E7-2006-18

Yu. Ts. Oganessian

REACTIONS OF SYNTHESIS OF HEAVY NUCLEI: RESULTS AND PERSPECTIVES

Submitted to «Ядерная физика»

Оганесян Ю. Ц. Е7-2006-18

Реакции синтеза тяжелых ядер: результаты и перспективы

На основе полученных к настоящему времени экспериментальных и теоретических данных о свойствах изотопов сверхтяжелых элементов рассматриваются возможные реакции синтеза более тяжелых ядер, расположенных вблизи замкнутых протонных и нейтронных оболочек. Показано, что продвижение к предельно тяжелым ядрам, для которых микроскопические модели предсказывают дальнейший рост стабильности, неразрывно связано с дальнейшими исследованиями механизма реакций синтеза. Обсуждается постановка прямых и модельных опытов, нацеленных на решение этой задачи.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2006

Oganessian Yu. Ts. E7-2006-18

Reactions of Synthesis of Heavy Nuclei: Results and Perspectives

The experimental and theoretical results on the properties of the isotopes of superheavy elements, obtained up to now, have made it possible to consider different reactions for the synthesis of heavier nuclei located in the vicinity of the closed proton and neutron shells. It is shown that the advance to the heaviest possible nuclei, for which the microscopic models predict further rise of stability, is inseparably linked to the future investigation of the mechanism of synthesis reactions. Direct and model experiments, aimed at solving this problem, are also discussed.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2006

Introduction

The advance in the theory of extremely heavy nuclei, which is observed recently, is due mainly to the accumulation of new experimental data during the last 30 years. The different models, which describe the obtained data and predict the properties of heavier nuclei, require the commissioning of new experiments.

At the same time, all approaches to solving the problem of the artificial synthesis of heavy and superheavy elements in heavy-ion-induced reactions are directly connected to the investigation of the dynamics of the collective motion of complex nuclei, this being one of the fundamental problems of the physics of atomic nuclei. The situation is further complicated by the fact that even when using the basic heavy nuclei synthesis technique – the fusion reactions – experiments are performed at the limit of experimental sensitivity. The advantages of using beams of secondary radioactive ions with some (usually – not significant) neutron excess, but with considerably lower beam intensity, are not yet clearly obvious due to the loss of luminosity. It seems that the quest of new ways, similarly to the estimation of the already used reactions, is connected with the staging of new experiments, in conditions maximally close to solving the problem of the synthesis of superheavy elements with $Z \geq 120$.

Some of them are considered in the present work.

Fusion reactions

It is well known that the heaviest nuclei were synthesized in fusion reactions with heavy ions. Such synthesis reactions, according to the mechanism of formation and revival probability of the nuclei during the neutron evaporation process, are conditionally classified as of the following two types – cold and hot fusion, by using one parameter only – the excitation energy of the compound nucleus at the maximum of the resulting excitation function. Actually, the difference is much more profound.

Cold fusion

Indeed, in the fusion reactions of the magic nuclei ^{208}Pb (or ^{208}Bi) with massive projectiles (A = 50-70), the maximum yield of evaporation products with Z = 104-112 is observed at an excitation energy of the compound nucleus E* = 20-22 MeV, respectively [1-3]. The decay of the weakly heated nucleus to the ground state is accompanied by the emission of one neutron only and γ-rays. And this is the main advantage of this type of reactions. However, with increasing the projectile mass, the formation cross sections of the evaporation products drastically decreases, which is due to factors hindering fusion already in the entrance reaction channel. In fact, as it follows from calculations of static nuclear shapes that determine the potential surface (Fig. 1), the hindrance takes place along the whole trajectory of the collective motion – from the touching point to the final configuration of the compound nucleus. The basic limitations are connected with the necessity to increase the nuclear potential energy on the way to reaching compact configurations, which in turn, can be achieved only by fluctuations of the shape in the conditions of high viscosity of nuclear matter. The fluctuations of nuclear shapes depend on the dynamic properties of the nuclear system (the many-body problem) and its temperature. The increase of temperature is disastrous, since cold fusion is no longer "cold" and it thus loses its basic property – the high survival probability of the compound nucleus.

Theoretical models, such as "extra-extra push" [4,5], the variations of the fusion barrier [6], complex many-dimensional calculations of the collective motion in the framework of transport models [7-10], and many other approaches, each containing definite assumptions about the dynamic properties of heavy nuclei, can, in principle, describe the situation, but they do not find ways to eliminate the above mentioned problem. On the contrary, all models predict further drastic fall of cold-fusion reaction cross sections with the increase of the atomic number of the synthesized nucleus. This is confirmed by the latest experiments on the synthesis of element 113: the cross section of the 1n-evaporation channel of the fusion of ^{209}Bi with ^{70}Zn (Z = 113) decreases in comparison to the ^{209}Bi + ^{48}Ca (Z = 103) by a factor of 10^7 [12]. It is difficult to assume that in this way it will be possible to advance to the nuclei with Z = 114, 120 or 122, for which the different microscopic models predict the existence of closed proton shells and, therefore, a relatively high stability of the new nuclides.

Another question concerns the decay properties of the superheavy nuclei.

The necessity to use magic target nuclei – the isotopes of Pb and Bi, leads to the formation of very neutron deficient evaporation products. With the increase of the atomic number of the compound nucleus the neutron excess $\Delta N = N-Z$ practically does not change, staying in the range $\Delta N = 52\text{-}54$ for all nuclei with $Z \geq 102$. As a result, the half-lives of the synthesized nuclei

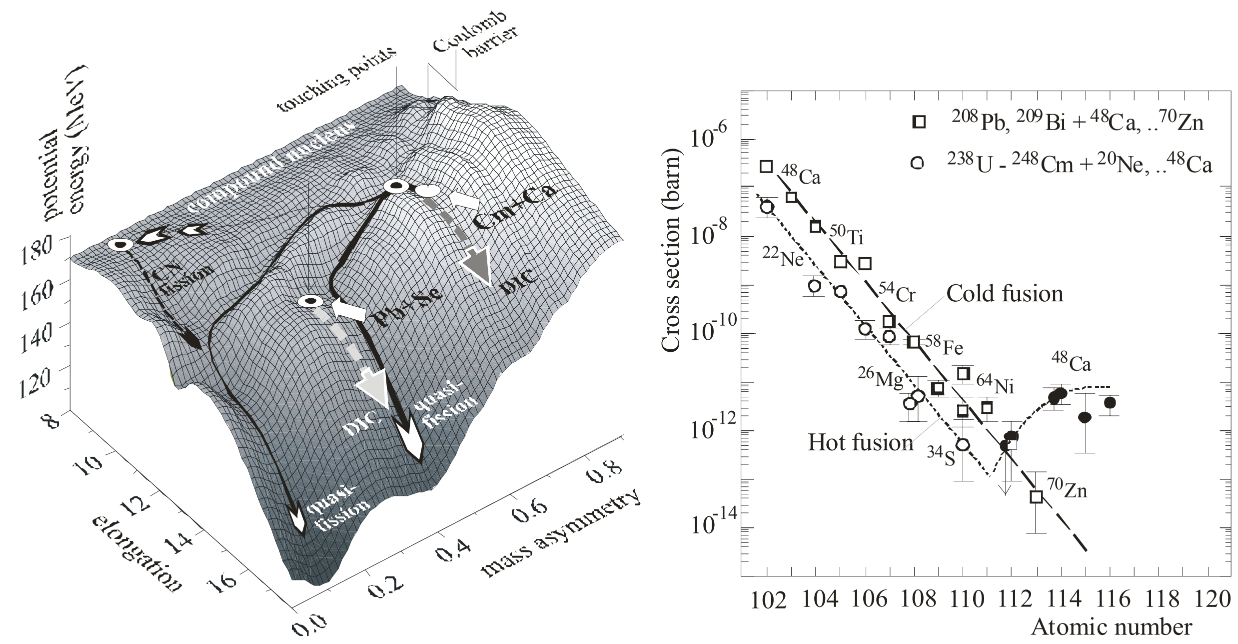

Fig. 1. *Left:* Potential energy surface of the compound nucleus $^{296}116$ in the $^{208}Pb+^{88}Se$ (cold fusion) and $^{248}Cm+^{48}Ca$ (hot fusion) reactions. The arrows show the deep-inelastic (DIC), quasi-fission and compound nucleus formation channels.
Right: Experimental cross sections for the formation of nuclei with $Z \geq 102$ in the 1n-evaporation channel of cold fusion reaction (open squares) and 4n-evaporation channel of hot fusion (open circles). The black points denote the fusion reaction Act.+^{48}Ca.

strongly decrease with the increase of the atomic number: for the even-odd isotopes with Z = 110-112 they are $T_{1/2} \sim 0.1$-1 ms [13,14]. This tendency is expected to continue also for the heavier elements. Thus for instance, the isotope ^{283}114, a product of the reaction ^{208}Pb(^{76}Ge,n), has only 169 neutrons, while the rise of stability of superheavy nuclei is expected at $N \geq 172$.

At the same time, it was just in cold fusion reactions that elements with atomic numbers 107-112 were synthesized for the first time and their decay properties studied [15]. The observed long decay chains of the new nuclides, the lifetimes and α-decay energies, as well as the weak competition from spontaneous fission (SF) were the first experimental evidence of the influence of the closed deformed shells with Z = 108 and N = 162, which were predicted by the macro-microscopic nuclear models [16,17].

Hot fusion in reactions induced by ^{48}Ca ions

In asymmetric reactions, when heavy actinide isotopes are used as targets and ^{48}Ca nuclei – as projectiles, the dynamic hindrances to fusion are considerably smaller, because the final state (the compound nucleus) is reached along another trajectory of the collective motion (see Fig. 1). The competition to the formation of the compound nucleus comes from the strongly asymmetric fission – quasi-fission, the probability of which depends on the entrance fusion reaction channel and the profile of the potential energy surface [18]. But, this process is not as dramatic as in the case of cold fusion. As a result, the probability of formation of the compound nucleus turns out to be by 3-4 orders of magnitude higher than in cold fusion experiments. However, the mass excess and the difference in the potential energy of the heavy nuclei in the initial and final states of its motion leads to heating of the compound nucleus up to about 30-40 MeV of excitation energy (hot fusion). The main loss ($\sim 10^{-6} - 10^{-8}$) in reactions of this type is connected with the survival probability of the compound nucleus, in the cooling process by the emission of 3-4 neutrons and γ-rays.

Considering now a different task – the thermodynamic behaviour of the heated compound nucleus – it is possible to make a conclusion that the basic reason for the low survival probability of the compound nucleus is fission, which interrupts the process of cooling by neutron emission. The fission probability, in turn, depends on the height of the fission barrier, which, as is well known, for the heavy nuclei is completely determined by shell effects. For this reason, in the region of superheavy elements, the advent to the closed shells must lead to an increase in the fission barriers and, therefore, to a significant increase of the yield of hot fusion reactions [19]. The choice of the neutron-rich nucleus ^{48}Ca as a projectile and neutron-rich targets, such as ^{244}Pu and ^{248}Cm, was directed to the production of compound nuclei with Z_{CN} = 114-116 and N_{CN} = 178-180, located in the vicinity of the closed shells Z = 114 and N = 184. The advantages of this method manifested themselves in the synthesis of heavy nuclei with $Z \geq 112$, where the yield of the cold fusion reactions showed to be at the limit of experimental capacities.

It should be noted that the increase of the neutron number in the above mentioned isotopes of elements 110-112 by $\Delta N = 8$ led to an increase of their half-lives by a factor of 10^4-10^5. Among the daughter nuclei of the sequential α-decay, nuclei with even longer lifetime are observed including the isotopes ^{267}Rf ($T_{SF} \sim$ 1h) or ^{268}Db ($T_{SF} \sim$ 1.2 d). This made it possible to check experimentally not only the predictions of the microscopic nuclear models, what concerns the investigated region of nuclei, but also to significantly extend this region by using radiochemical methods, mass-separators, etc.

There are good reasons to assume that any further increase of the neutron excess in the evaporation residues will bring forth a large increase in the lifetime of superheavy nuclei. Unfortunately, all possible fusion reactions with stable beams exclude this possibility. Because of the enormous difficulties to accumulate nuclei heavier than Cf (Z = 98) in amounts that would be necessary for the target material (~ 10 mg), the isotope ^{294}118 (N = 178) appears to be the last and heaviest nucleus to be synthesized in ^{48}Ca-induced fusion reactions [20]. How much will the cross section decrease, when the more massive projectiles ^{50}Ti, ^{54}Cr or ^{58}Fe are used, can be determined only experimentally. A first step then can be the measurement of the cross section for producing the known isotopes of element 116 in the 2n-4n evaporation channels of the reactions ^{244}Pu + ^{50}Ti and ^{246}Cm + ^{48}Ca, leading to the formation of the compound nucleus ^{294}116. But it should be noted that approaching the shell N = 184 is possible only for the heavier elements ($Z \geq 120$) in the fusion reactions of ^{244}Pu, ^{248}Cm with projectiles like ^{58}Fe or ^{64}Ni and this needs a further study of the mechanism of hot fusion reactions.

However, independent of the different reasons hindering the formation of superheavy nuclei in either cold or hot fusion reactions, they have common features, too. In both cases, the shape of the nucleus in the initial and final states strongly differ and the compact configuration, which is close to the ground (compound) state is reached by passing a long trajectory of the collective motion. The main loss of compound nucleus takes place just along this path: in cold fusion there are dynamic hindrances, in hot fusion – the competing channel of quasi-fission, more probable at the early stage of the fusion process. In connection with this, a shortening of the path could decrease the loss and increase the probability of formation of a compound nucleus.

Taking into account this circumstance, as well as the new data on the properties of superheavy nuclides, obtained during the last few years, it seems reasonable to consider some other reactions of synthesis.

Deep-inelastic reactions and quasi-fission

Long ago it had been suggested to synthesize superheavy nuclei with a large neutron excess (up to N = 184) as products of the fission of even heavier nuclei that are produced in a fusion reaction of two extremely massive nuclei [21,22]. It was assumed that similar to classic fission, the heavy fragments would exhibit wide mass, charge, excitation energy, deformations, and other spectra. The majority of heavy fragments would themselves undergo fission, but it could not be excluded that some of them, with low excitation energy, situated near the closed shells (small deformations, high fission barriers), would decay to the ground state by emission of neutrons and γ-rays. Obviously, such a strong restriction (by so many parameters) on the initial states of the heavy fragments would lead to very small formation cross section of the heavy nuclei in the ground state. The question lies in the quantitative estimation of these cross sections.

In the radiochemical experiments, performed in the reactions ^{238}U+^{136}Xe [23], ^{238}U+^{238}U [24] and ^{248}Cm+^{238}U [25] practically all known neutron-rich isotopes of the actinides up to ^{252}Cf, ^{257}Fm and ^{258}Md, respectively, were observed. The results obtained with the ^{248}Cm+^{238}U reaction are presented in Fig. 2. The cross sections $\sigma(A_F)$ for the isotopes with Z_F = 98-101, observed in this reaction (up to 10 nucleons are transferred from the incident ^{238}U nucleus to the target nucleus ^{248}Cm), as shown by the calculations [26], can be explained by deep-inelastic reactions. From calculations it also follows, that the inelastic cross sections, characterized by the transfer of a large number of nucleons, will exponentially decrease with the increase of the fragment mass and charge.

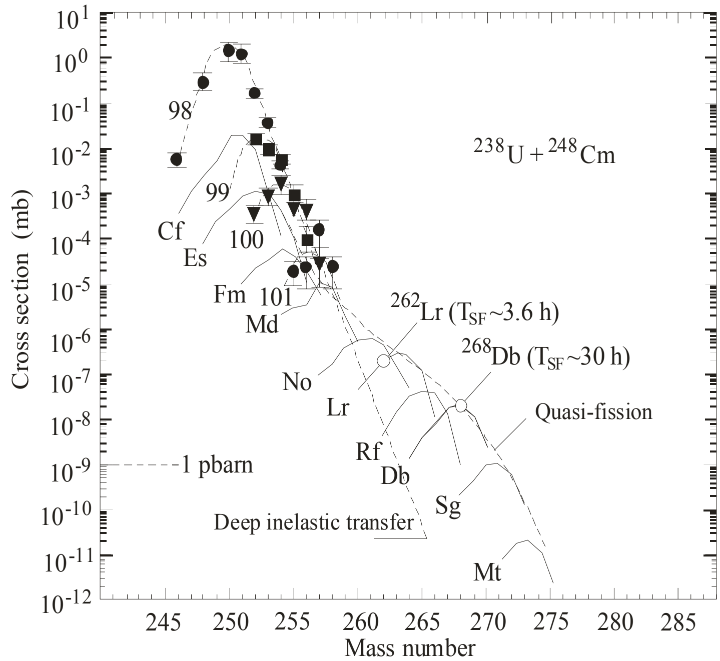

Fig. 2. Cross sections for the formation of isotopes of elements with Z ≥ 98 in the ^{248}Cm+^{238}U reaction. The experimental points are taken from ref. [25], the dashed curves (deep-inelastic reactions) and the solid curves (quasi-fission) show the calculations of ref. [26].

At the same time, going down to cross sections values $\sigma(A_F) \leq 1$ nb, a contribution to the formation of nuclei with $Z_F \geq 103$ could be expected from another process – quasi-fission, in which nuclei near the closed shells with $Z_F = 82$, $N_F = 126$ are formed as light fragments, similarly to what has been observed in the ^{244}Pu, ^{248}Cm + ^{48}Ca reactions.

If in the ^{248}Cm+^{238}U reaction, the calculated formation cross sections of nuclei, e.g. of ^{262}Lr (~200 pb) and ^{268}Db (~20 pb), are experimentally confirmed, then the channel of strongly mass asymmetric fission of the type Pb + Hs ($A_1/A_2 = 1.34$) may happen to be an efficient method of synthesis of neutron-rich and long-lived nuclei near the closed deformed shells Z=108, N=162. Naturally, the capacities of such a method are limited by the masses of the interacting nuclei (practically the reaction ^{248}Cm+^{238}U is that limiting case), while the yield from the quasi-fission channel leads, as it can be seen from Fig. 2, to a strong decrease of the formation cross section of nuclei with $A_F > 270$.

Fusion of fission-fragment-like nuclei

Another way is to form a compound nucleus in a fusion reaction of two nuclei, which are close in mass and nuclear composition to the fission fragments. At first sight, this idea seems unfeasible, since the process inverse to fission needs additional energy and has a direction opposite to the collective motion in the fission process. In fact, in fission a practically spherical nucleus is transformed at the scission point into two nuclei, while in fusion the scenario is just the opposite: two touching nuclei evolve into a compact configuration of total mass. However, in a limited region of deformation, close to the top of the fission barrier, the shapes of the nuclei moving in opposite directions (to fusion and to fission) is equilibrated, in particular, if in the fusion reaction two fission-like fragments are used. In order to approach this region as close as possible, it is necessary in both processes to shorten the path of collective motion: in fission – by moving the scission point closer to the saddle point (so-called cold fission – see below), in fusion – by choosing a compact configuration, closest to the shape of the nucleus at the top of the fission barrier. All this is demonstrated by an experiment, which we have performed with the compound nuclei $^{222\text{-}224}$Th, obtained in the ^{206,208}Pb+^{16}O reactions [27].

The total fission-fragment mass distribution, shown in Fig. 3a, is determined by the whole set of nuclear shapes in the moment of scission into two fission fragments. Both factors – the symmetric mass distribution and TKE = 160 MeV, observed for the ^{224}Th nuclei (E* = 35 MeV) give evidence of the prevailing rupture into symmetric forms with deformation corresponding to the distance between the fission-fragment centers at the scission point of about $\rho \approx 17$ fm. In addition, selecting events with the maximum value of TKE, in our case TKE $\geq$ 194 MeV, the mass distribution becomes asymmetric with a maximum yield at masses $A_L \approx 86$ and $A_H \approx 136$. In ref. [28], where the charge distribution for the photofission of ^{222}Th (E* $\approx$ 11 MeV) was measured, it was shown that the maximum mass yields correspond to charges $Z_L \approx 36$ and $Z_H \approx 54$. In other words, the nuclei ^{86}Kr (N = 50) and ^{136}Xe (N = 82) with closed neutron shells are observed at the maxima of the mass and charge distributions of the fission fragments of ^{222}Th. Thus, considering the reverse process – it seems reasonable to use the fusion reaction ^{86}Kr + ^{136}Xe to form the compound nucleus ^{222}Th.

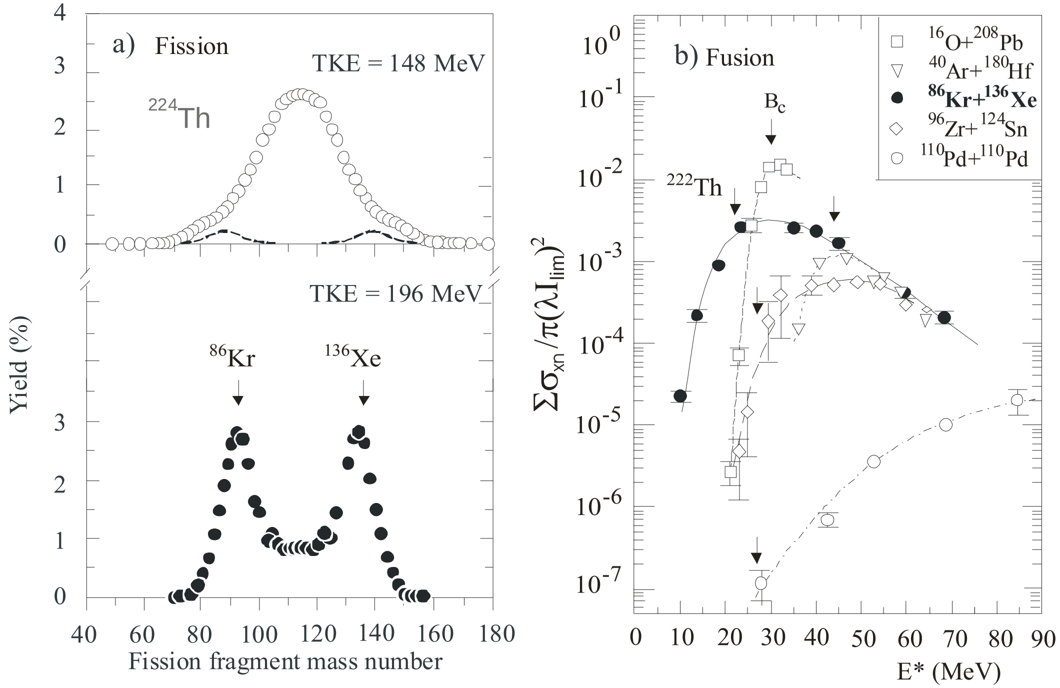

Fig. 3. a) Mass distributions of fission fragments of the compound nucleus ^{224}Th from the reaction ^{208}Pb+^{16}O [27]. Upper panel: TKE = 148 MeV, lower panel: TKE ≥ 194 MeV.
b) Black points – reduced cross sections for the production of evaporation residues of the compound nucleus at different excitation energies E*, obtained by summing up the experimental cross sections of the xn-channels of the ^{86}Kr+^{136}Xe reaction [29]. The open

The experimental cross section $\sigma_{EVR} = \Sigma\sigma_{xn}$ for the formation of evaporation residues in the $^{86}Kr(^{136}Xe,xn)^{221-x}Th$ reaction, measured for the channels x=1-7 in the range of excitation energies E* = 10÷70 MeV [29], are shown in Fig. 3b. The highest cross section, $\sigma_{EVR} \approx 30$ μb, corresponds to the 2n-evaporation channel at E* ~ 25 MeV. In other reactions, the cross section $\sigma_{EVR}(E^* \leq 25$ MeV) is considerably lower; in the symmetric reaction $^{110}Rh+^{110}Rh$ (in Fig. 3b the cross sections for the fusion of neighbouring nuclei $^{110}Pd + ^{110}Pd$ [30] are shown) the formation cross sections of the evaporation residues – the isotopes of Th (or U), at E* ≤ 25 MeV are almost ~ 10^5 times smaller than in the $^{86}Kr + ^{136}Xe$ reaction.

What are the possibilities of using reactions of fusion of fission-fragment-like nuclei for the synthesis of heavier and superheavy nuclei?

Fission and the production of superheavy nuclei

In the fusion reactions ^{238}U, ^{244}Pu, ^{248}Cm and $^{249}Cf + ^{48}Ca$ the superheavy nuclei, as has been shown in [31], undergo predominantly asymmetric fission. From the analysis of the mass, charge and energy distributions of the fission fragments, obtained in these reactions, a conclusion can be drawn that the asymmetric fission mode is connected with the nuclear shell effects at Z = 50, N = 82 forming the light fragment (see Fig. 4a). It is well known that this effect plays role when heavy fragments are formed in the fission of the actinides (Fig. 4b); for some of them, particularly for ^{236}U [32] and ^{252}Cf [33], the characteristics of "cold fission" have been studied. Then it follows that in the opposite process – in the fusion of nuclei aimed at the production of a superheavy compound nucleus, similarly to the previous case with the formation of ^{222}Th, it is necessary to use a fusion reaction involving nuclei close to ^{132}Sn.

In spite of the enormous difficulties in producing an intense beam of the radioactive ^{132}Sn ($T_{1/2}$ = 39 s) nuclei, the neutron excess in ^{132}Sn could make it possible to approach the closed N = 184 neutron shell, which is not feasible with stable beams. Experiments with the ^{132}Sn ions open possibilities for further investigation of fusion reactions of fission-fragment-like nuclei in the region of the light U-Cf isotopes. However, the data obtained in this region, exactly as in the case of the $^{86}Kr + ^{136}Xe$ reaction, cannot reveal all the complexity of the way in which superheavy elements are synthesized, for example in the $^{132}Sn(^{176}Yb,xn)^{308-x}120$ reaction, where the fusion process is strongly suppressed by the significant increase (by a

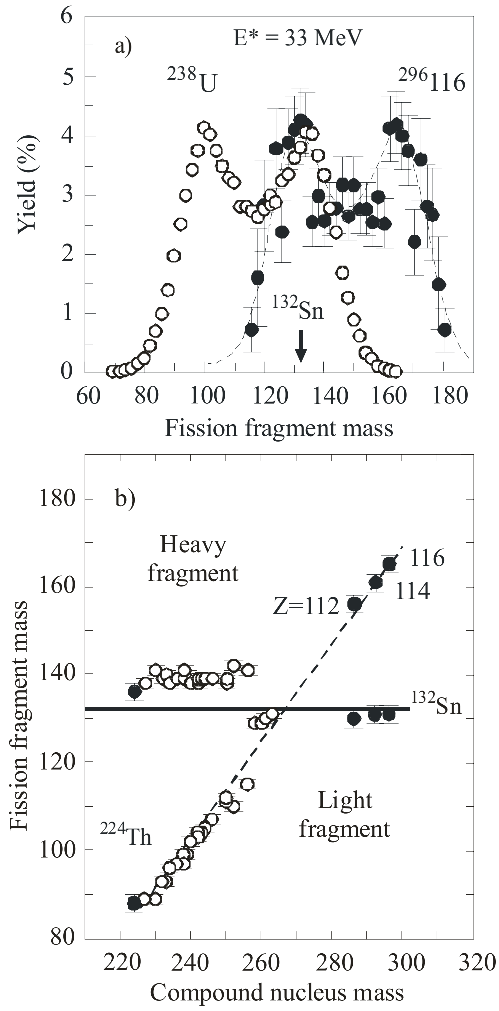

Fig. 4. a) Mass distributions of fission fragments of the compound nuclei ^{238}U and ^{296}116 at an excitation energy E* = 33 MeV.
b) Mass of the heavy and light fragments from the fission of excited nuclei of different mass. The black points are experimental data, obtained with the CORSET setup in the ^{208}Pb+^{16}O [27] and Act.+^{48}Ca reactions, respectively [31].

factor of ~ 1.7-1.8) of the Coulomb repulsion. Since experimental data are scarce for the region of heavy nuclei, and indeed – for the region of the superheavy ones, it is difficult to estimate, even approximately, the hindrances staying in the way. But it is quite possible to obtain these estimates in an experimental way. Let us consider an experiment, which can lead to the formation of a heavy enough compound nucleus ($Z_{CN} = 108$). In this experiment, the evaporation cross sections $\sigma_{EVR}(E^*)$ can be used to reconstruct the values of $\sigma_{CN}(E^*)$ and in this way determine the hindrances arising in the fusion process when going from the above-mentioned nucleus ^{222}Th ($Z_{CN} = 90$) to the considerably heavier nucleus ^{272}Hs ($Z_{CN} = 108$).

Fission and production of the ^{272,274}Hs (Z = 108) nuclei

The light isotopes of element 108 with N = 153-155 were produced in the cold fusion reactions $^{206\text{-}208}$Pb(^{58}Fe,n)$^{263\text{-}265}$Hs [34]. In recent years, in the hot fusion reactions ^{26}Mg(^{248}Cm, 3-5n)$^{271\text{-}269}$Hs, the heavier isotopes of element 108 with N = 161-163 were produced and their decay properties studied [35,36]. It is as important that in the same reaction the fission of the compound nucleus ^{274}Hs was studied in the excitation energy interval E* = 35-50 MeV [37]. The results of the two experiments, obtained in the ^{26}Mg+ ^{248}Cm reaction lie in the basis of the plan for a new experiment aimed to synthesize nuclei of element Hs in the symmetric reaction ^{136}Xe+^{136}Xe [38]. From the total kinetic energy (TKE) spectrum of the fission fragments, shown in Fig. 5a, it follows that in the fission of the compound nucleus ^{274}Hs the symmetric fission mode prevails and is characterized by high kinetic energy TKE ≈ 230 MeV. This is confirmed by a direct measurement of the fragment masses for all values of TKE ≥ 210 MeV (Fig. 5b). The increase in the dispersion of the symmetric mass distribution is determined by the relatively high excitation energy of the compound nucleus ^{274}Hs (E* ~ 40 MeV); for lower excitation energies, unfortunately unavailable in this reaction, the mass dispersion will be much smaller.

The fission scenario in these experiments can be easily explained.

The nucleus ^{274}Hs (or the considered nucleus ^{272}Hs) is situated in the vicinity of the closed deformed shells Z = 108, N = 162 and has in its ground state, according to calculations, a shape that is axially symmetric with a deformation $\beta_2 \sim 0.25$. Its collective motion to fission, up to the scission point, will take place via symmetric shapes, due to the closed spherical shell N = 82 in both fragments. The configuration of two touching spherical nuclei

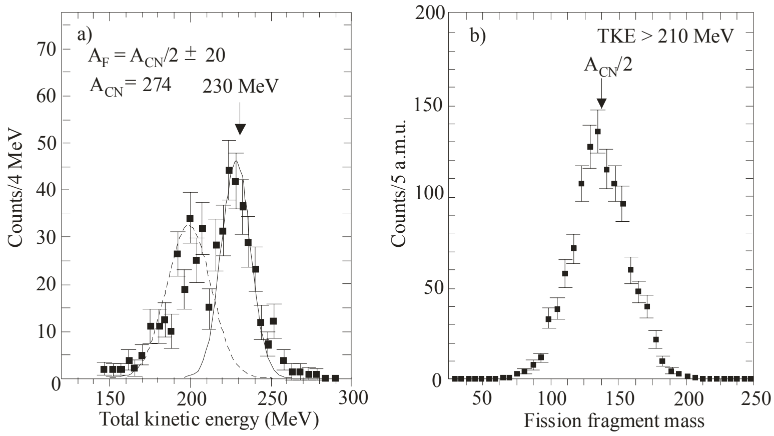

Fig. 5. a) Total kinetic energy spectrum of the fission fragments of the compound nucleus ^{274}Hs (E* = 39 MeV) in the fusion reaction ^{248}Cm + ^{26}Mg [37].
b) Mass distributions of events with TKE ≥ 210 MeV.

^{136}Xe (N = 82) is similar, in deformation and mass symmetry, to the shape of the ^{272}Hs nucleus, when it is near the top of its fission barrier (β_2=0.45); the conditions for two ^{136}Xe nuclei to fuse seem to be most favourable. An obstacle on the way of forming a compound nucleus could come from dynamical hindrances that arise in the process of collective motion, mainly because of the strongly repulsive Coulomb field. However, having an intense beam of ^{136}Xe nuclei and using efficient methods of separation of the well-known short-lived isotopes $^{269\text{-}271}$Hs [36], it is possible to reach high experimental sensitivity in determining the cross sections of the evaporation residues of the order of $\sigma_{EVR} \geq 0.1$ pb. This value is about a factor of 10^7 smaller than the production cross section of Th isotopes in the ^{86}Kr+^{136}Xe reaction.

If, when going from the fusion of the nuclei ^{86}Kr+^{136}Xe ($Z_1{\cdot}Z_2$ = 1944) to the heavier system ^{136}Xe+^{136}Xe ($Z_1{\cdot}Z_2$ = 2916), the factors hindering the production of Hs evaporation residues turn out to be 7 orders of magnitude less compared to Th, then they can be determined quantitatively. The obtained data can be used to estimate the cross sections of production of superheavy elements in reactions induced by the radioactive ^{132}Sn ions.

Such an experiment is now being prepared at the U400 cyclotron of FLNR (JINR).

Conclusions

For the synthesis of isotopes of elements 120 and 122 with N = 175 and 181 in cold fusion reactions, it is necessary to use massive projectiles – ^{88}Sr and ^{96}Zr. The yield of the isotopes ^{295}120 (N = 175) and ^{303}122 (N= 181), which are products of the 1n-evaporation channel of the fusion reaction with the ^{208}Pb nuclei, will be strongly diminished due to the exponential decrease of the fusion probability with the increase of the atomic number and the mass of the compound nucleus. More perspective for this purposes seem to be hot fusion reactions with the use of neutron-rich targets such as ^{244}Pu and ^{248}Cm and projectiles like ^{58}Fe and ^{64}Ni, leading to the formation of superheavy nuclides with N = 179-184 in the 2n- and 3n- evaporation channels. Compared to the reaction ^{248}Cm + ^{48}Ca (Z_{CN} = 116), the production cross section of compound nuclei with Z_{CN} = 120-124 decreases when heavier projectiles are used. However, this can be compensated by the increase of their survival probability, due to the decrease of the excitation energy and the neutron binding energy, as well as the increase of the fission barrier near the closed shells Z = 122, N = 184.

Realistic estimations of the cross sections of reactions induced by fission-fragment-like nuclei, such as ^{132}Sn(^{176}Yb, xn)$^{308-x}$120, can be obtained on the basis of the experimental cross sections for the xn-channels of the symmetric reaction ^{136}Xe(^{136}Xe, xn)$^{272-x}$Hs. The high experimental sensitivity together with the intense beam of ^{136}Xe ions ($\sigma_{EVR} \geq 0.1$ pb) will allow to estimate quantitatively the hindrances to the fusion of massive nuclei compared to the already studied reaction ^{86}Kr(^{136}Xe, xn)$^{222-x}$Th.

It cannot be excluded that the neutron-rich isotopes of Rf, Db and even Sg, firstly synthesized among the α-decay products of the heavier nuclei ^{287}114 and ^{288}115, can be produced also as the heavy fragment of the quasi-fission reaction in the process of interaction of extremely massive nuclei – like ^{248}Cm + ^{238}U. The probability of quasi-fission, which defines the efficiency of the given method, can be estimated on the basis of the cross sections for producing light fragments near the closed shells Z_F = 82, N_F = 126 and heavy fragments with known properties (for example, ^{262}Lr and ^{268}Db).

Acknowledgements

I am grateful to Prof. V.I. Zagrebaev for performing the calculations of the fragment production cross sections in the ^{248}Cm + ^{238}U reaction and for fruitful discussions.

References

1. Yu.Ts. Oganessian and Yu.A. Lazarev, in *Treatise on Heavy-Ion Science*, edited by D.A. Bromley (Plenum Press, NY, 1985) p. 3; Yu.Ts. Oganessian, Nucl. Phys. **A488**, 65 (1988).
2. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
3. K. Morita et al., Nucl. Phys. **A734**, 101 (2004); Jap. Phys. Soc. J. **73**, 1738 (2004).
4. W.J. Swiatecki, Phys. Scr. **24**, 113 (1981).
5. S. Bjørnholm and W.J. Swiatecki, Nucl. Phys. **A391**, 471 (1982).
6. K.-H. Schmidt and W. Morawek, Rep. Prog. Phys. **54**, 949 (1991).
7. Y. Aritomo, T. Wada, M. Ohta, and Y. Abe, Phys. Rev. C **59**, 796 (1999).
8. V.I. Zagrebaev, Phys. Rev. C **64**, 034606 (2001); in *Tours Symposium in Nuclear Physics*, edited by M. Arnould et al., AIP Conf. Proc. No. **704** (AIP, Melville, NY, 2004), p. 31.
9. Y. Abe, B. Bouriquet and G. Kosenko, in *Proceedingsof the Symposium on Exotic Nuclei,* Peterhof, 2004, edited by Yu.E. Penionzhkevich and E.A. Cherepanov (World Scientific, Singapore, 2005) p. 240.
10. W.J. Swiatecki, K. Siwek-Wilczynka, and J. Wilczynki, Phys. Rev. C **71**, 014602 (2005).
11. P. Frobrich and R. Lipperheide, Theory of Nuclear Reactions (Clarendon Press, 1996) p. 418.
12. K. Morita et al., J. Phys. Soc. Jpn. 23, 2593 (2004)**.**
13. S. Hofmann, Rep. Prog. Phys. **61**, 639 (1998).
14. S. Hofmann et al., Eur. Phys. J. A **14**, 147 (2002).
15. S. Hofmann, On Beyond Uranium (Science Spectra Book Series, ed. V. Moses, 2002).
16. Z. Patyk and A. Sobiczewski, Nucl. Phys. **A533**, 132 (1991).
17. P. Möller and J. R. Nix, J. Phys. G: Nucl. Part. Phys. **20**, 1681 (1994).
18. M.G. Itkis et al., in *Proceedings on Fusion Dynamics at the Extremes*, Dubna, 2000, edited by Yu. Oganessian and V. Zagrebaev (World Scientific, Singapore, 2001), p.93; V.I. Zagrebaev, M.G. Itkis, Yu.Ts. Oganessian, Yad. Fiz. **66**, 1069 (2003) [Phys. At. Nucl. **66**, 1033 (2003)].
19. Yu.Ts. Oganessian et al., Phys. Rev. C **70**, 064609 (2004).
20. Yu.Ts. Oganessian et al., JINR Report No. D7-2002-287, Dubna, 2002.
21. G.N. Flerov et al., “Perspectives of the synthesis of transuranium elements”, Znanie Publ., Moscow, 1965 (in Russian).
22. Yu.Ts. Oganessian et al., Yad. Fiz. **19,** 245 (1974).

23. Yu.Ts. Oganessian and Yu.E. Penionzhkevich, Nucleonica. **21**, 237 (1976).
24. M. Schädel et al., Phys. Rev. Lett. **41**, 469 (1978).
25. M. Schädel et al., Phys. Rev. Lett. **48**, 852 (1982).
26. V.I. Zagrebaev, Yu.Ts. Oganessian, M.G. Itkis, and W. Greiner, submitted for publication.
27. M.G. Itkis et al., Nucl. Phys. **A654**, 870c (1999).
28. K.-H. Schmidt et al., Nucl. Phys. **A665**, 221 (2000).
29. Yu.Ts. Oganessian et al., Scientific Report 1995-1996, JINR, FLNR, Dubna, 1997, p.62.
30. W. Morawek, GSI Report No. GSI-91-26, Darmstadt, 1991.
31. M. Itkis et al., Nucl. Phys. A734, 136 (2004).
32. F. Gönnenwein, in *The Nuclear Fission Process*, edited by C. Wagemans (CRC Press, Boca Raton, 1991), p. 300.
33. M. Cröni, A. Möller, A. Kötzler, F. Gönnenwein, A. Gagarski, G. Petrov, in *Fission and Properties of Neutron-Rich Nuclei*, Eds. J.H. Hamilton and A.V. Ramayya (World Scientific, Singapore, 1998) , p. 109.
34. G. Münzenberg et al., Z. Phys. **A317**, 235 (1984).
35. Ch.E. Düllman et al., Nature **418**, 859 (2002).
36. A. Tuerler, Talk at the 3rd Sandanski Coordination Meeting on Nuclear Science, 26-30 September 2005, Albena, BULGARIA.
37. E.V. Prokhorova et al., in *Proceedings of the Symposium on Exotic Nuclei,* Peterhof, 2004, edited by Yu.E. Penionzhkevich and E.A. Cherepanov (World Scientific, Singapore, 2005) p. 325.
38. Yu.Ts. Oganessian, Eur. Phys. J. A **13**, 135 (2002).

Корректор *Т. Е. Попеко*

Подписано в печать 14.02.2006.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 1,18. Уч.-изд. л. 1,67. Тираж 300 экз. Заказ № 55227.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/