*Pure & Appl. Chem.*, Vol.53, pp.925-947.
Printed in Great Britain.

0033-4545/81/050925-23$02.00/0
Pergamon Press Ltd.


# PROBLEMS INVOLVED IN THE SYNTHESIS OF NEW ELEMENTS

Yuri Ts.Oganessian and Yuri A.Lazarev

Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, USSR

Abstract - The present status and perspectives of the development of the synthesis of new elements in the nuclear reactions induced by heavy ions are reviewed. The efficiency of various reactions leading to the synthesis is analysed, the radioactive properties of heavy and hypothetical superheavy nuclei are considered and the physical methods of identification of new elements are discussed.

## INTRODUCTION

In a couple of years, we shall celebrate one of the outstanding events of the physics of the 20th century - the fiftieth anniversary of the discovery of a neutron by Chadwick (Ref.1). Apparently, the onset of work on the synthesis of new elements is to be related to that event - as early as 1934, Fermi published (Ref.2) the results of his first experiments, in which an attempt had been made to observe elements with atomic numbers above 92 by bombarding uranium with neutrons. That problem immediately attracted the attention of the investigators of many countries.

In considering the present state of the subject of synthesis of new elements - its successes, problems, and future prospects - and in evaluating its importance and role in modern physics and chemistry, it is useful to view the latest results in retrospect by comparing the achievements with the efforts spent. This is the reason why we allow ourselves to make this somewhat general introduction mentioning some of the known facts which have already become a piece of the science history.

It is remarkable that Hahn and Strassmann discovered nuclear fission (Ref.3) prior to the separation and identification of the Np activity in the products of the bombardment of uranium with neutrons.

It is also significant that before the first transuranium element, Np, had been produced, Pertzhak and Flerov were the first to observe (Ref.4) the spontaneous fission of uranium - the new mode of radioactive decay - the detection of which at once determined the existence of the limit of stability of the atomic nuclei. Now the conception of the influence of spontaneous fission on the stability of heavy nuclei and on the boundaries of the Mendeleev Periodic Table underlies all the present-day investigations aimed at the synthesis of new elements and at the study of their properties.

At the same time, Alvarez (Ref.5) reported on the acceleration at the Berkeley cyclotron of multiply-charged $^{12}C^{+6}$ ions to an energy of 50 MeV with an intensity of several particles per minite.At that time, this communication did not seem to relate to the problem of transuranium elements, and it remained in the shade up to the early fifties (presently we are well aware of the potential possibilities of this short note of Alvarez).

Subsequently, McMillan and Abelson first isolated reliably element 93 - neptunium (Ref.6). Then followed a cascade of significant papers by Seaborg and his colleagues, which have led to the discovery of plutonium (Ref.7) and seven new transuranium elements from Am to Md inclusive (Ref.8). All this took some 15 years.

Although this seemed to be the limit of the possible at that time, research into the new elements underwent further substantial development in the early fifties. Owing to the efforts of Fremlin in Birmingham, Kurchatov, Flerov and their colleagues in Moscow, Seaborg and his coworkers at Berkeley, and many others, the problem of producing new elements has been inseparably related to the acceleration and experimental use of heavy ions. It should be noted that no one other problem had and could hardly have such a strong impact on the development of techniques of heavy ion acceleration.

Heavy ions, in turn, have considerably contributed to the development of nuclear physics as a whole. Moreover, they sort of have bridged the gap between nuclear physics and high energy physics, and on the other hand, between nuclear physics and the atomic physics of superstrong electric fields and superheavy quasiatoms. This mutually beneficial union occurred when these fields of research looked to be quite apart. Heavy ions have made and, undoubtedly, are still promising to make a more substantial contribution to applied fields such as the production of nuclear filters, the study of materials under radiation conditions, medicine, production of condensed matter at high pressure and temperature and, possibly, thermonuclear fusion.

The application of heavy ions to experimental nuclear physics has caused the renaissance of fission physics. The concept of induced radioactivity has become broader (it now includes such new kinds as $\beta$-delayed proton activity (Ref.9), $\beta$-delayed fission (Ref.10), two-neutron $\beta$-delayed decay (Ref.11), etc.). A deeper understanding of nuclear isomerism has been obtained - by generalizing over the nuclear shape (Ref.12) and, theoretically, over density (Ref.13).

Still, the existence of superheavy elements (SHE) remains to be one of the main problems of modern nuclear physics, which by itself has originated in the rapid development of research using heavy ions.

The present stage of research in this field seems to us rather complicated. We have stopped at element 107, and the more than ten year attempts to synthesize SHE's with $Z \gtrsim 110$ in different heavy ion reactions have not given direct and positive results, but only revealed additional serious difficulties to be overcome. However, the elaboration of any scientific idea or problem seldom proceeds in a straightforward manner, and practically, can never be predicted with full certainty. Despite the fact that a large amount of experimental material has been accumulated nowadays, the present-day rapid development of technical facilities (accelerators, experimental techniques, computers, and so on) give us a ground for thinking that we are rather at the starting point of unraveling this interesting enigma of nature.

Returning to history, we shall remember that whereas Np was first produced by neutron irradiations, the following elements, Pu, Am, Cm, Bk, and Cf, were observed for the first time and identified in bombardments of uranium and transuranium elements (Pu, Am, and Cm) with deuterons and $\alpha$-particles accelerated on a cyclotron (Refs.7,8,14). The elements Es and Fm were isolated (Ref.15) in the explosion of the thermonuclear device "Mike". At present, all elements from Np through Fm can be accumulated in large amounts in nuclear reactors used to synthesize transuranium elements by the sequential neutron capture and corresponding $\beta$-decays. However, the method of producing new elements with intense neutron fluxes, including those from thermonuclear explosion, has exhausted its possibilities already with element 100. The greatest achievement of this method has been production of the isotope $^{257}$Fm, which was isolated (Ref.16) in largest amounts from the debris of the thermonuclear explosion "Hutch". It has turned out that $^{258}$Fm undergoes complete spontaneous fission with a half-life $T_{sf}$ = = 0.38 ms (Ref.17). Such a short half-life for spontaneous fission appeared to be an insuperable obstacle to further progress in Z and A. Therefore, it is not surprising that the first 17 atoms of the new element with Z=101 - mendelevium - were produced (Ref.18) only in the bombardment of $^{253}$Es with an $\alpha$-particle beam.

A way out of this difficult situation was provided by the development of another method of synthesis of new elements, based on the use of heavy ion reactions. For the time being, the use of heavy ions has permitted production of elements with Z ranging from 102 to 107 inclusive (Refs.19-24), and of many dozens of new isotopes of transuranium elements with Z lying in the range 93 to 107 (Ref.25). Attempts are currently being made to synthesize element 108 (Ref.26), the heavier and superheavy elements with $Z \gtrsim 110$ (Refs.21,22,24,27-34), which are predicted to have enhanced stability (Refs.33,34).

The present paper is devoted to an analysis of the state of the art and future prospects in the field of synthesis of new elements in the nuclear reactions induced by heavy ions.

## SYNTHESIS REACTIONS

Traditionally, the processes of complete fusion of the interacting nuclei, which lead to equilibrated compound nucleus formation, are used to synthesize new elements in the nuclear reactions induced by heavy ions. In accordance with the concepts of Bohr (Ref.35) and Weisskopf (Ref.36), the compound nucleus is formed immediately after a collision between the projectile and the target nucleus, and its decay is described using statistical theories that rest upon the hypothesis of thermal equilibrium.

Within the framework of the classical concept, the total reaction cross section $\sigma_R(E)$, as a function of the projectile energy E, can be approximately described by a simple relation for the collision of charged black spheres (with a sharp boundary), i.e.,

$$\sigma_R(E) = \pi R^2 (1 - E_0/E) \quad \text{with} \quad R \approx 1.45 (A_I^{1/3} + A_T^{1/3}) \text{ fm}, \tag{1}$$

where $A_I$ and $A_T$ are, respectively, the masses of the projectile and the target nucleus, in a.m.u.

The probability of forming one or another nuclide in the ground state can be calculated in terms of the statistical theory rather accurately, if we know the complete-fusion cross section $\sigma_{CF}(E)$, the initial conditions (the compound nucleus excitation energy E*, the angular momentum distribution, and some others) at a set level density function of the intermediate nucleus, $\rho(E^*,\ell)$, for the states through which "proceeds" the cascade of the particles. The level density function plays a major role in the statistical theory of nuclear reactions, and it can be determined by using the simple and illustrative analogies with macrophysics - extensive investigations show that the statistical characteristics of excited nuclei are similar in many respects to the thermodynamical functions of the ideal Fermi gas (Refs.36-39).

On the basis of the above concepts, the cross section of the heavy ion reaction involving the emission of $\nu_i$ particles of (different) kind $\nu_i (i = 1,2,\ldots,x)$ from the excited compound nuc-

leus can be presented in the following form

$$\sigma_{\nu_i} = \sigma_{CF}(E) \prod_{i=1}^{i=x} \bar{G}_{\nu_i}^{(i)}(E^*), \tag{2}$$

where $\bar{G}_{\nu_i}^{(i)}(E^*)$ is the probability for a particle of the kind $\nu_i$ to be emitted from the compound nucleus with excitation energy $E^*$, and $\sigma_{CF}(E)$ is the cross section for the complete fusion of the projectile with energy E and the target nucleus.

The value of $\sigma_{CF}(E)$ makes up a certain part of the total reaction cross section $\sigma_R(E)$, which, in turn, is often interpreted "in the spirit" of the optical model by expansion along partial waves (impact parameters), i.e.,

$$\sigma_R(E) = \sum_{\ell=0}^{\infty} \pi \lambda\!\!\!^{-2} (2\ell+1) T_\ell , \tag{3}$$

where $T_\ell$ is the transmission coefficient of the $\ell$-th partial wave through the nucleus, which can be calculated using the set optical potential, and $\lambda\!\!\!^{-}$ is the reduced wave length of the system of two interacting nuclei. The probability of absorption of the bombarding particle is determined by the value of the imaginary part of the optical potential, and this absorption occurs with some delay in time. Following Weisskopf (Ref.40), we can note that in the optical model compound nucleus formation no longer occurs immediately and for sure.

In accordance with the above-said, for $\sigma_{CF}(E)$ in the sharp cutoff approximation one can write

$$\sigma_{CF} = \pi \lambda\!\!\!^{-2} \ell_{crit}(\ell_{crit}+1), \tag{4}$$

where $\ell_{crit}$ is the maximum value of $\ell$, at which fusion still occurs; $\ell_{crit} \leq \ell_{max}$ and correspondingly, $\sigma_{CF} < \sigma_R$ in the general case.

It should, however, be noted that the concepts of Bohr and Weisskopf were advanced to interpret the mechanism of the nuclear reactions induced by neutrons and light charged particles. In passing to heavy ion reactions, one could expect substantial differences from the simple classical picture and considerable limitations on the probability of complete fusion of the interacting nuclei, which leads to a statistically equilibrated compound system.

On the other hand, as early as in the middle of the fifties, it was shown experimentally (Refs.20,41-43) that in bombardment of heavy nuclei with $A \gtrsim 200$ by ions with mass $A \lesssim 20$, the fusion cross section $\sigma_{CF}(E)$ remains (surprisingly) high and comparable to the total reaction cross section $\sigma_R$, and the behaviour of $\sigma_{CF}(E)$ can be described in general outline with the help of the same physical ideas that have been widely used to explain the mechanism of light particle induced reactions. Essentially, this nontrivial and not a priori obvious circumstance has conditioned the fruitful trend of modern nuclear physics and chemistry - the synthesis of new elements in the nuclear reactions induced by heavy ions.

However, the use of heavy ions for the synthesis of new elements involves some specific problems, the main of which is that in this case the compound nucleus has a high excitation energy, as a rule, of about several tens of MeV.

At such a high excitation energy, there exist a great number of channels for compound nucleus decay, among which of primary interest to us is the channel of sequential emission of several neutrons since just this channel leads to the evaporation residues with maximum Z. According to Weisskopf (Ref.36), the partial width of the decay of a compound nucleus with excitation energy $E^*$ and angular momentum $\ell$ via neutron emission, can be written as follows

$$\Gamma_n(E^*,\ell) \sim \sum_{I=0}^{\infty} \sum_{J=|\ell-I|}^{\ell+I} (2J+1) \int_0^{E^*-E_{rot}(J)-B_n} \rho_n [E^*-E_{rot}(J)-B_n-\epsilon] T_n^I(\epsilon)\, d\epsilon , \tag{5}$$

where $\rho_n$ and J, respectively, are the level density and angular momentum of the daughter nucleus (after neutron emission), $T_n^I(\epsilon)$ is the transmission coefficient for the emission of a neutron with kinetic energy $\epsilon$ and angular momentum I, $E_{rot}(\ell)$ is the rotational energy of the nucleus at equilibrium deformation, and $B_n$ is the neutron binding energy. Then the neutron emission probability $G_n(E^*,\ell)$ will be defined as $\Gamma_n / \Gamma_{tot}$, where $\Gamma_{tot}$ is the total decay width.

Similar expressions to (5) can be written for the partial widths of decay by the emission of particles of another kind $\nu$. Fortunately, in the region of heavy nuclei of interest to us, the evaporation probability for other particles is generally small, hence $\Gamma_\nu \lesssim 1\% \, \Gamma_n$ (Refs.20,42,43). However, in the case of heavy nuclei a strong competetion occurs between neutron evaporation and fission to two fragments. According to Bohr and Wheeler (Ref.44) the partial width of the latter process, taking into account the angular momentum effect, can be written down as

$$\Gamma_f(E^*,\ell) \sim (2\ell+1) \int_0^{E^*-E_{rot}(\ell)-B_f(\ell)} \rho_f [E^*-E_{rot}(\ell)-B_f(\ell)-K]\, dK, \tag{6}$$

where $\rho_f$ is the level density of the fissioning nucleus at the saddle point, $B_f(\ell)$ is the fission barrier height, K is the kinetic energy of the fission degree of freedom; the fission barrier penetrability in eq. (6) is taken to be equal to unity for all energies above $B_f(\ell)$ and equal to zero for those below $B_f(\ell)$.

Then at high excitation energies, the total decay width

$$\Gamma_{tot} = \Gamma_n + \Gamma_f + \sum_\nu \Gamma_\nu \approx \Gamma_n + \Gamma_f ,$$

and, consequently, the survival probability for the compound nucleus against fission is determined by the value of the ratio $\Gamma_n/(\Gamma_n+\Gamma_f)$ or $\Gamma_n/\Gamma_f$. For the latter, in terms of the fermi-gas model ($\rho \sim \exp(2\sqrt{a E})$) one can write (Refs.36-39 and 44)

$$\frac{\Gamma_n}{\Gamma_f} = f(\ell)\,\frac{2A^{2/3}}{K\,a_n^{1/2}}\,\frac{(E^*-B_f')^{3/2}}{(E^*-B_n')}\,\exp\left[\,2\sqrt{a_n(E^*-B_n')}-2\sqrt{a_f(E^*-B_f')}\,\right], \qquad (7)$$

where $a_n$ and $a_f$ are, respectively, the level density parameters of the residual nucleus (after the emission of a neutron) at equilibrium deformation and of the fissioning nucleus at the saddle point; the primes of $B_f$ and $B_n$ indicate the introduction of corrections for nucleon pairing. From eq. (7) it follows that the value of $\Gamma_n/\Gamma_f$ is substantially determined by the fission barrier height $B_f$, as well as by the exponential energy dependence of the ratio of the level density parameters, $a_n/a_f$. This is a qualitative explanation of the experimental fact that the absolute values of $\Gamma_n/\Gamma_f$, on the average, are very small in the region of highly fissile nuclei (Refs.45-48).

Now, by making use of eq.(2) one can write the following relation for the cross section of complete fusion reaction followed by the evaporation of several ($\underline{x}$) neutrons from the compound nucleus with excitation energy $E^*$

$$\sigma_{xn}(E^*) = \sigma_{CF}(E)\,P_{xn}(E^*)\,[1-\bar{G}_f(E^*_{res})]\prod_{i=1}^{i=x}\bar{G}_n^{(i)} , \qquad (8)$$

where $P_{xn}(E^*)$ is the probability of emission of exactly $\underline{x}$ neutrons, if all other modes of compound nucleus decay are forbidden; $\bar{G}_n^{(i)}=(\Gamma_n/\Gamma_{tot})_i$ is the average value of the probability of neutron emission for a given cascade stage $\underline{i}$; $\bar{G}_f(E^*_{res})$ is the fission probability for the final nucleus at residual excitation energy $E^*_{res}$, which has not been carried off by the cascade of $\underline{x}$ neutrons.

At the bombarding energy E exceeding the reaction Coulomb barrier (in the c.m.s.)

$$E_B = (Z_I \cdot Z_T)\,/\,[\,r_0\,(A_I^{1/3}+A_T^{1/3})\,] , \qquad (9)$$

where $r_0 \sim 1.45$ fm is the interaction radius constant, the excitation energy of the compound nucleus is defined by the following simple relation

$$E^* = Q + [\,1 - A_I/(A_I+A_T)\,]\,E , \qquad (10)$$

where $Q=[(M_I+M_T)-M_{CN}]$ is the reaction energy, and $M_I$, $M_T$ and $M_{CN}$ are the masses in MeV of the projectile, target nucleus and compound nucleus, respectively. One can easily see that the minimum value of $E^*$ is

$$E^*_{min} = Q + E_B . \qquad (11)$$

As $A_I$ increases from 4 to 20-30, the values of $E^*_{min}$ increase and amount as a rule, to $\approx$30-50 MeV at $A_I \approx$ 10-30 in the case of using transuranium nuclei as a target.

Since the minimum excitation energy of the compound nucleus, $E^*_{min}$, is strictly fixed in a complete-fusion reaction, the number of evaporated neutrons $\underline{x}$ at given $E^*_{min}$ is determined strictly enough - at $E^*_{min}$= 30-50 MeV the average value of $\underline{x}$ is typically $\langle x\rangle$ = 3-5, and its variance $D\equiv(\langle x^2\rangle-\langle x\rangle^2) \sim 0.3$ in the given range of $E^*$. As a result, the excitation functions $\sigma_{xn}(E^*)$ of the reactions (HI, xn) are very narrow and characterised by the FWHM values of about 8-10 MeV (Fig.1).

Numerous experiments show (Ref.20&21) that in the transfermium region, at $\underline{x}$ = 3-5

$$\prod_{i=1}^{i=x}\bar{G}_n^{(i)} \approx [\,\langle\Gamma_n/(\Gamma_n+\Gamma_f)\rangle\,]^x \sim 10^{-5}-10^{-10} ,$$

and, consequently, the values of $\sigma_{xn}(E^*)$ make up an extremely small fraction of the total reaction cross section, say $\sim 5\times10^{-6}$ of $\sigma_R$ for the reaction $^{249}$Bk($^{15}$N,4n)$^{260}$104.

Therefore, in experiments on the synthesis of new elements in complete-fusion reactions, for which the values of $E^*_{min}$ and, consequently, $\underline{x}$, are strictly definite, the principal problem is the necessity to decrease $E^*_{min}$ as much as possible. As a result, already in the initial experiments on the synthesis of element 102, the combination of the heaviest possible target plus a light ion was traditionally considered to be the most advantageous in view of a low value of the Coulomb barrier. For evident reasons, however, the practical use of the heaviest nuclei as targets is restricted to elements with $Z \leq 100$ (if not $Z \leq 98$). Therefore, the use of the increasingly heavier projectiles has been inevitable in advancing in the traditional way from element 102 to 106 and the heavier elements. An immutable consequence of this fact is a sharp decrease in cross sections for the formation of the nuclei of new elements (Fig.2).

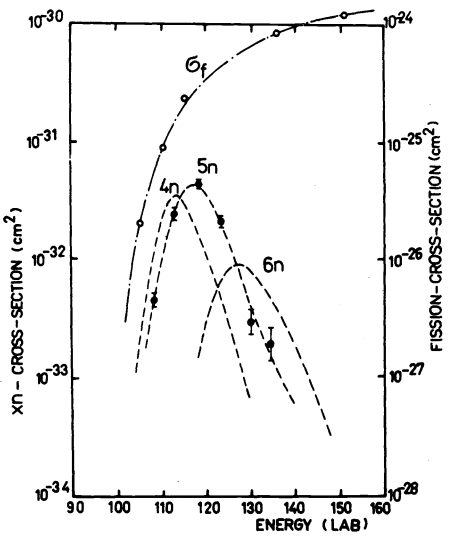


Fig. 1. The experimental(•) (Ref.63) and calculated (Ref.47) excitation functions of the reactions $^{235}U(^{22}Ne,xn)102$. The calculated excitation function $\sigma_f$ of the reaction $^{235}U(^{22}Ne,f)$ is shown by a dash-dotted line, (o) are the experimental values of $\sigma_f$ (right-hand scale).

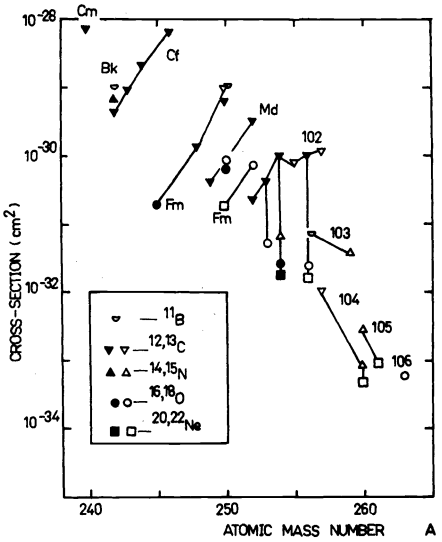


Fig. 2. The cross sections of the reactions (HI, 4n) induced by ions with $A \leq 20$ as a function of the Z and A of the nucleus synthesized (see Ref. 19-24 and references therein).

However, $E^*_{min}$ depends directly not only on the Coulomb barrier height but also on the Q value, which is determined by the mass difference of the nuclei involved in the reaction. The nuclear masses are known to undergo noticeable variations in the vicinity of closed nucleon shells. Bearing this in mind and changing Z and A of the projectile particle and target nucleus over a wider range, one can considerably decrease the value of Q and, consequently, $E^*_{min}$. In the region of compound nuclei with $Z \geq 100$, this possibility materializes if ions with mass $A_I \geq 40$ are used as projectiles, and nuclei close in Z and N to the doubly magic nucleus $^{208}Pb$ are used as targets (Fig. 3). Now the question arises as to what extent the mechanism of fusion of the interacting nuclei can change if the Coulomb repulsive forces increase significantly as a result of the increasing charge of the projectile.

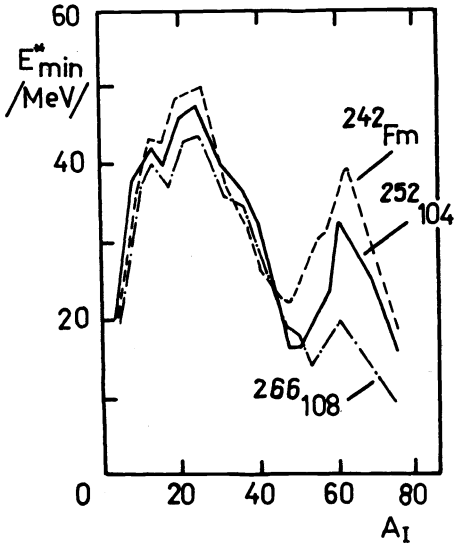


Fig. 3. The minimum compound-nucleus excitation energy $E^*_{min}$ as a function of the projectile mass $A_I$ for different target-projectile combinations leading to the same compound nucleus - $^{242}Fm$, $^{252}104$, or $^{266}108$.

An answer to this question was first obtained in the experiments (Ref.49) carried out by us in 1973, which showed that to produce Fm isotopes, instead of the usual reaction

$$^{235}U(^{16}O,5n)^{246}Fm,$$

one can successfully use the reaction

$$^{208}Pb(^{40}Ar,2n)^{246}Fm,$$

for which $E^*_{min}$ is nearly twice lower than in the former case. For the time being, a large number of similar complete-fusion reactions induced by ions from $^{40}Ar$ to $^{54}Cr$ have been produced leading to the formation of isotopes with Z=100-107 following the emission of 1 to 3 neutrons from a slightly excited compound nucleus (Refs.21,26,49-59).

Among complete-fusion reactions, the reactions induced by $^{48}Ca$ ions occupy a special position. The use of these doubly magic nuclei with a considerable neutron excess, as projectile particles, gives an additional gain in the Q value of the reaction. Moreover, the extreme neutron excess of $^{48}Ca$ allows one to minimize the neutron deficit occurring at the SHE synthesis and to approach the closed neutron shell N=184.

Despite these quite obvious advantages, the $^{48}Ca$ ions have not been accelerated until recently because the $^{48}Ca$ content of the natural isotopic mixture is very low (0.19%), and its separation is a quite complicated and costly problem. The world resources of enriched $^{48}Ca$ seem to be as little as several tens of grams.

The construction of a new type of ion source has allowed us to produce in 1975 at the U-300 cyclotron the first beam of $^{48}Ca^{+7}$ ions with an energy of 260 MeV and an intensity of $5\times10^{11}$-$10^{12}$ particles/s (Ref.50) and to carry out a number of various experiments by bombarding Pb isotopes with these ions.

(i) The elastic scattering of $^{48}Ca$ and $^{40}Ca$ ions on $^{208}Pb$ nuclei was studied (Ref.60) and this permitted the determination of the interaction potential parameters, which are required to calculate the compound nucleus formation cross section, in particular the interaction radius parameter $r_{eff} \approx 1.44$ fm. In these experiments the difference of the radii of the interaction of the $^{48}Ca$ and $^{40}Ca$ ions with the $^{208}Pb$ nuclei has also been determined to be equal to $0.19\pm0.03$ fm (Ref.60).

(ii) The dependence of the yield of symmetric fission fragments upon the energy of the $^{48}Ca$ ions was measured (Ref.61), and on this basis, assuming $\Gamma_f \sim \Gamma_{tot}$, the energy dependence of the fusion cross section $\sigma_{CF}(E) \approx \sigma_f(E)$ was determined. It was shown that the latter is well describable by expression (1) with $R = r_{eff}(A_1^{1/3} + A_T^{1/3})$ at $r_{eff} = 1.44\pm.02$ fm and $E_0 = (Z_1 \cdot Z_T)/[r_{eff}(A_1^{1/3} + A_T^{1/3})]$ (Fig. 4a). Then, by using the $\sigma_{CF}(E)$ found and the empirical systematics of $\Gamma_n/\Gamma_f$ on the basis of eq.(8) it is possible to calculate the excitation functions of the reactions $(^{48}Ca,xn)$ (Ref.47). The calculation can be checked experimentally by making direct measurements of cross sections for the evaporation residues.

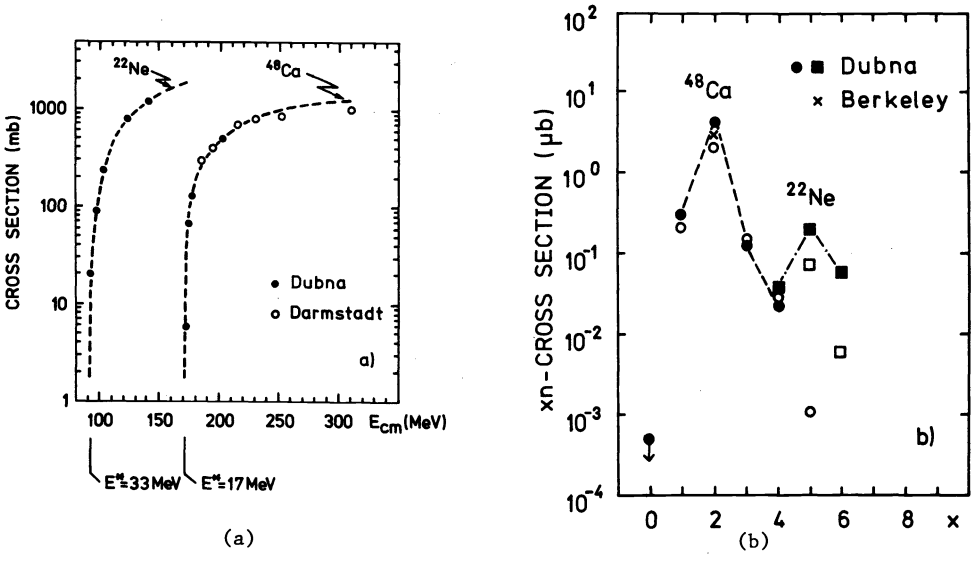


Fig. 4. (a) The energy dependence of cross sections for the formation of symmetric fission fragments in the reactions $^{238}U+^{22}Ne$ and $^{208}Pb+^{48}Ca$, following from the experimental data obtained at Dubna (Ref.61 & 63) and at Darmstadt (Ref.62). (b) Cross sections of the $^{48}Ca$ and $^{22}Ne$ -induced complete-fusion reactions leading to isotopes of element 102 (maximum values); (•), (■) and (×) are experimental data (Ref.20,52-55), o and □ are calculated values (Ref.47).

(iii) The verification was done in experiments to synthesize the isotopes of element 102 in the reactions $Pb(^{48}Ca,xn)$ (Ref .50&51). It has been shown that the maximum value of cross section corresponds to $x = 2$ and is equal to about 4 $\mu$barn (Ref.51 & 52). For the radiative capture of $^{48}Ca$ ($x=0$), the upper limit of the cross section has been obtained to be $5\times10^{-34}cm^2$ (Ref.50).

As follows from fig.4b, good agreement is observed between the experimental values of $\sigma_{xn}$ and those calculated (Ref.47) in the above manner. The consideration made permits the important conclusion that the formation of a compound nucleus with Z=102, induced by $^{48}Ca$ ions, is governed mainly by the same regularities that take place for the reactions induced by the lighter ions with mass $A_I \lesssim 20$.

The availability, in addition to $^{48}Ca$, of the $^{50}Ti$ ion beam has made it possible to obtain the reactions $Pb(^{50}Ti,xn)$ and to synthesize a number of new spontaneously fissioning neutron-deficient isotopes of element 104 and observe a sharp and surprising change in the usual picture of the properties of transfermium nuclei (Refs.53-56) (see next section).

Subsequently, isotopes of elements with atomic numbers 106 (Ref.54) and 107 (Ref.55) have been synthesized for the first time in the reactions induced by $^{54}Cr$ and $^{55}Mn$ ions. Experiments have also been carried out to synthesize the isotopes of element 108 in the reactions $^{207,208}Pb(^{58}Fe,xn)$. These experiments, however, allowed one to determine only the upper limit of cross sections for their formation, $\sigma_{xn} \lesssim 10^{-35}cm^2$, under the assumption that the odd isotopes $^{263,265}108$ have spontaneous fission half-lives $T_{sf} > 10^{-3}s$ (Ref.26).

Considering now the whole set of experimental data (Refs.21,26,49-59) on the reactions (HI, xn) induced by ions with mass $A_I$ ranging from 40 to 58, we arrive at the conclusion that, in general, these data can also be interpreted in terms of the compound nucleus concepts borrowed from experiments with the lighter charged particles. This conclusion follows directly from the dependence $\sigma_{2n} = f(Z_I \cdot Z_T)$ presented in Fig.5, and from the results of measuring the dependence of the symmetric fission cross section in the bombardment of $^{208}Pb$ by ions with mass $A_I$ lying in the range 26 to 64 (Refs.61,62,64). We note, however, that for ions heavier than $^{48}Ca$ the value of $\sigma_{2n}$ decreases considerably because of the necessity to impact additional energy required to overcome the reaction barrier. As shown in Ref.47,65, the value of this energy increases noticeably with the increasing mass of the projectile, and this is likely to cause the sharp decrease in the production cross sections for the isotopes of element 108. Apparently, the same circumstance eliminates the possibility of using symmetric target-projectile combinations like $_{50}Sn + _{50}Sn$ or $_{54}Xe + _{54}Xe$ for synthesis of heavy elements. In fact, the experiments aimed at producing the known isotopes of Fm and element 104 in the reactions

$$^{110}Pd(^{136}Xe,2n)^{244}Fm \qquad \text{and} \qquad ^{122}Sn(^{136}Xe,2n)^{256}104$$

allowed one to set only the upper limits for the cross sections of producing these nuclei (Ref.21). Hence it follows that in the given cases the fusion cross section decreases by a factor of $10^3$ at least.

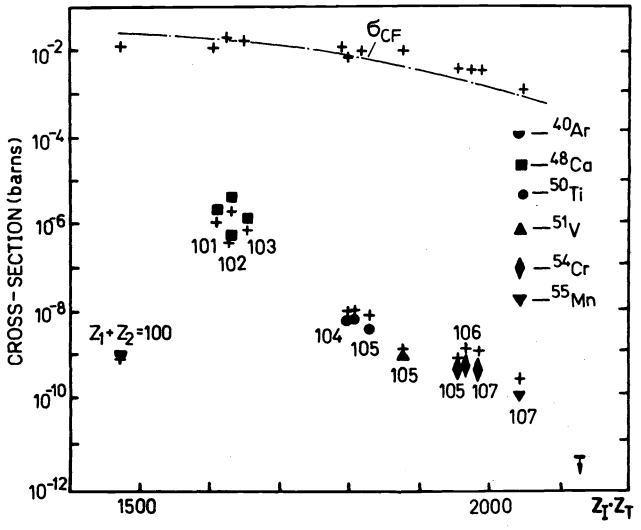


Fig.5. Cross sections of the (HI,2n) reactions induced by ions with $A_I \geq 40$ as a function of the Coulomb parameter $Z_I \cdot Z_T$; closed symbols are experimental data (Ref.21,26,49-59), ( + ) are calculated values (Ref.47). The dependence of the fusion reaction cross section on $Z_I \cdot Z_T$ is shown by ( + ) in the upper part of the figure. The arrow shows the upper limit of the cross section of producing isotopes of element 108 in $^{58}Fe$-induced reactions (see text).

Thus, if the limitations on the compound nucleus formation are mainly due to the static properties of the system of the interacting nuclei and are characterized by the product $Z_I \cdot Z_T$ that reflects the magnitude of Coulomb forces at the distance of closest approach, one then can assume that the complete fusion reactions of the $^{48}Ca$ ions with U, Pu, and Cm nuclei (for which $Z_I \cdot Z_T = 1840-1920$) will occur with no smaller probability than those fusion reactions that have led to the synthesis of isotopes with $Z = 104-107$. Then, if going from $Z = 104-107$ to the region of $Z = 110-114$ the fissility of nuclei with $E^* \approx 20-25$ MeV does not decrease sunstantially (the reverse would rather indicate the absence of the region of enhanced stability), the cross sections for formation of superheavy nuclides in the ground state should be quite accessible to experimental studies at modern heavy ion accelerators. On the other hand, in the region of SHE the expected cross sections for the reactions $(^{48}Ca,xn)$ at $x = 1$ and 2 can be about $10^{-34}cm^2$ and even less, as follows from fig.5. This fact necessitates a substantial increase in the experimental sensitivity compared with the previous experiments (Refs.66&67) aimed at the synthesis of SHE in the $^{48}Ca$ induced reactions.

Above, we have considered complete fusion reactions. It is of interest, however, to analyse other possibilities. One of them are the reactions involving the emission of a light particle that may carry off a considerable portion of the projectile energy. Since in such a process, the energy is redistributed between the particle emitted and the residual nucleus, the latter may have a wide range spectrum of excitation energy, in contrast to the case of compound nucleus formation. In particular, it is known that the emission of energetic $\alpha$ -particles is observed with high probability in heavy ion reactions (see, e.g., Ref.68 and references therein). As an example, we present in Fig. 6 the energy spectrum of the $\alpha$ -particles emitted in the reaction $^{197}Au + ^{22}Ne$.

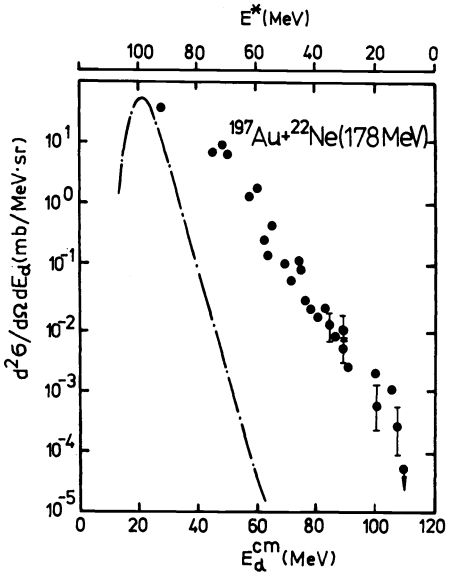


Fig. 6. The c.m. $\alpha$ -particle energy spectrum for the reaction $^{197}Au + ^{22}Ne$ (Ref.68). Closed points are experimental data. The $\alpha$-particle spectrum calculated in terms of the equilibrium evaporation model is shown by a dashed line. The upper scale gives the excitation energy E* of the residual nucleus with $A = (A_{CN} - 4)$.

In a considerable number of experiments it has been shown (Ref.68) that the emission of fast $\alpha$-particles is conditioned by the "direct" interaction of the bombarding ion with the target nucleus, which may result in the formation of an intermediate system with mass $(A_{CN}-4)$. The deexcitation of this nucleus will occur by neutron and $\gamma$ -ray emission, as in the case of compound nucleus decay. However, in contrast to the compound nucleus, the probability of decay of the intermediate system $(A_{CN}-4)$ via various channels and, consequently, the yields of various nuclei from the reaction (HI,$\alpha$xn) will be determined not only by the value of the average excitation energy, but also by the variance of its distribution. Experiments (Ref.69) have shown that here one can achieve very small excitation energies corresponding to $x = 0,1,2$, and 3. Since the cross sections of reactions involving $\alpha$ -particle emission may amount to several hundreds of millibarns, it is possible to assume that the yields of isotopes in (HI,$\alpha$xn) reactions can be comparable to or even greater than those in complete-fusion xn -reactions.

On the other hand, from experiments (Refs.68-70) it follows that the fast $\alpha$ -particle emission is likely to lead to the formation of a "cold" residual nucleus with high angular mo-

mentum. This circumstance can increase the fissility of the residual nucleus considerably, especially at large values of the angular momentum, and this in turn will decrease the yields of the reactions (HI, $\alpha$xn), particularly, at small values of $\underline{x}$. This comment, however, does not change the general conclusion that in some cases the reactions (HI, $\alpha$xn) can be successfully used to produce new heavy isotopes of transfermium elements. This conclusion is well illustrated in Ref.71, where the isotope $^{259}102$ was produced in the reaction $^{248}Cm(^{18}O,\alpha 3n)$ whose cross section, $(2\text{-}3)\times10^{-32}cm^2$, as compared to the value $(3\text{-}5)\times10^{-33}cm^2$ expected (Ref.72) for the reaction $^{248}Cm(^{18}O,4n)$.

The reactions involving the emission of the heavier fragments such as Li, Be, and C, are of great interest from the point of view of the synthesis of new nuclei with Z > 100. Despite the fact that the probability of the emission of more complex particles is lower, such processes can provide favourable conditions in terms of the excitation energy of the residual nucleus. This interesting possibility is illustrated in Fig. 7, which shows the experimental data obtained by Demin et al. (Ref. 73&74) on the cumulative cross sections for the formation of various isotopes of Fm in the reaction $^{249}Cf+^{22}Ne$ and of Md isotopes in the reaction $^{249}Bk+^{22}Ne$, together with the calculated values of these cross sections from Ref.75. The fact that the isotope $^{256}Md$ is formed with a cross section of $\approx 10^{-29}cm^2$ characterizes the potential possibilities offered by this type of reactions for the production of still heavier nuclei (Ref.74).

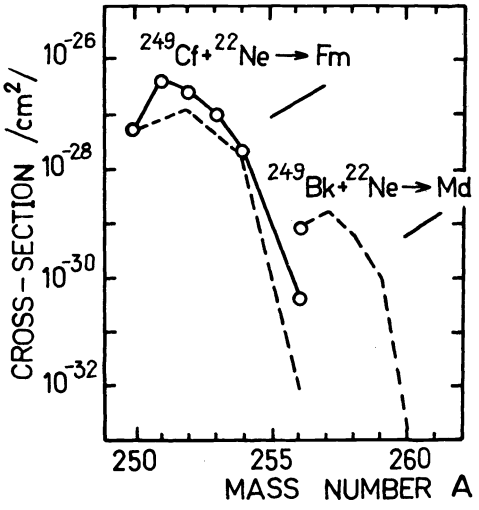


Fig. 7. Experimental (o) (Ref.73&74) and calculated (dashed line) (Ref.75) values of cross sections for producing Fm isotopes in the reaction $^{249}Cf+^{22}Ne$ and Md isotopes in the reaction $^{249}Bk+^{22}Ne$.

In considering this type of reactions induced by the heavier projectiles say $^{40}Ar$ it would seem reasonable to assume that they should involve the transfer (addition) to the target nucleus of a still larger complex of nucleons. Then, taking into account both the fluctuations in the ratio N/Z of the complex transferred and energy fluctuations in such collisions one could produce with noticeable probability slightly excited intermediate nuclei lying in the region of large Z or far from the line of $\beta$-stability.

In fact, the picture has appeared to be more complicated. Already in the initial experiments of Volkov and coworkers (Ref.76) the transfer of a large complex of particles, up to 20-30 nucleons, to the target nucleus has been observed. Subsequently it became clear (Ref.77) that the mechanism of these reactions has the features of a two-body process which is characterized by the strong dissipation of energy and angular momentum. The compound system formed in such collisions lives for a considerable period of time - several times $10^{-21}s$ - and then disintegrates. As a result, the values of the yields of various isotopes in deep inelastic reactions involving the transfer of a large number of nucleons obey, in general, the statistical regularities, as in the case of the fission of excited nuclei. In multi-nucleon transfer reactions the excitation energy is distributed, on the average, proportionally to the product masses, i.e., it is almost fully concentrated in the heavy product. The further fate of the latter depends on the value of the factor $\prod_{i=1}^{\bar{x}} \bar{G}_n^{(i)}$, where $\bar{x} \sim (\langle E_h^* \rangle / 8)$ We emphasize that the transfer (diffusion) of a large number of nucleons - about 20-30 - can take place only at sufficiently large values of the time of interaction between the nuclei, and this leads to a high excitation energy.

Since multinucleon transfer reactions have a statistical quasiequilibrium nature in terms of the formation of individual isotopes, the fluctuations of N/Z are not large and the excitation energy is distributed proportionally to the masses of the products. In these reactions the isotopic yields decrease sharply both as Z increases and one goes farther from the line

of $\beta$ -stability. This has just been observed experimentally. For instance, only the upper limits of production cross sections for the known emitters of spontaneous fission fragments among the isotopes of Am, Cm, and Cf, which might be produced in bombardment of the targets made of Tl, Pb, and Bi isotopes by different ions with $A_I \approx 40$-60, were obtained to be at a level of $10^{-34}$-$10^{-35}$cm$^2$ (see table II in Ref.55 and reviews Ref.21). We note that up to now not any new transuranium nucleus has been produced in multinucleon transfer reactions.

By going the way of further increasing the mass of the projectile one can hope for the advantages which might be offered by the use of such ions as Xe and U in combination with targets made of heavy actinides up to Cm, Cf, and Es. In fact, in a series of our experiments to study nuclear fission by heavy ions (Ref.78) it has been shown that as the projectile mass increases and one goes to the region of the heavier elements, the variance of the distributions of fission fragments in mass, charge, excitation energy, etc. increases considerably. Then it was natural to assume that despite a considerable increase in the average value of excitation energy, owing to its variance, the nuclei of heavy elements can be produced as neutron-rich fragments with noticeable yields in the reactions $^{136}Xe+^{238}U$ or $^{238}U+^{238}U$.

In 1964, Flerov (Ref.79) was the first to point out this possibility, and some concrete calculations were done in Ref. 80. With this idea in mind, a $^{136}Xe$ ion beam with an energy of $\approx$ 0.9-1.0 GeV and an intensity of $\approx 3\times10^{10}$ part/s was produced in 1971 at the tandem cyclotron U-300 + U-200 at Dubna and the experiments were performed (Ref.81). These experiments showed that the isotopic distributions of the heavy products of the reactions $^{136}Xe+^{181}Ta$ and $^{136}Xe+^{238}U$ are actually rather close to those that might be expected for highly asymmetric fission of an excited compound nucleus.

However, the detailed picture of the interaction of two very heavy and complex nuclei was clarified in a series of experiments (Refs.82 & 83) carried out at Darmstadt and also in the investigations using SUPERHILAC at Berkeley (Ref.84). It turned out that in this case no compound nucleus is formed, and, instead, deep inelastic collisions occur which are characterised by an intensive exchange of the mass, energy and angular momentum between the reaction partners; the formation of heavy products occurs, roughly speaking, according to the laws that have been established previously for the multinucleon reactions induced by the ions like $^{40}Ar$. In other words, the decay of the intermediate system formed in a deep inelastic collision between two very heavy nuclei has statistical nature. This is the main reason why the complicated process of interaction can be described satisfactorily within the framework of rather simple and illustrative models, such as the semi-phenomenological diffusion model of Nörenberg (Refs.85 & 86). With the known time of interaction, the distribution of primary fragments $p(E^*/Z)$ in Z and excitation energy can be calculated (Ref. 87) by solving the Fokker-Planck equation that describes the mass transfer and the angular momentum dissipation. Further, if we consider in the usual way the process of the decay of an excited fragment taking into account the variance of the excitation energy distribution and a factor of the type $[\Gamma_n/(\Gamma_n+\Gamma_f)]^x$ one can determine the cross sections $d^2\sigma/dZ \cdot dA$ for the ground state formation of nuclei with given Z and A.

The experimental data (Refs.88 & 89) on the cross sections for the formation of transuranium nuclei in the reactions $^{136}Xe+^{238}U$ and $^{238}U+^{238}U$, obtained at the UNILAC at a bombarding energy of $\leq$ 7.5 MeV/nucleon (for "thick" targets) are shown in Fig. 8. From this figure it follows that even for the combinations of the heaviest possible projectile and target nuclei there occurs a sharp decrease in cross sections for the formation of actinide isotopes as their Z and A values increase with moving farther from the Z and A values of the target. A similar decrease was observed in multinucleon transfer reactions induced by $^{40}Ar$ and $^{48}Ca$ ions. Even in the case of the combination U+U, a removal by 7-8 units in Z leads to a decrease of the yields of heavy nuclei by a factor of $10^7$-$10^8$ and more; as a result, the Fm isotopes with A = 252-256 are formed with cross sections of about $10^{-33}$cm$^2$.

Thus, considering the various methods of producing the isotopes of transfermium elements, we can draw the conclusion that reactions of the type (HI, $\alpha$xn) induced by ions with $A_I \leq 20$-25 seem to be promising in terms of the production of new neutron-rich nuclei with Z = 101-107 and N = 157-161. The lifetimes of many nuclei in this region (Refs.90 & 91) can be sufficiently long to permit, on the one hand, the use of radiochemical methods to separate them and, on the other one, the detailed studies of their properties, especially spontaneous fission ones.

In our view, the fusion reactions induced by the $^{48}Ca$, $^{50}Ti$, $^{54}Cr$ and other ions on targets made of heavy actinides including isotopes ranging from $^{244}Pu$ to $^{249}Cf$, are the most effective for the production of nuclei with $Z \geq 108$. The first runs of experiments to synthesize SHE in the reactions induced by $^{48}Ca$ ions, carried out at Dubna (Refs.21,66) and at Berkeley (Refs.32,67) in 1975-77, showed that production cross sections for these elements are small and, therefore, the sensitivity and the rapidity of response of the detection methods should be enhanced considerably. With a new generation of accelerators, such as the U-400, the intensity of ion beams with $A_I \geq 40$, in particular, of $^{48}Ca$ ion beams, can be increased substantially to permit the next run of experiments to synthesize superheavy nuclei with Z = 110-118 and N = 174-178 on a new footing.

The possibilities of producing new elements and isotopes in various nuclear reactions are illustrated in Fig. 9.

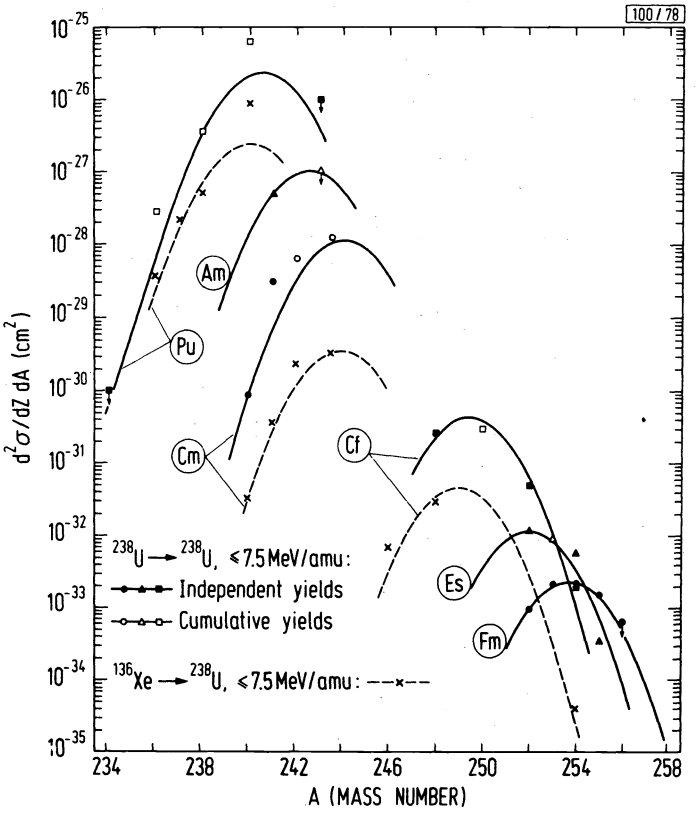


Fig. 8. Cross sections for the formation of heavy actinide isotopes in the U+U reaction at $\leq$ 7.5 MeV/amu (Ref. 88 & 89). For comparison similar data for the $^{136}Xe + ^{238}U$ reaction at $\leq$7.5 MeV/amu (dashed curves) are given. The curves are drawn to guide the eye. (This figure has been kindly provided by Dr. J.V.Kratz, GSI, Darmstadt).

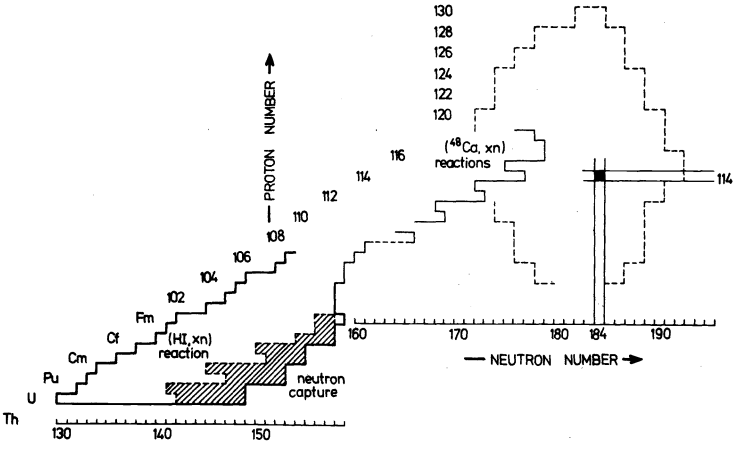


Fig. 9. The possibilities of synthesizing the isotopes of transuranium elements in various nuclear processes - multiple neutron capture reactions, (HI, xn) reactions, deep inelastic collisions of the type U+U (shaded area).

RADIOACTIVE PROPERTIES

As follows from Fig. 9, both intense neutron fluxes and deep inelastic collisions of the type U+U lead to the formation of transuranium nuclei with $Z \lesssim 100$ lying in the vicinity of the valley of $\beta$ -stability. Practically all the presently known isotopes of transfermium elements have been produced in the (HI, xn) reactions, whose products are, as a rule, neutron-deficient

and, therefore, undergo $\alpha$- or $\beta^+$(EC)-decay. As the Z of the nucleus increases (and/or one goes farther from the line of $\beta$-stability), a sharp increase in the probability for spontaneous fission is observed and just this type of radioactive decay plays the main role in the problem of the stability of heavy elements.

The stability of the atomic nucleus against radioactive decay is determined by the value of its mass or the total binding energy $B_0(Z,N)$, which should be known to a high accuracy, up to $\sim 10^{-1}$ to $10^{-2}$%. However surprising it may seem, despite the absence of the unique and consistent theory of the nucleus, the phenomenological description of the binding energies of nuclei in the ground state reproduces experimental data, on the average, to an accuracy of ~0.3% if it takes into account only the macroscopic (liquid-drop) properties, and to an accuracy of $\sim$ 0.1% if nuclear structure effects are also included. Therefore, bearing in mind the main structural features of an individual nucleus, which are responsible for strong variations in nuclear properties in the vicinity of the magic numbers, one can make rather accurate and far-reaching extrapolations for the ground-state binding energies and predict the values of the $\alpha$- and $\beta$-decay total energies (see Fig. 10), as well as the corresponding half-lives $T_{1/2\alpha}$ and $T_{1/2\beta}$ (see, for instance, the recent predictions by Kolesnikov et al. (90)).

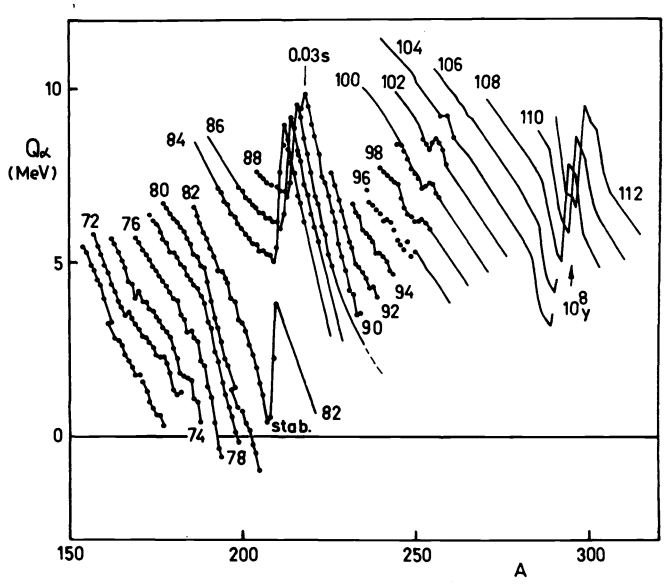


Fig. 10. Experimental (•) (Ref. 25) and calculated (Ref. 92) values of the total $\alpha$-decay energy $Q_\alpha$ for heavy nuclei with $Z \geq 70$.

The situation with respect to spontaneous fission is far more complicated. For its consideration, of crucial importance are the deformation dependence of the total nuclear binding energy B(Z,N)and its absolute saddle point value $B_{SP}(Z,N)$, or the fission barrier height

$$B_f = B_{SP}(Z,N) - B_0(Z,N). \tag{12}$$

Since we calculate the difference between two quantities that are large and close in magnitude, the requirements to the knowledge of mass and its dependence on nuclear shape are significantly higher.On the other hand,nuclear structure effects and their change with deformation become of crucial importance. If these effects make up $\lesssim 0.5\%$ of $B_0(Z,N)$, as it follows from what is said below, they may amount to 100% for the difference (12).

Moreover, the spontaneous fission half-life

$$T_{sf} = (\ell n\, 2/n)\, P^{-1}, \tag{13}$$

where n is the number of assaults of the nucleus on the fission barrier per unit time, determined by barrier penetrability P which, in turn, exponentially depends on the height (and "width") of the barrier. In a quasiclassical (WKB) one-dimensional approximation (see, e.g., Ref. 93)

$$P = [\, 1 + \exp S(L_{min})\,]^{-1}, \tag{14}$$

where

$$S(L) = 2 \int_{s_1}^{s_2} \sqrt{\frac{2}{\hbar^2}\,[\, V(s) - E\,]\, M_s(s)}\; ds \tag{15}$$

is the action integral along trajectory L set in the deformation space. In eq. (15) V(s) is the potential energy, $M_s(s)$ is the effective inertia (mass) along trajectory L, and E is

the energy of the fissioning nucleus; the parameter s determines the position of a point on trajectory L, and $s_1$ and $s_2$ are the positions of the classical turning points set by the condition V(s) = E. Note that $B_f$ is the maximum value of [ V(s) − E] on trajectory L. Then the dynamical calculations of $T_{sf}$ reduce to finding the trajectory $L_{min}$ that minimizes the action integral (15).

Relations (13)-(15) that are exponentially sensitive to fine properties of the fission process such as the height and shape of the fission barrier and the effective mass, characterize fairly well the complexity of the theoretical determination of $T_{sf}$.

Now let us turn to experimental data on fission barrier heights for heavy nuclei and their spontaneous fission half-lives, presented in Fig. 11a and 11b. The liquid-drop model predictions for these quantities are also given in this Figure.

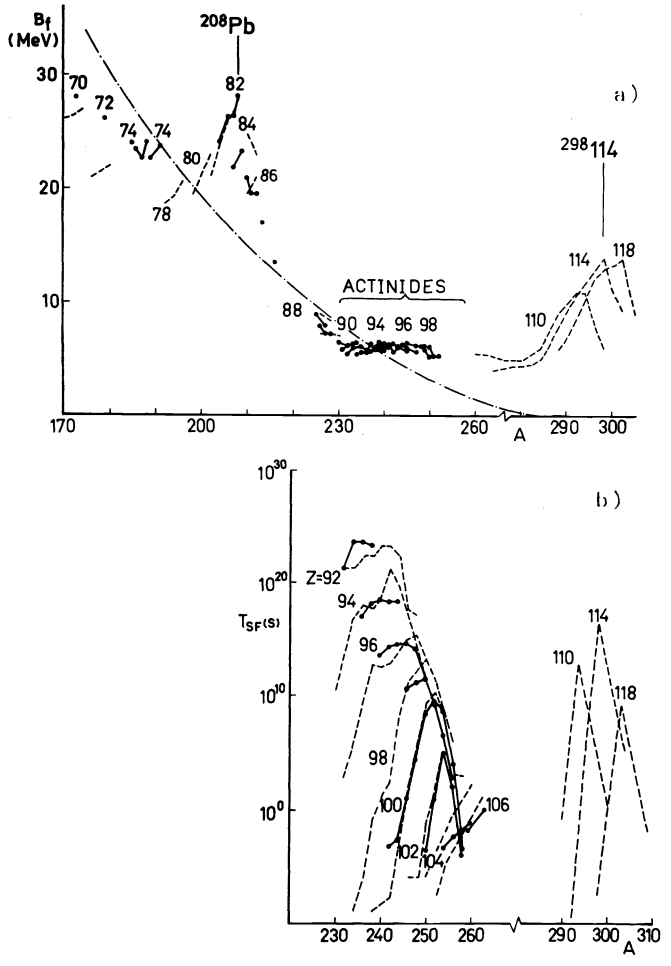


Fig. 11. Fission barrier heights of heavy and superheavy nuclei and their spontaneous fission half-lives. (a) Experimental and theoretical values of fission barrier heights $B_f$ for nuclei with $Z \geq 70$; (•) - experimental data (Ref. 94-98), the dashed line is the prediction of calculations (Ref.104-111) using the Strutinsky method, the dash-dotted line is the liquid drop model prediction. (b) Systematics of spontaneous fission half-lives $T_{sf}$ for even-even nuclei; (•) - experimental data (Ref.14,20,21,99), the dashed line shows theoretical predictions (Ref.93,111,120).

From Fig. 11 it follows that the experimental results (see, e.g., Refs. 14,21,94,100 and references therein) change drastically from the liquid-drop model predictions and these differences are essential. Among them are, first of all, the substantial (by 10-13 MeV) increase in the fission barriers at Z=82 and N=126 (the fission barriers of the doubly magic $^{208}$Pb and its neighbours) and the surprising constancy of $B_f^{max} \approx 6$ MeV (Note a) in the region of actinides.

Note a. We call $B_f^{max}$ the fission barrier amplitude to be determined as the maximum peak height in a one-dimensional curve for the deformation dependence of nuclear potential energy.

Still more impressive are the differences between the experimental $T_{sf}$ and the liquid-drop values calibrated by the value obtained 40 years ago in the experiments of Petrzhak and Flerov (Ref. 4) by measuring $T_{sf} \approx 10^{16}$ years for $^{238}U$, on one hand, and by the calculations by Bohr and Wheeler (Ref. 44) of the value of $(Z^2/A)_{crit} \approx 47.8$ at which $T_{sf} \sim 10^{-21}$s, on the other.

For instance, there exists the isospin dependence $T_{sf} = f(N)$, whose strength grows with increasing Z, and at Z = 100 the $T_{sf}$ variations are characterised (in the range of the nuclei investigated) by a factor of about $10^{13}$. At the same time, at N=152 the $T_{sf}$ versus N dependence shows a sharp "peak", especially for the isotopes of Cf, Fm, and element 102. However, as we have shown in Ref. 53, for Z = 104 the isospin dependence of $T_{sf}$ sharply changes its character and, in the range of N from 152 to 158, a factor of nearly 10 increase in $T_{sf}$ is observed, whereas for Fm, in the same range of N, a factor of $10^{13}$ decrease of $T_{sf}$ takes place. Despite the limited amount of experimental information, it is possible to suppose that in the region of $Z > 104$ a weak dependence of $T_{sf}$ on N takes also place, and as Z increases, the $T_{sf}$ values for nuclei with $Z \gtrsim 104$ decrease much more slowly than in the actinide region. The latter circumstance deserves special attention to be paid.

At first sight it may seem paradoxical that at a constant amplitude of fission barriers $B_f^{max} \approx 6$ MeV for the nuclei from $^{230}Th$ to $^{246}Fm$ or $^{256}Fm$ the value of $T_{sf}$ decreases by a factor of more than $10^{26}$. It is still more remarkable that spontaneous fission from a metastable state with half-lives $T_{sf}^{(m)} \approx 10^{-11}$-$10^{-2}$s has been observed for 35 isotopes from the region between U and Bk (Refs. 99-101). These $T_{sf}^{(m)}$ values differ $10^{20}$ to $10^{30}$ times from the $T_{sf}$ ground state values of the same nuclei.

These and many other data clearly indicate that spontaneous fission many properties of which are described by exponentially strong functions is an extremely complicated phenomenon. The diversity of its surprising properties, of course, it not exhausted by the liquid-drop model - it is elegant in its simplicity (Ref. 102) but neglects completely the individual structure and gives a description of only averaged "macroscopic" properties of the nucleus. Therefore, it is natural and reasonable to consider, in addition to the average properties, the shell structure effects of an individual nucleus and their influence on the fission barrier and, consequently, on $T_{sf}$.

Although the necessity of such consideration arose long ago, real progress has been made only after the development by Strutinsky of a method for calculating microscopic corrections to the ligiud-drop potential energy at an arbitrary deformation of the nucleus (Ref. 103). The consideration and inclusion of shell effects at large deformations permitted explanation of many experimental facts in the field of fission physics, as well as a large number of other phenomena related to considerable changes in the nuclear shape. On the other hand, this led to the creation of a rather effective theoretical machinery (Refs. 103 and 104) that is suitable for the real calculations of the total potential energy as a function of nuclear shape and particle number, and consequently, for the theoretical determination of the height and shape of the fission barriers. The numerous calculations (Refs. 104-110) performed so far indicate that the theoretical values of fission barrier heights agree rather well with experimental ones (Refs. 94-98) (see Fig.11a), on the average, within 1-2 MeV over a wide range of known heavy nuclei with Z lying between 70 to 100.

By using the theoretical values of fission barriers (or the potential energy surfaces in a more real multi-dimensional case) and introducing certain assumptions about fission dynamics (the value of the effective mass $M_s(s)$ and its dependence on nuclear shape) one can obtain, on the basis of relations (13)-(15), a satisfactory description of the systematics of the experimental values of $T_{sf}$ - on the average, within an accuracy of a factor of about 50 (Refs. 93, 111). It is noteworthy that in this case the calculations allow one to reproduce all the principal "irregularities" of the $T_{sf}$ systematics that we have discussed above, in particular, the sharp change in the character of the isospin dependence of $T_{sf}$ at $Z \gtrsim 104$.

In this case it is natural to use a given theoretical machinery to predict the spontaneous fission properties of the new, heavier nuclides. As known, such predictions were made during the recent decade or so by many groups of authors (see, e.g., Refs. 104, 112-115). As a result, it has been shown that in the region of superheavy nuclei lying around Z=114 and N=184, the fission barrier heights can reach 8-14 MeV, i.e., be considerably higher than those for actinides; consequently, the half-lives $T_{sf}$ can be relatively large (Refs. 116 & 117).

Considering now the stability of hypothetic superheavy nuclei against other modes of decay (Refs. 90 &116), such as $\alpha$- or $\beta$-decay, we can conclude that in these processes shell effects also lead to a significant increase in lifetimes. Thus, the performance of experiments on search in nature for primordial SHE with $T_{1/2} \gtrsim 10^9$ years is well justified.

Naturally, the qualitative predictions of radioactive properties (especially of spontaneous fission half-lives) in a region so far from the known nuclei have a limited accuracy. In the case of spontaneous fission half-lives the sensitivity to calculational details is such that each of the uncertainties - 1 MeV in the barrier height, 5% in the barrier "width" or 10% in the effective mass value - leads to a factor of about 100 change in $T_{sf}$ (Ref. 118). Therefore, the uncertainty involved in the $T_{sf}$ predictions for SHE is commonly accepted (Refs.116 &118) to be characterized by a factor of $10^{\pm 10}$. To compare the uncertainty of predictions for $T_{1/2\alpha}$ and $T_{1/2\beta}$ for the same nuclear region is considerably smaller, about $10^{\pm 3}$ (Ref.116).

At first sight, such an uncertainty can give rise to some pessimism concerning the possibility of producing the new heavier elements and especially SHE. In fact, however, the general situation with the predicted radioactive properties of nuclei with $Z > 107$ is more encouraging at present than 20 years ago, when, according to liquid-drop model predictions, the limit of nuclear stability was expected to be observed at $Z^2/A \approx 45$-48, i.e., practically already for nuclei with $Z \sim 108$. The present-day theoretical predictions enable us to assume that the half-lives $T_{sf}$ for nuclei with $Z \gtrsim 108$ are large enough for their experimental observation with modern techniques.

On the other hand, this problem is very complicated, first of all, because of large uncertainties involved in the lifetimes of the isotopes of new elements. These uncertainties arise from extrapolations of our knowledge on fission barriers and nuclear masses into the region of large Z and N values. Therefore, additional information is badly needed. In the first place, this applies to the nature of changes in the fission barrier heights (and, consequently, the stability) of nuclei as one goes farther from the closed nucleon shells since, in principle, the nuclear reactions induced by $^{48}Ca$ ions (even in the case of the reaction $^{48}Ca + ^{248}Cm$), which are used for the synthesis of SHE, lead to the formation of neutron-deficient isotopes. The experimental (and equally theoretical) problems of this kind can be "transferred" to the region of nuclei with $Z = 82$ and $N < 126$ or $N \sim 126$ and $Z \gtrsim 85$, in which the production cross sections for nearly magic (in Z or N) isotopes are relatively large, and, moreover, the radioactive properties of a large number of nuclides is well known. As we have shown in Ref. 119, the studies of $\beta^+$(EC) -delayed fission is rather a promising method for obtaining information about the fission barriers of nuclei in this region. This possibility is exemplified by thorium isotopes with $N \lesssim 126$ in Fig. 12.

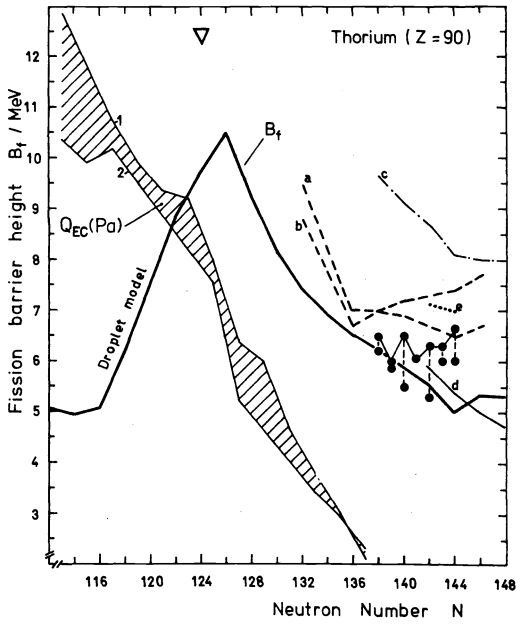


Fig. 12. Experimental ( • ) (Ref. 94) and theoretical values of fission barrier heights $B_f$ for Th isotopes. The solid line shows the Myers droplet model predictions, the curves a,b,c,d,e and point(▽)are the results of calculations (Refs. 105,108-110) using the Strutinsky method. The shaded area is the $Q_{EC}$ values predicted for Pa isotopes on the basis of various semiempirical systematics (see Ref.119).

It is also of interest to consider heavy isotopes ($N \gtrsim 159$) with $Z \gtrsim 100$, which undergo spontaneous fission with high probability. The spontaneous fission properties of these isotopes are rather unusual and differ substantially from those for nuclei with $N < 157$. Certain possibilities of producing isotopes with $N \gtrsim 159$ are offered by multinucleon transfer reactions. However, in all likelihood, these possibilities are still limited and, therefore, the use of the heaviest targets such as $^{254}Es$ and $^{257}Fm$ is a topical problem.

Finally, the most difficult way of the successive synthesis and study of isotopes with Z= 107, 108, 109 is of great importance. One can assume that the "anomalies" of the spontaneous fission half-lives which have permitted observation of relatively long-lived isotopes with $Z \lesssim 106$ and $N < 157$, should manifest themselves still more strongly at $Z \gtrsim 106$ and $N > 157$. As already noted, quite certain experimental possibilities are available for carrying out these investigations and, for the time being, a number of experiments has been performed on the synthesis of heavy isotopes of elements 104 to 108 by the reactions induced by $^{18}O$, $^{22}Ne$,

and $^{48}Ca$ ions. Unfortunately, theoretical predictions for nuclei with $N > 157$ are absent or not certain enough to make reliable estimates of spontaneous fission half-lives for new isotopes lying in Z and N close to the known ones.

However, irrespective of the real values of lifetimes, the synthesis and study of very heavy and superheavy nuclei are of fundamental importance. These investigations allow one to test our notions of nuclear structure and, in particular, the shell structure of the nucleus - the main nuclear model which has proven very efficient in elucidating a wide range of nuclear properties in the region of known elements, the forces that act in the nucleus and virtually determine nuclear stability and, consequently, the limiting number of elements in the Mendeleev Periodic Table.

## METHODS OF IDENTIFICATION

All transuranium elements up to fermium inclusive have been identified unambiguously by classical radiochemistry methods, and this looked quite natural because of large lifetimes and considerable amounts of the nuclides produced. At present the chemical properties of elements ranging from Np to Fm are known in detail with the accuracy required for their industrial production and practical application.

For transfermium elements, the problem of identification (the Z and A assignment for the nuclides) is substantially complicated because of a sharp decrease in lifetimes and of a rapid decrease in the probability of production for nuclides with increasing Z, and this forced the experimenters to work with single atoms.

It is conceivable that the use of the methods of classical (aqueous) chemistry is problematic already at $T_{1/2} \lesssim 1$ min, and the use of more rapid gas chemistry (Ref. 120) methods is unlikely to permit the investigation of nuclides with $T_{1/2} < 0.1$ s. Naturally, these limits of the technique rapidity are conventional; however, one can be easily convinced that in any case radiochemical methods prove to be inapplicable to a large number of short-lived isotopes of transfermium elements. As to quantities, present-day radiochemistry can certainly operate with a countable number of atoms (see, e.g., the classical experiments on discovery of plutonium in Ref. 7).

At the same time, at the present level of development of the methods of nuclear physics and nuclear technology, the problem of detection of extremely rare, including single events of the formation and decay of nuclei, involves no problems even if their lifetimes are $\sim 10^{-9}$s.

Thus the great interval of lifetimes from $10^{-1}$s to $10^{-9}$s and less lies beyond the possibilities of radiochemistry and, consequently, it is necessary to develop the physical methods of identification of new nuclides and use them to advance towards larger Z values until we reach a favourable situation at $T_{1/2} > 0.1$ s, if theoretical predictions about the enhanced stability of superheavy elements are justified.

In general, physics has at its disposal a great variety of methods for the determination of atomic number Z and mass number A of a radioactive emitter. Each of these methods, however, has a certain selectivity, sensitivity and rapidity. It is evident that at fairly large yields of new radioactive nuclei their Z and A values can be determined by many methods of classical physics, e.g., by their characteristic X-radiation, by mass-spectrometric analysis, and others, as it was done repeatedly for many new short-lived isotopes of known elements. We shall not discuss these possibilities in more detail and only touch upon those situations in which the probability of the formation of new nuclides is so small that none of the above mentioned classical methods can be used. In such situations, unfortunately, no unambiguous prescription exists for solving this problem, and the information available to the experimenter appears to be more indirect and, consequently, more complicated. This information contains the facts the decoding and analysis of which allow one to establish only with a certain probability the data of interest to us, such as Z,A, decay mode, and $T_{1/2}$, and to compare these data to one or another conception of the properties of new heavy nuclei.

Thus in the case of short lifetimes we have to use a complex approach, which is based on the regularities involved in the formation of the new nuclide in nuclear reactions, and on the expected radioactive properties of this nuclide (Note a). Despite the fact that just the latters are the subject of investigations, they can often be predicted reliably enough, as, for instance, in the case of $\alpha$- or $\beta$-decay. This circumstance has just been taken into account at the synthesis of the $\alpha$-radioactive isotopes of transfermium elements. However, certain difficulties exist here. Although the $\alpha$-particle energy spectrum and the new $\alpha$-emitter half-life can be determined rather accurately and in some cases one can measure the characteristics of not only the parent, but also daughter nucleus, the fact of observing the expected properties cannot be the proof of the formation of an isotope of the new element. Because of possible backgrounds (see, e.g., Ref. 121) the experimenters must use additional information, in particular, investigate in detail the regularities of formation of the new emitter and carry out long control experiments, each of which is not crucial, but, together with others, enhances the reliability of conclusions considerably.

---

Note a. In some cases the correlations of the formation regularities and radioactive properties can be employed.

As a whole, this approach has been justified in experiments on synthesis of many isotopes of elements 102, 103 and the heavier ones (Refs. 19, 20,23). However, from the consideration of the properties of heavy elements it follows that the field of its application is limited.

As shown in the previous Section, the stability of heavy and superheavy elements depends mainly on spontaneous fission which determines the half-lives of many even-even nuclei with $Z \geq 100$ and odd nuclei with $Z \geq 104$ (see the $T_{sf}$ systematics in fig.11b). It is rather likely that decay by spontaneous fission can occur for the overwhelming majority of nuclei in the region of somewhat larger atomic numbers. On the other hand, the predictions of spontaneous fission half-lives are significantly less reliable and the energy spectra of fragments are known (Ref. 122) to be characterized by a considerable variance. Naturally this changes the situation and generally complicates the problem if we use the same experimental arrangement as that for $\alpha$-active nuclides.

This circumstance gave rise to wide discussions and even statements that spontaneous fission is not informative enough for identification of new elements (Note a). In our view, these difficulties are overrated artificially since in spontaneous fission detection there is no necessity to search for information in the same characteristics that are measured in $\alpha$-decay. On the contrary, spontaneous fission is exceptionally rich in intrinsic specific and diverse properties. It is accompanied by high energy release and the emission of a very characteristic set of particles including a pair of highly ionizing heavy fragments with a certain mass ratio and several fast neutrons. The average value $\bar{\nu}$ and the variance of the multiplicity distribution $\sigma_\nu^2$, of prompt fission neutrons depend on the Z and (less strongly) on the A of the fissioning nucleus as systematically as do the parameters of the distribution of the total kinetic energy of the fragments (Ref. 122). Various aspects of identification of the new elements on the basis of spontaneous fission were considered by Flerov and coworkers, e.g., in Refs. 20 & 124, in which one can find the analysis and evaluation of the advantages of this approach over other possible ones, as well as its application limitations. We emphasize that the investigations aimed at the synthesis of new elements have virtually led us to the region of nuclei the most characteristic feature of which is a high probability of spontaneous fission. Therefore it is quite natural that, in discussing a complex physical approach to the identification of short-lived nuclides, we turn first of all, to the most probable mode of their radioactive decay.

On the other hand, the majority of isotopes in the region of transfermium elements have been produced in (HI,xn) reactions, which seem to us to be the most promising also for reaching the region of SHE. The main specific feature of the kinematics of these reactions is the compound nucleus momentum which is fairly definite in value and direction. Accordingly, the angular distribution of recoil nuclei is strictly specified - it is strongly peaked in the direction of the incident particle beam and has a small variance (Refs. 125-127). On the other hand, the products of other types of reactions, e.g., nuclear transfer reactions or those involving the partial absorption of the projectile by the target nucleus - have, in general, quite different angular distributions (Refs. 126-129), Fig.13a. The energy and range distributions of recoil nuclei in matter in the reactions (HI,xn) are also rather characteristic (Refs. 125,127,130-132) and fairly well describable by calculations. They considerably differ from those observed in other heavy ion reactions (Refs. 127 & 129) (fig.13b). These specific properties can be employed for separation of complete-fusion reaction products from other reaction products to reach discrimination factors of about $10^3$.

This has been done in the studies of the regularities of production of transfermium nuclides in a large series of experiments (Ref. 133). The most detailed studies were performed to reveal the regularities of formation of the isotope $^{260}104$ ($T_{sf} \approx 80$ ms) in the following target projectile combinations

$$^{249}Bk(^{15}N,4n), \quad ^{246}Cm(^{18}O,4n), \text{ and } ^{242}Pu(^{22}Ne,4n),$$

for which the compound nucleus $^{264}104$ has an excitation energy of about 40 MeV. The cross sections of these reactions differ strongly and, undoubtedly, in terms of the yields, the use of the lightest projectile appears preferable. However, in this case the total background due to formation of the spontaneously fissioning isomer $^{242m}Am$, the Fm and Md isotopes that undergo spontaneous fission or electron capture is significantly higher. Despite this, by separating the recoil nuclei in both the angular and energy distributions it is possible to separate well the spontaneously fissioning activity $^{260}104$ (Ref. 133). A similar method can be used also for the separation of the heavier nuclei with $Z \geq 104$.

The technique of separating nuclear reaction products on the basis of their angular and energy distributions can be complicated and considerably imrpoved by introducing electric and

---

Note a. We bear in mind the point of view of some of our colleagues, outlined in the journal "Science" (Ref.123). Developing the idea that spontaneous fission is not informative enough, the authors of this paper set the limits of possible studies on the synthesis and identification of the isotopes of new transfermium elements. Leaving aside the general problem of legitimacy of the a priori elaboration of the criteria that should be met to prove the discovery of a new natural phenomenon, we would like only to note that such ideology virtually excludes completely the possibility of research in the very important field of heavy and superheavy elements.

magnetic fields. This has been done, for instance, in the separator SHIP (Ref. 134) at Darmstadt, which has recently permitted observation (Ref. 59) of the reaction $^{208}Pb(^{50}Ti,n)^{257}104$. The $\alpha$-radioactive isotope $^{257}104$ is formed in this reaction with a cross section of about 1 nbarn and, consequently, in this case a discrimination factor of $10^6$-$10^7$ is required to separate the "dangerous" isotopes of Po to Ac, formed with large cross sections in nucleon transfer reactions on a $^{208}Pb$ target (Refs. 121 & 129). Such separation took place in the experiments described in Ref. 59.

On the other hand, another light isotope of element 104 - $^{256}104$ - that undergoes spontaneous fission was first produced, as known (Ref. 53), under completely backgroundless conditions with no special measures taken, and its identification was performed on the basis of the energy dependence of the production cross section $\sigma_{xn}$, which is informative enough in this case.

Therefore, there can be no universal solution to the problem of identifying the new emitter. It depends substantially on the conditions of a concrete experiment and on the art of the experimenter.

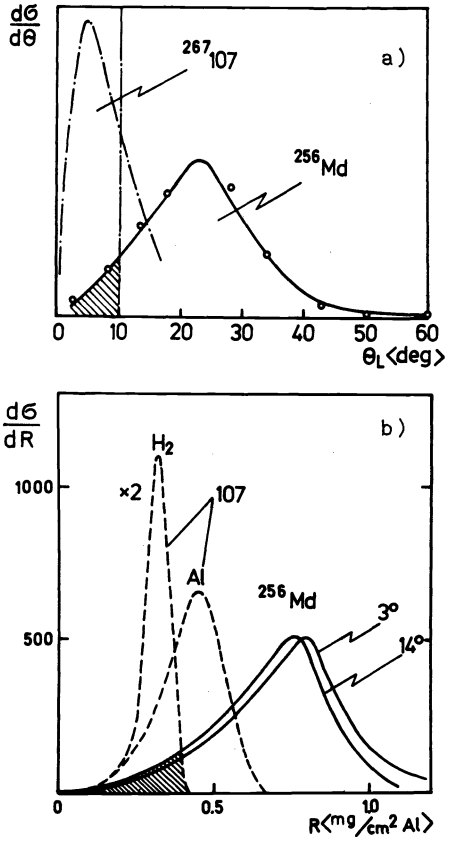


Fig. 13. (a) The angular distribution of the $^{249}Bk + ^{22}Ne$ reaction products (Ref.127); ( o ) - experimental data for $^{256}Md$, the dash-dotted curve shows a calculation for the Z=107 nuclei. (b) The range distribution of the $^{249}Bk + ^{22}Ne$ reaction products in aluminium (Ref. 127); solid curves are experimental data for $^{256}Md$, dashed lines are the calculated range distributions of recoil nuclei with Z = 107 in hydrogen and aluminium.

As for the identification based on detection of spontaneous fission fragments, this approach can be developed substantially by obtaining in experiments of more detailed information about the characteristics of this type of decay, such as the TKE spectrum of the fragments, the multiplicity ( $\bar{\nu}$ , $\sigma_\nu^2$ , etc) of prompt neutrons emitted at fission, the mass distribution (or mass ratio) of the fragments, and about correlations between these characteristics. Even in a problem as complicated as the synthesis and identification of SHE, the combined measurement of the TKE spectra of the fragments and $\bar{\nu}$ can be a proof of detection of superheavy nuclei if, for instance, it is found experimentally that $E_k$ = 230-240 MeV and, at the same time, $\bar{\nu}$ = 8-10. We note that from these data one can reconstruct with satisfactory accuracy the value of the total energy release Q from spontaneous fission, i.e., virtually to estimate Z of the fissioning nucleus. The experimental setups which are designed for such studies and permit determination of the energy of coincident fragments and the number of

prompt neutrons per each spontaneous fission of a short-lived nucleus ($T_{1/2} \gtrsim 0.2$ s) have recently been created at Dubna (Refs. 135 & 136).

Returning to the problems of the technique rapidity, we would like to emphasize that in the case of using physical methods to identify new nuclei the minimum accessible lifetimes are determined by the velocity of their transportation from the target to the detectors, which is comparable to the velocity of the compound nucleus motion in the extreme case. For reactions induced by ions such as $^{48}Ca$ at a projectile energy close to the Coulomb barrier (about 5 MeV/nucleon) the velocity of recoil nuclei is such that it provides a minimum detection time of about $10^{-6}$ - $10^{-7}$s in on-line systems.

We believe that the problem of identification of heavy and superheavy elements lies rather in the magnitude of the new nuclide yields, which are determined, in the first place, by the efficiency of the technique and the ion beam intensity. The present-day accelerators such as U-400, UNILAC and the future ones are capable of producing heavy ion beams with intensity of $10^{13}$ - $10^{14}$ particles/s, thus offering wide possibilities for the synthesis and study of new nuclei even at very small production cross sections, to $10^{-36}cm^2$.

## CONCLUSION

The analysis of various types of processes between complex nuclei shows that the fusion reactions induced by $^{48}Ca$ , $^{50}Ti$ , $^{54}Cr$ , and other ions, which lead to slightly excited intermediate nuclei are the most efficient ones for the synthesis of new transfermium elements. The use of intense beams of say $^{48}Ca$ ions from modern accelerators such as the U-400, UNILAC and others, in combination with targets made of heavy actinides - from $^{244}Pu$ to $^{249}Cf$ - allows one to produce slightly excited nuclei with Z = 110-118 and N = 176-180 with the required and, in our view, sufficient probability.

The possibility of observing such nuclei in the ground state is essentially determined by their radioactive properties, the sensitivity and rapidity of the detection method used. It is quite likely that the experimental attempts to synthesize SHE in reactions induced by $^{48}Ca$ ions, undertaken at Dubna and at Berkeley in 1975-77 (Refs. 21,32,66,67), have led to the formation of nuclides whose spontaneous fission half-lives, $T_{sf}$, were beyond the rapidity of the detection technique. Analyzing in this context the available knowledge about the stability of nuclei against spontaneous fission and about the fission mechanism as a whole we see no grounds for revising the concept of the existence of the region of enhanced stability in the vicinity of the supermagic numbers of Z and N. On the contrary, the data on fission barriers, spontaneous fission half-lives, the properties of spontaneously fissioning isomers and many other data, accumulated for the recent 10-15 years, indicate unambiguously the strong stabilizing effect of nuclear shells on barrier structure and stability against fission, in agreement with the generally accepted theoretical ideas.

The further accumulation of information in this respect is very important. In particular, it is of great interest to investigate the fission barrier heights and the fission probabilities of cold and heated neutron-deficient nuclei lying near the known closed shells Z=82 or N = 126, on the basis of $\beta$-delayed fission and heavy ion reactions involving the emission of a small number of neutrons x ( $x \leq 2$) from the slightly excited intermediate nucleus (Ref. 119). It is also important to obtain information on the fission barriers of nuclei with Z > 100 from experimental data on $\Gamma_n / \Gamma_f$ extracted for the reactions (HI, xn ) with $x \leq 2$, or for any other processes leading to formation of slightly excited nuclei (Ref. 119). The studies of the mass, kinetic energy and excitation energy distributions of the fragments (the multiplicity of prompt neutrons), which characterize the last stages of the fission process, are also of fundamental importance to solve the problem of SHE. With the existing experimental technique, these investigations can be carried out for a wide range of new nuclei.

The identification of new elements does not seem problematical at present, although it is possible that traditional methods (radiochemical separation in combination with the subsequent measurement of radioactive properties) may be rejected because of their insufficient rapidity. Sufficiently large yields of the new nuclei, knowledge of the mechanism of the nuclear processes leading to their formation (kinematics, energy correlations, etc.) and use, in some cases, of the methods of electric and magnetic separation are the factors that can lead to the Z and A assignment for the new spontaneous fission emitter with the required reliability.

The experimental and theoretical studies of the mechanism of fission of nuclei lying beyond the known region are of paramount importance for the synthesis of new transfermium and superheavy elements. The studies of the fission mechanism should be extended not only to large Z values, but also to nuclei far from the line of $\beta$-stability. How valuable this extension is has been exemplified by the heavy isotopes of fermium, mendelevium and element 102 (Refs. 122,135,137-143).

Undoubtedly the experimental and theoretical studies of various aspects of nuclear fission will be a problem of primary importance for the next few years. Only they will allow us to obtain a more definite notion of the boundaries of the Mendeleev Periodic Table.

REFERENCES


1. J.Chadwick, Proc.Roy.Soc. A136, 692 (1932).
2. E.Fermi, Nature 133, 898-899 (1934).
3. O.Hahn and F.Strassmann, Naturwiss. 27, 11 (1939); ibid. 27, 89-95 (1939).
4. K.A.Petrzhak and G.N.Flerov, Compt.Rend.Acad.Sci. USSR (in Russian), 25, 500-501 (1940); J.Phys.USSR 3, 275-280 (1940).
5. L.W.Alvarez, Phys.Rev. 58, 192 (1940).
6. E.M.McMillan and P.H.Abelson, Phys.Rev. 57, 1185-1186 (1940).
7. G.T.Seaborg, E.M.McMillan, J.W.Kennedy and A.C.Wahl, Phys.Rev. 69, 366 (1946); ibid. 69, 367 (1946).
8. G.T.Seaborg, Man-Made Transuranium Elements, Prentice-Hall, New Jersey (1964); Actinides Rev. 1, 3-38 (1967).
9. V.A.Karnaukhov, G.M.Ter-Akopyan and V.G.Subbotin, Proc. of the Third Conf. on Reactions Between Complex Nuclei, pp.434-437, University of California Press, Berkeley (1963); Preprint P-1072, JINR, Dubna (1962).
10. V.I.Kuznetsov, N.K.Skobelev and G.N.Flerov. Yadernaya Fizika 4, 279-281 (1966); ibid. 5, 271-273 (1967); V.I.Kuznetsov and N.K.Skobelev, Yadernaya Fizika 5, 1136-1137 (1967); N.K.Skobelev, Yadernaya Fizika 15, 444-447 (1972).
11. R.E.Azuma, L.C.Carraz, P.G.Hansen, B.Jonson, K.-L.Kratz, S.Mattson, G.Nyman, H.Ohm, H.L.Ravn, A.Schröder and W.Ziegert, Phys.Rev.Lett. 43, 1652-1654 (1979).
12. G.N.Flerov and V.A.Druin, in "Structure of Complex Nuclei" (in Russian), pp.249-271, Atomizdat, Moscow (1966).
13. A.B.Migdal, Fermions and Bosons in Strong Fields (in Russian), Nauka, Moscow (1978).
14. E.K.Hyde, I.Perlman and G.T.Seaborg, The Nuclear Properties of the Heavy Elements, Vol. II: Detailed Radioactivity Properties, Prentice-Hall, New Jersey (1964).
15. A.Ghiorso, S.G.Thompson, G.H.Higgins, G.T.Seaborg, M.H.Studier, P.R.Fields, S.M.Fried, H.Diamond, J.F.Mech, G.L.Pyle, J.R.Huizenga, A.Hirsch and W.M.Manning, Phys.Rev. 99, 1048-1049 (1955).
16. R.W.Hoff and E.K.Hulet, in Proc. Symp. on Engineering with Nuclear Explosives (Las Vegas, 1970),CONF-700101, Vol.2, pp.1283-1294, Clearinghouse for Federal Sci.Techn. Information, Nat. Bureau of Standards, U.S. Dep. of Commerce, Springfield, Virginia (1970).
17. E.K.Hulet, J.F.Wild, R.W.Lougheed, J.E.Evans, B.J.Qualheim, M.Nurmia and A.Ghiorso, Phys.Rev.Lett. 26, 523-526 (1971).
18. A.Ghiorso, B.G.Harvey, G.R.Choppin, S.G.Thompson and G.T.Seaborg, Phys.Rev. 98, 1518-1519 (1955).
19. G.N.Flerov, Atomnaya Energiya 24, 5-17 (1968).
20. G.N.Flerov, V.A.Druin and A.A.Pleve, Uspekhi Fiz.Nauk 100, 45-92 (1970); G.N.Flerov and I.Zvara, Preprint D7-6013, JINR, Dubna (1971); G.N.Flerov and V.A.Druin, Atomic Energy Review 8, 255 (1970).
21. Yu.Ts.Oganessian, Proc. Int. School-Seminar on Reactions of Heavy Ions with Nuclei and Synthesis of New Elements (Dubna, 1975), pp.9-32, D7-9734, JINR, Dubna (1976); Lecture Notes in Physics 33, pp.221-252, Springer-Verlag, Heidelberg (1975); Nukleonika 22, 89-106 (1977).
22. G.N.Flerov, J.Phys.Soc.Japan 44 (Suppl.), 723-729 (1977); in Future Directions in Studies of Nuclei Far from Stability (Proc. Int.Symp., Nashville, Tennessee, 1979), pp.339-352, North-Holland, Amsterdam (1980).
23. G.T.Seaborg, Annual Rev. Nucl.Sci. 18, 53-152 (1968).
24. O.L.Keller and G.T.Seaborg, Annual Rev. Nucl.Sci. 27, 139-166 (1977).
25. Table of Isotopes, 7-th Ed.,Edited by C.M.Lederer and V.S.Shirley, Wiley-Interscience, New York (1978).
26. Yu.Ts.Oganessian, O.A.Orlova, G.M.Ter-Akopian, Yu.A.Muzychka, A.A.Pleve, B.I.Pustylnik, V.I.Chepigin and G.N.Flerov, Physics and Chemistry of Fission (Proc. Symp. Jülich, 1979), Vol.1, pp.129-141, IAEA, Vienna (1980).
27. G.N.Flerov and G.M.Ter-Akopian, Plenary Lecture at Int. Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980); Pure and Applied Chemistry, this volume.
28. G.Herrmann, Int.Rev.Sci.Inorg.Chem., Ser.2, Vol.8 (Ed. A.G.Maddock), pp.221-272, Butterworth, London (1975).
29. G.Herrmann, Nature 280, 543-549 (1979).
30. G.Herrmann, Plenary Lecture at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980); Pure and Applied Chemistry,this volume.
31. E.K.Hulet, R.W.Lougheed, J.M.Nitschke, R.L.Hahn, R.L.Ferguson, W.Brüchle, H.Gäggeler, J.V.Kratz, M.Schädel, G.Wirth, G.Herrmann, G.Tittel and N.Trautmann, Plenary Lecture at Int. Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980); Pure and Applied Chemistry, this volume.
32. G.T.Seaborg, W.Loveland and D.J.Morrissey, Science 203, 711-717 (1979).
33. Superheavy Elements - Theoretical Predictions and Experimental Generation (ed. S.G.Nilsson and N.R.Nilsson), Almqvist & Wiksell, Stockholm (1974); Physica Scripta 10A,(1974).
34. Proceedings of the International Symposium on Superheavy Elements (Lubbok, 1978), Ed. M.A.K.Lodhi, Pergamon Press, New York (1978).
35. N.Bohr, Nature 137, 344-348 (1936); N.Bohr and F.Kalckar, Kgl. Danske Videnskab. Selsk., Mat-Fys.Medd. 14, No. 10, 1-40 (1937).

36. V.F.Weisskopf, Phys.Rev. 52, 295 (1937).
37. H.A.Bethe, Revs.Mod.Phys. 9, 69-244 (1937).
38. J.R.Huizenga and L.G.Moretto, Annual Rev.Nucl.Sci. 22, 427-464 (1972).
39. A.V.Ignatyuk, Nuclear Theory in Neutron Data Evaluation, Vol.1, 211-250, IAEA, Vienna (1976).
40. V.F.Weisskopf, Physics in the Twentieth Century: Selected Essays, the MIT Press, Cambridge (1972).
41. G.N.Flerov, in Proc. 2nd U.N. Int.Conf. Peaceful Uses At.Energy (Geneva, 1958) 14, Nucl.Phys. and Instrumentation, pp.151-157, United Nations, Geneva (1959).
42. J.H.Fremlin, In Nuclear Reactions (Ed. P.M.Endt and M.Demeur), vol.1, pp.86-158, North-Holland, Amsterdam (1959).
43. A.Zucker, Annual Rev.Nucl.Sci.10, 27 (1960).
44. N.Bohr and J.A.Wheeler, Phys.Rev. 56, 426-450 (1939).
45. T.Sikkeland, Arkiv Fysik 36, 539-552 (1967).
46. T.Sikkeland, A.Ghiorso and M.J.Nurmia, Phys.Rev. 172, 1232-1238 (1968).
47. A.S.Iljinov and E.A.Cherepanov, Preprint P-0090, Institute of Nuclear Physics of the USSR Academy of Sciences, Moscow (1978).
48. K.-H.Schmidt, W.Faust, G.Münzenberg, W.Reisdorf, H.-G.Clerc, D.Vermeulen and W.Lang, Physics and Chemistry of Fission (Proc. Symp. Jülich, 1979), vol.1, pp.409-420, IAEA, Vienna (1980).
49. Yu.Ts.Oganessian, A.S.Iljinov, A.G.Demin and S.P.Tretyakova, Nucl.Phys. A239, 353-364 (1975).
50. G.N.Flerov, Yu.Ts.Oganessian, A.A.Pleve, N.V.Pronin and Yu.P.Tretyakov, Nucl.Phys. A267, 359-364 (1976).
51. O.A.Orlova, H.Bruchertseifer, Yu.A.Muzychka, Yu.Ts.Oganessian, B.I.Pustylnik, G.M.Ter-Akopian, V.I.Chepigin and Choi Val Sek, Yadernaya Fizika 30, 618-625 (1979).
52. J.M.Nitschke, R.E.Leber, M.J.Nurmia and A.Ghiorso, Preprint LBL-6534 Rev., Berkeley (1978).
53. Yu.Ts.Oganessian, A.G.Demin, A.S.Iljinov, S.P.Tretyakova, A.A.Pleve, Yu.E.Penionzhkevich, M.P.Ivanov and Yu.P.Tretyakov, Nucl.Phys. A239, 157-171 (1975).
54. Yu.Ts.Oganessian, 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, Pis'ma ZhETF 20, 580-585 (1974).
55. Yu.Ts.Oganessian, A.G.Demin, N.A.Danilov, M.P.Ivanov, A.S.Iljinov, N.N.Kolesnikov, B.N.Markov, V.M.Plotko, S.P.Tretyakova and G.N.Flerov, Nucl.Phys. A273, 505-522 (1976).
56. G.M.Ter-Akopyan, A.S.Iljinov, Yu.Ts.Oganessian, O.A.Orlova, G.S.Popeko, S.P.Tretyakova, V.I.Chepigin, B.V.Shilov and G.N.Flerov, Nucl.Phys. A255, 509-522 (1975).
57. H.Gaeggeler, A.S.Iljinov, G.S.Popeko, W.Seidel, G.M.Ter-Akopian and S.P.Tretyakova, Z.Physik A289, 415-420 (1979).
58. G.Münzenberg, P.Armbruster, W.Faust, S.Hofmann, T.Kitahara, W.Reisdorf, K.H.Schmidt, K.Güttner and B.Thuma, Jahresbericht 1978, GSI 79-11, Darmstadt (1979).
59. G.Münzenberg, P.Armbruster, W.Faust, K.Güttner, E.P.Hessberger, S.Hofmann, W.Reisdorf, K.-H.Schmidt, B.Thuma and D.Vermeulen, Contribution to Int. Symp. on the Synthesis and Properties of New Elements (Dubna, 1980) D7-80-556 p.27, JINR, Dubna (1980).
60. Yu.Ts.Oganessian, Yu.E.Penionzhkevich, V.I.Man'ko and V.N.Polyansky, Nucl.Phys. A303, 259-264 (1978).
61. R.Kalpakchieva, Yu.Ts.Oganessian, Yu.E.Penionzhkevich, H.Sodan and B.A.Gvozdev, Phys.Lett. 69B, 287-289 (1977).
62. H.Sann, S.Bjørnholm, R.Bock, Y.T.Chu, A.Gobbi, E.Grosse, U.Lynen, E.Morenzoni, W.Müller, A.Olmi, D.Schwalm and W.Wolfli, Proc. Int. Conf. on Nucl. Phys. (August 24-30, 1980 Berkeley), vol.1, p.570, LBL-11118, Berkeley (1980).
63. G.N.Flerov, Yu.Ts.Oganessian, Yu.V.Lobanov, Yu.A.Lazarev, S.P.Tretyakova, I.V.Kolesov and V.M.Plotko, Nucl.Phys. A160, 181-192 (1971).
64. Yu.Ts.Oganessian, Yu.E.Penionzhkevich, K.A.Gavrilov and Kim De En, Preprint P7-7863, JINR, Dubna (1974).
65. W.J.Swiatecki, Preprint LBL-10911, Berkeley (1980).
66. Yu.Ts.Oganessian, H.Bruchertseifer, G.B.Buklanov, V.I.Chepigin, Choi Val Sek, B.Eichler, K.A.Gavrilov, H.Gaeggeler, Yu.S.Korotkin, O.A.Orlova, T.Reetz, W.Seidel, G.M.Ter-Akopian, S.P.Tretyakova and I.Zvara, Nucl.Phys. A294, 213-224 (1978).
67. E.K.Hulet, R.W.Lougheed, J.F.Wild, J.H.Landrum, P.G.Stevendon, A.Ghiorso, J.M.Nitschke, R.J.Otto, D.J.Morrissey, P.A.Baisden, B.F.Gavin, D.Lee, R.J.Silva, M.M.Fowler and G.T.Seaborg, Phys.Rev.Lett. 39, 385-389 (1977).
68. Yu.Ts.Oganessian, Proc. of Int. School on Nucl.Struct., Alushta, USSR, April 1980, D4-80-385, pp.261-276, JINR, Dubna (1980).
69. H.Bruchertseifer, E.Langrock, Yu.A.Muzychka, T.Pawlat, Yu.E.Penionzhkevich, B.I.Pustylnik and K.Schilling, Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, 1980) D7-80-556, p.61, JINR, Dubna (1980).
70. V.I.Chepigin, V.M.Vas'ko, S.V.Stepantsov, S.P.Tretyakova, H.Bruchertseifer, G.M.Ter-Akopian and O.Constantinescu, Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, 1980), D7-80-556, p.63, JINR, Dubna (1980).
71. R.J.Silva, P.F.Dittner, M.L.Mallory, O.L.Keller, K.Eskola, P.Eskola, M.Nurmia and A.Ghiorso, Nucl.Phys. A216, 97-108 (1973).

72. L.P.Somerville, in Future Directions in Studies of Nuclei Far From Stability (Proc. Int. Symp., Nashville, Tennessee, 1979), pp.337-338, North-Holland, Amsterdam (1980).
73. A.G.Demin, V.A.Druin, Yu.V.Lobanov, R.N.Sagaidak, V.K.Utyonkov, S.Hübener, Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, 1980), D7-80-556, p.60, JINR, Dubna (1980).
74. A.G.Demin, in Abstracts of Papers presented at Int. Symp. on the Synthesis and Properties of New Elements (Dubna, 1980), D7-80-556, p.26, JINR, Dubna (1980).
75. A.S.Iljinov and E.A.Cherepanov, in Abstracts of Papers presented at Int. Symp. on the Synthesis and Properties of New Elements (Dubna, 1980), D7-80-556, p.29, JINR, Dubna (1980).
76. A.G.Artukh, G.F.Gridnev, V.L.Mikheev, V.V.Volkov and J.Wilczynski, Nucl.Phys. A215, 91-108 (1973).
77. V.V.Volkov, Phys.Rep. 44, 93-157 (1978).
78. Yu.Ts.Oganessian, in Nuclear Structure (Proc. IAEA Symp., Dubna 1968), pp.489-499, IAEA, Vienna (1968).
79. G.N.Flerov, in Comptes Rendus du Congres Intern. de Physique Nucleaire, vol.1, p.373, Paris (1964).
80. S.A.Karamyan, Yu.Ts.Oganessian, Preprint P7-4339, JINR, Dubna (1969).
81. G.N.Flerov and Yu.Ts.Oganessian, In Proc.Symp. on the Chemistry of Transuranium Elements (Moscow, 1972), J.Inorg.Nucl.Chem.Suppl.1976, 131-138 (1976).
82. R.Bock, First Results at GSI, GSI - Bericht M-2-77, Darmstadt (1977).
83. K.D.Hildebrand, H.Freiesleben, F.Pühlhofer, W.F.W.Schneider, R.Bock, D.V.Harrach and H.J.Specht, Phys.Rev.Lett. 39, 1065 (1977).
84. W.U.Schröder and J.R.Huizenga, Annual Rev.Nucl.Sci. 27, 465-547 (1977).
85. W.Nörenberg, Phys.Lett. 52B, 289-292 (1974).
86. G.Wolschin and W.Nörenberg, Z.Phys. A284, 209-216 (1978).
87. C.Riedel and W.Nörenberg, Z.Phys. A290, 385-391 (1979).
88. M.Schädel, J.V.Kratz, H.Ahrens, W.Brüchle, G.Franz, H.Gäggeler, I.Warnecke, G.Wirth, G.Herrmann, N.Trautmann and M.Weis, Phys.Rev.Lett. 41, 469-472 (1978).
89. J.V.Kratz, GSI-Report 80-1, Darmstadt (1980).
90. N.N.Kolesnikov, A.G.Demin and E.A.Cherepanov, Preprint D4-80-572, JINR, Dubna (1980).
91. K.Pomorski, Nukleonika 23, 125-131 (1978).
92. W.D.Myers and W.J.Swiatecki, Report UCRL-11980, Berkeley (1965).
93. A.Baran, K.Pomorski, A.Lukasiak and A.Sobiczewski, Preprint"p"IBJ Nr. 4/VII/80/P, Inst. Nucl.Res., Warszawa (1980): submitted to Nucl.Phys.A.
94. H.C.Britt, Nukleonika 25, 71-103 (1980).
95. L.G.Moretto, S.G.Thompson, J.Routti and R.C.Gatti, Phys.Lett. 38B, 471-474 (1972).
96. A.V.Ignatyuk, K.K.Istekov, V.N.Okolovich and G.N.Smirenkin, Physics and Chemistry of Fission (Proc. Symp. Jülich, 1979), vol.1, pp.421-444, IAEA, Vienna (1980).
97. D.Türck, H.-G.Clerc and H.Träger, Phys.Lett. 63B, 283-285 (1976).
98. A.Kernohan, T.E.Drake, A.Chung and L.Pai, Phys.Rev. C16, 239-242 (1977).
99. K.A.Petrzhak and G.N.Flerov, Atomnaya Energiya, 44, 22-36 (1978).
100. R.Vandenbosch, Annual Rev.Nucl.Sci. 27, 1-35 (1977).
101. D.N.Poenaru, Ann.Phys. (Paris) 2, 133-168 (1977).
102. L.Wilets, Theories of Nuclear Fission, Clarendon Press, Oxford (1964).
103. V.M.Strutinsky, Nucl.Phys. A95, 420-442 (1967); ibid. A122, 1-33 (1968).
104. M.Brack, J.Damgaard, A.S.Jensen, H.C.Pauli, V.M.Strutinsky and C.Y.Wong, Revs. Mod.Phys. 44, 320-405 (1972).
105. H.C.Pauli and T.Ledergerber, Nucl.Phys. A175, 545-555 (1971).
106. U.Mosel and H.W.Schmidt, Phys.Lett. 37B, 335-337 (1971).
107. U.Mosel, Phys.Rev. C6, 971-985 (1972).
108. P.Möller, Nucl.Phys. A192, 529-580 (1972).
109. P.Möller and J.R.Nix, Nucl.Phys. A229, 269-291 (1974); Physics and Chemistry of Fission (Proc.Symp. Rochester, 1973) vol.1, pp.103-143, IAEA, Vienna (1974).
110. P.Möller, Physics and Chemistry of Fission (Proc.Symp.Jülich 1979), vol.1, p.283, IAEA, Vienna (1980).
111. A.Baran, K.Pomorski, S.E.Larsson, P.Möller, S.G.Nilsson, J.Randrup, A.Lukasiak and A.Sobiczewski, Physics and Chemistry of Fission (Proc. Symp. Jülich, 1979), vol.1, pp.143-151, IAEA, Vienna (1980).
112. Yu.A.Muzychka, V.V.Pashkevich and V.M.Strutinsky, Yadernaya Fizika 8, 716-720 (1968).
113. S.G.Nilsson, C.F.Tsang, A.Sobiczewski, Z.Szymanski, S.Wycech, C.Gustafson, I.-L.Lamm, P.Möller and B.Nilsson, Nucl.Phys. A131, 1-66 (1969).
114. M.Bolsterli, E.O.Fiset, J.R.Nix and J.L.Norton, Phys.Rev.Lett. 27, 681-685 (1971); Phys.Rev. C5, 1050 (1972).
115. H.C.Pauli, Phys.Reports 7, 35-100 (1973).
116. E.O.Fiset and J.R.Nix, Nucl.Phys. A193, 647-671 (1972).
117. J.Randrup, S.E.Larssen, P.Möller, A.Sobiczewski and A.Lukasiak, Phys.Scripta 10A, 60-64 (1974).
118. A.Sobiczewski, Phys.Scripta 10A,47-52 (1974).
119. Yu.A.Lazarev, Yu.Ts.Oganessian and V.I.Kuznetsov, Preprint E7-80-719, JINR, Dubna (1980).
120. I.Zvara, Plenary Lecture at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980); Pure and Applied Chemistry, this volume.

121. G.N.Akapiev, V.A.Druin, V.I.Rud' and G.Y.Sun Tsin-Yang, Yadernaya Fizika 12, 466-470 (1970).
122. Yu.A.Lazarev, Atomic Energy Rev. 15, 75-107 (1977); in Proc. EPS Topical Conf. on Large Amplitude Collective Nuclear Motions (Keszthely, Hungary 1979), vol.1, pp.244-255, Centr.Res.Inst.Phys., Budapest (1979).
123. B.G.Harvey, G.Herrmann, R.W.Hoff, D.C.Hoffman, E.K.Hyde, J.J.Katz, O.L.Keller, Jr., M.Lefort and G.T.Seaborg, Science 193, 1271-1272 (1976).
124. G.N.Flerov, Preprint E7-8610, JINR, Dubna (1975).
125. G.N.Simonoff and J.M.Alexander, in Proc. Third Conf. on Reactions Between Complex Nuclei (Asilomar 1963), pp.345-352, University of California Press, Berkeley (1963); Preprint UCRL-10099-Rev., Berkeley (1962).
126. V.A.Druin, S.A.Karamyan and Yu.Ts.Oganessian, Preprint 1670, JINR, Dubna (1964).
127. A.G.Demin, V.A.Druin, Yu.V.Lobanov, Yu.Ts.Oganessian, R.N.Sagaidak, V.K.Utyonkov and G.N.Flerov, in Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, 1980), D7-80-556, p.74, JINR, Dubna (1980).
128. H.Kumpf and E.D.Donetz, ZhETF 44, 798-803 (1963).
129. D.Gardes, R.Bimbot, J.Maison, M.F.Rivet, A.Fleury, F.Hubert and Y.Llabador, Phys.Rev. 21C, 2447-2466 (1980).
130. M.Kaplan and R.D.Fink, in Proc. Third Conf. on Reactions Between Complex Niclei (Asilomar, 1963), pp.353-359, Univ. of California Press, Berkeley (1963).
131. L.Winsberg and J.M.Alexander, Phys.Rev. 121, 518-528 (1961); ibid. 121,529-537(1961).
132. J.Gilat and J.M.Alexander, in Proc. Third Conf. on Reactions Between Complex Nuclei (Asilomar, 1963), pp.387-388, Univ. of California Press, Berkeley (1963).
133. A.G.Demin, V.A.Druin, V.B.Zlokazov, Yu.V.Lobanov, Yu.Ts.Oganessian, R.N.Sagaidak and V.K.Utyonkov, in Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980), D7-80-556, p.25, JINR, Dubna (1980).
134. G.Münzenberg, W.Faust, S.Hofmann, P.Armbruster, K.Güttner and H.Ewald, Nucl.Instr. & Methods 161, 65-82 (1979).
135. Yu.A.Lazarev, O.K.Nefediev, Yu.Ts.Oganessian and M.Dakowski, Phys.Lett. 52B, 321.324 (1974).
136. A.V.Amirbekyan, V.M.Vas'ko, V.A.Gorshkov, G.G.Gulbekyan, I.V.Kolesov, A.V.Nesterov, Yu.Ts.Oganessian, V.M.Plotko, A.G.Popeko, L.A.Rubinskaya, T.S.Salamatina, V.I.Smirnov, E.A.Sokol, S.V.Stepantsov, G.M.Ter-Akopian, B.V.Fefilov, L.P.Chelnokov and V.I.Chepigin, in Abstracts of Papers presented at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, September 1980), D7-80-556, p.72, JINR, Dubna (1980).
137. E.K.Hulet, J.F.Wild, R.W.Lougheed, P.A.Baisden, R.J.Dougan and M.G.Mustafa, Plenary Lecture at Int.Symp. on the Synthesis and Properties of New Elements (Dubna, September, 1980); Pure and Applied Chemistry, this volume.
138. D.C.Hoffman, Talk presented at the 4th IAEA Symp. on Physics and Chemistry of Fission (Jülich, 1979); Preprint LBL-9126, Berkeley (1979).
139. C.E.Bemis, Jr., R.L.Ferguson, F.Plasil, R.J.Silva, F.Pleasonton and R.L.Hahn, Phys.Rev. 15C, 705-712 (1977).
140. D.C.Hoffman, G.P.Ford, J.P.Balagna and L.R.Veeser, Phys.Rev. 21C, 637-646 (1980).
141. D.C.Hoffman, J.B.Wilhelmy, J.Weber, W.R.Daniels, E.K.Hulet, R.W.Lougheed, J.H.Landrum, J.F.Wild and R.J.Dupzyk, Phys.Rev. 21C, 972-981 (1980).
142. E.K.Hulet, J.F.Wild, R.W.Lougheed, P.A.Baisden, J.H.Landrum, R.J.Dougan, M.Mustafa, A.Ghiorso and J.M.Nitschke, in Proc. 4th IAEA Symp. on Physics and Chemistry of Fission (Jülich, 1979), Paper SM/241-F15.
143. E.K.Hulet, R.W.Lougheed, J.H.Landrum, J.F.Wild, D.C.Hoffman, J.Weber and J.B.Wilhelmy, Phys.Rev. 21C, 966-971 (1980).