, J. R. and A. J. Sierk (1986). In Int. School-Seminar on Heavy Ion Physics, Dubna, 1986, Abstracts. JINR D7-86-434, Dubna. p. 117.
Oganessian, Yu. Ts. (1974). Lect. Notes Phys., 33, 221-252.
Oganessian, Yu. Ts. (1977). Nucleonica, 22, 90-106.
Oganessian, Yu. Ts. (1982). In N. M. Edelstein (Ed.), Actinides in Perspective. Pergamon, Oxford and New York. pp. 203-221.
Oganessian, Yu. Ts. (1983). In Int. School-Seminar on Heavy Ion Physics, Alushta, 1983. JINR D7-83-644, Dubna. pp. 55-75.
Oganessian, Yu. Ts. and Yu. A. Lazarev (1981). Pure Appl. Chem., 53, 925-947.
Oganessian, Yu. Ts., Yu. P. Tretyakov, A. S. Iljinov, A. G. Demin, A. A. Pleve, S. P. Tretyakova, V. M. Plotko, M. P. Ivanov, N. A. Danilov, Yu. S. Korotkin, and G. N. Flerov (1974). Zh. Eksp. Teor. Fiz. Pisma, 20, 580-585.
Oganessian, Yu. Ts., A. S. Iljinov, A. G. Demin, and S. P. Tretyakova (1975a). Nucl. Phys., A239, 353-364.
Oganessian, Yu. Ts., A. G. Demin, A. S. Iljinov, S. P. Tretyakova, A. A. Pleve, Yu. E. Penionzhkevich, M. P. Ivanov, and Yu. P. Tretyakov (1975b). Nucl. Phys., A239, 157-171.
Oganessian, Yu. Ts., A. G. Demin, N. A. Danilov, G. N. Flerov, M. P. Ivanov, A. S. Iljinov, N. N. Kolesnikov, B. N. Markov, V. M. Plotko, and S. P. Tretyakova (1976). Nucl. Phys., A273, 505-522.
Oganessian, Yu. Ts., A. G. Demin, M. Hussonnois, S. P. Tretyakova, Yu. P. Kharitonov, V. K. Utyonkov, I. V. Shirokovsky, O. Constantinescu, H. Bruchertseifer, and Yu. S. Korotkin (1984a). Z. Phys., A319, 215-217.
Oganessian, Yu. Ts., M. Hussonnois, A. G. Demin, Yu. P. Kharitonov, H. Bruchertseifer, O. Constantinescu, Yu. S. Korotkin, S. P. Tretyakova, V. K. Utyonkov, I. V. Shirokovsky, and J. Estevez (1984b). Radiochimica Acta, 37, 113-120.
Oganessian, Yu. Ts., A. G. Demin, S. P. Tretyakova, V. K. Utyonkov, I. V. Shirokovsky, and G. N. Ivanov (1986). In Int. School-Seminar on Heavy Ion Physics, Dubna, 1986, Abstracts. JINR D7-86-434, Dubna. p.14.
Orlova, O. A., H. Bruchertseifer, Yu. A. Muzychka, Yu. Ts. Oganessian, B. I. Pustylnik, G. M. Ter-Akopian, V. I. Chepigin, and Choi Val Sek (1979). Yad. Fiz., 30, 618-625.
Phillips, L., R. Gatti, A. Cheshé, L. Muga, and S. Thompson (1958). Phys. Rev. Lett., 1, 215-217.
Quint, A. B., K. - H. Schmidt, P. Armbruster, G. Berthes, F. P. Hessberger, S. Hofmann, J. G. Keller, G. Münzenberg, W. Reisdorf, H. Stelzer, H. - G. Clerc, and C. - C. Sahm (1986). In GSI Scientific Report 1985. GSI 86-1, Darmstadt. p.62.
Randrup, J., S. E. Larsson, P. Möller, S. G. Nilsson, K. Pomorski, and A. Sobiczewski (1976). Phys. Rev., C13, 229-239.
Reisdorf, W. (1981). Z. Phys., A300, 227-238.
Reisdorf, W., F. P. Hessberger, K. D. Hildenbrand, S. Hofmann, G. Münzenberg, K. - H. Schmidt, J. H. R. Schneider, W. F. W. Schneider, K. Sümmerer, and G. Wirth (1985a). Nucl. Phys., A438, 212-252.

Reisdorf, W., F. P. Hessberger, K. D. Hildenbrand, S. Hofmann, G. Münzenberg, K. - H. Schmidt, W. F. W. Schneider, K. Sümmerer, G. Wirth, J. V. Kratz, K. Schlitt, and C. - C. Sahm (1985b). Nucl. Phys., A444, 154-188.
Sahm, C. - C., H. - G. Clerc, K. - H. Schmidt, W. Reisdorf, P. Armbruster, F. P. Hessberger, J. G. Keller, G. Münzenberg, and D. Vermeulen (1985). Nucl. Phys., A441, 316-343.
Schädel, M., W. Brüchle, H. Gäggeler, J. V. Kratz, K. Sümmerer, G. Wirth, G. Herrmann, R. Stakemann, G. Tittel, N. Trautmann, J. Nitschke, E. Hulet, R. Lougheed, R. Hahn, and R. Fergusson (1982). Phys. Rev. Lett., 48, 852-855.
Schädel, M., W. Brüchle, M. Brügger, H. Gäggeler, K. J. Moody, D. Schardt, K. Sümmerer, E. K. Hulet, A. D. Dougan, R. J. Dougan, J. H. Landrum, R. W. Lougheed, J. F. Wild, and G. D. O'Kelley (1986). Phys. Rev., C33, 1547-1550.
Seaborg, G. T. (1963). Man-Made Elements. Prentice-Hall, New Jersey.
Seaborg, G. T. (1967). Actinides Rev., 1, 3-38.
Seaborg, G. T. (1968). Ann. Rev. Nucl. Sci., 18, 53-152.
Seaborg, G. T. and W. D. Loveland (1985). In D. A. Bromley (Ed.)., Treatise on Heavy-Ion Science, vol.4, Extreme Nuclear States. Pergamon, New York. pp. 255-330.
Sierk, A. J. and J. R. Nix (1974). In Proc. Third IAEA Symp. on the Physics and Chemistry of Fission, Rochester, 1973. vol. 2. IAEA, Vienna. pp. 273-287.
Sikkeland, T., J. Maly, and D. F. Lebeck (1968a). Phys. Rev., 169, 1000-1006.
Sikkeland, T., A. Ghiorso, and M. J. Nurmia (1968b). Phys. Rev., 172, 1232-1238.
Somerville, L. P., M. J. Nurmia, J. M. Nitschke, A. Ghiorso, E. K. Hulet, and R. W. Lougheed (1985). Phys. Rev., C31, 1801-1815.
Strutinsky, V. M. (1966). Yad. Fiz., 3, 614-625.
Strutinsky, V. M. (1967). Nucl. Phys., A95, 420-442.
Swiatecki, W. J. (1980). Prog. Part. Nucl. Phys., 4, 383-450.
Swiatecki, W. J. (1981). Phys. Scr., 24, 113-122.
Swiatecki, W. J. and S. Bjørnholm (1972). Phys. Rep., 4, 325-342.
Taagapega, R. and M. Nurmia (1961). Ann. Acad. Sci. Fennicae, ser AVI, 78, 1-17.
Ter-Akopian, G. M., R. N. Sagajdak, A. A. Pleve, S. P. Tretyakova, G. M. Buklanov, A. G. Artukh, and A. M. Kalinin (1985). JINR P7-85-634, Dubna.
Tsang, C. F. (1974). In Nucl. Chem. Div. Ann. Rep., 1973. LBL-2366-1974, Berkeley.
Viola, V. E., Jr., A. C. Mignerey, H. Breur, K. L. Wolf, B. G. Glagola, W. W. Wilcke, W. U. Schröder, J. R. Huizenga, D. Hilscher, and J. R. Birkelund (1980). Phys. Rev., C22, 122-127.
Zager, B. A., M. B. Miller, V. L. Mikheev, S. M. Polikanov, A. M. Sukhov, G. N. Flerov, and L. P. Chelnokov (1966). Atomnaya Energiya, 20, 230-232.
Zvara, I. (1969). In Proc. R. A. Welch Found. Conf. on Chemical Res., XIII. The Transuranium Elements - The Mendeleev Centennial, 1969, Houston, Texas. pp. 153-185.

Zvara, I.(1981). Pure Appl. Chem., 53, 979-995.
Zvara, I., Yu. T. Chuburkov, R. Caletka, T. S. Zvarova, M. R. Shalaevsky, and B. V. Shilov (1966). Atomnaya Energiya, 21, 83-84.
Zvara, I., Yu. T. Chuburkov, R. Caletka, and M. R. Shalaevsky (1969). Radiokhimiya, 11, 163-173.
Zvara, I., Yu. T. Chuburkov, V. Z. Belov, G. V. Buklanov, B. B. Zakhvataev, T. S. Zvarova, O. D. Maslov, R. Caletka, and M. R. Shalaevsky (1970a). J. Inorg. Nucl. Chem., 32, 1885-1894.
Zvara, I., V. Z. Belov, Yu. S. Korotkin, M. R. Shalaevsky, V. A. Shchegolev, M. Hussonnois, and B. A. Zager (1970b). JINR R12-5120, Dubna.
Zvara, I., V. Z. Belov, L. P. Chelnokov, V. P. Domanov, M. Hussonnois, Yu. S. Korotkin, V. A. Shchegolev, and M. R. Shalaevsky (1971). Inorg. Nucl. Chem. Lett., 7, 1109-1116.

Received by Publishing Department
on March 18, 1987.

Флеров Г.Н., Тер-Акопьян Г.М. E7-87-167

Синтез и изучение атомных ядер с Z > 100

Изучение атомных ядер с Z > 100 - это область исследований, которая тесно связана с синтезом новых химических элементов и изучением пределов стабильности наиболее тяжелых нуклидов. С середины 50-х годов эта работа проводится с использованием интенсивных пучков тяжелых ионов и высокочувствительных методов физической и химической идентификации редких короткоживущих ядер. В результате двух этапов - первого, для которого было характерным использование реакций горячего слияния ядер U, Pu, Am, Cm, Cf с бомбардирующими ядрами C, N, O, Ne, и второго, основанного на применении реакций холодного слияния ядер Pb и Bi с бомбардирующими ядрами Cr, Mn, Fe, были синтезированы новые химические элементы с атомными номерами от 102 до 109. Изучен радиоактивный распад более 40 изотопов этих элементов и получены однозначные доказательства решающей роли эффектов оболочек в стабильности ядер с $Z \geq 104$ по отношению к спонтанному делению. Это дает экспериментальное обоснование известной гипотезы о существовании острова стабильности ядер около $Z \approx 114$ и $N \approx 178$ или 184. Для синтеза элементов с $Z \geq 110$ предложены и проанализированы реакции полного слияния ядер урана и соседних элементов с такими бомбардирующими ионами, как Ar и Ca. В двух реакциях - $^{232}Th + ^{44}Ca$ и $^{236}U + ^{40}Ar$, изученных в Дубне, было наблюдено спонтанное деление ядра-продукта /всего 26 случаев/, которое авторы этой работы рассматривают в качестве кандидата на распад ядер 110-го элемента.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1987

Flerov G.N., Ter-Akopian G.M. E7-87-167

Synthesis and Study of Atomic Nuclei with Z > 100

The studies of atomic nuclei with Z > 100 are closely related to the synthesis of new chemical elements and to the investigation of stability limits for the heaviest nuclides. From the mid-50s these studies have been carried out using intense heavy-ion beams and highly sensitive techniques designed for the physical and chemical identification of rare short-lived nuclei. The studies proceeded in two stages, the first one being characterized by the use of hot-fusion reactions between the U, Pu, Am, Cm and Cf target nuclei and the C, N, O, and Ne projectiles and the second being based on the use of the cold-fusion reactions induced by Cr, Mn, and Fe projectiles on Pb and Bi target nuclei. As a result, the chemical elements with atomic numbers from 102 to 109 have first been synthesized. The radioactive properties of over 40 isotopes of these elements have been investigated and unambiguous evidence has been obtained that shell effects play a decisive role for the stability of the $Z \geq 104$ nuclei against spontaneous fission. This provides an experimental substantiation for the known hypothesis that the island of nuclear stability should lie around $Z \approx 114$ and $N \approx 178$ or 184. It has been proposed to synthesize elements with $Z \geq 110$ by the complete fusion reactions of uranium and adjacent element nuclei with projectile nuclei such as Ar and Ca. The spontaneous fission of a product nucleus (a total of 26 events) has been observed in Dubna experiments with the $^{232}Th + ^{44}Ca$ and $^{236}U + ^{40}Ar$ reactions. The authors of those studies tentatively assigned this activity to the decay of the nuclei of element 110.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1987