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FORMATION OF HEAVY COMPOUND NUCLEI, THEIR SURVIVAL AND CORRELATION WITH LONGTIME-SCALE FISSION

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Образование тяжелых составных ядер, их выживание и корреляция со шкалой длительности деления

Как следует из анализа сечений ядерных реакций, образование сверхтяжелых составных ядер при слиянии двух массивных ядер регулируется градиентом потенциальной энергии системы. Консервативная энергия определена в простых приближениях на основе регуляризованных значений ядерной массы и барьера взаимодействия. Для синтеза ядер с $Z_c = 110{-}118$ сравнивались различные реакции и обнаружены благоприятные условия для слияния стабильных изотопов (W–Pt) с радиоактивными осколками деления, такими как ^{94}Kr и ^{100}Sr, в качестве бомбардирующих частиц. Таким образом, метод холодного слияния может быть распространен на синтез элементов с $Z > 113$. Выживание испарительного остатка определяется отношением вероятностей эмиссии нейтронов и деления, а также эмиссией гамма-квантов, реализующейся на финальной стадии реакции. Даны численные оценки. Фиксация испарительных продуктов реакций должна коррелировать с протяженной шкалой времени деления, обсуждаются соответствующие экспериментальные результаты.

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Karamian S. A., Yakushev A. B. E7-2006-11
Formation of Heavy Compound Nuclei, Their Survival and Correlation with Longtime-Scale Fission

Fusion of two massive nuclei with formation of super-heavy compound nucleus (CN) is driven by the potential energy gradient, as follows from the analysis of nuclear reaction cross-sections. The conservative energy of the system is deduced in simple approximation using regularized nuclear mass and interaction barrier values. Different reactions for the synthesis of $Z_c = 110{-}118$ nuclei are compared and the favourable conditions are found for fusion of the stable (W–Pt) isotopes with radioactive fission fragment projectiles, like ^{94}Kr or ^{100}Sr. Thus, the cold fusion method can be extended for a synthesis of elements with $Z > 113$. Survival of the evaporation residue is defined by the neutron-to-fission probability ratio and by the successful emission of gammas at the final step of the reaction. Numerical estimates are presented. Fixation of evaporation residue products must correlate with longtime-scale fission and available experimental results are discussed.

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

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1. INTRODUCTION

During the decade, a progress in the synthesis and studies of super-heavy elements (SHE) with $Z \geqslant 106$ has been reached using two experimental methods: 1) Cold fusion reactions with the ^{208}Pb and ^{209}Bi targets, mostly at Darmstadt; and 2) Hot fusion reactions induced by ^{48}Ca ions with U and transuranium targets at Dubna. The obtained results were described in many original publications and the actual review could be found in [1, 2]. The cold fusion method was productive for synthesis of $Z \leqslant 113$ elements and hot fusion for Z up to 118.

The theoretical approaches were also advanced extensively for understanding of the reaction mechanism and for estimating the SHE production cross-sections, see, in particular, Refs. [3–6]. The predictive capability of theories is still limited because of many uncertainties in the behaviour of heavy composite systems and because of not enough basis for the choice of numerical parameters. Despite different approaches in theory, there exists common understanding that the problem should be split into two almost independent parts corresponding to the sequential stages of a compound nucleus formation and of the SH nucleus survival during de-excitation to the ground state in competition with fission.

The CN formation probability in the case of very heavy systems is strongly reduced because the Coulomb plus centrifugal repulsion leads to the break-up of the di-nuclear system almost at any impact parameter and momentum of the projectile. Attracting potential is relatively weak and the landscape of a sum conservative energy (potential energy) may have no significant well near the CN spherical shape. In such a condition, the SHE formation cross-section must definitely be very low.

Accepting such a common view on restrictions for the SHE formation, we want to stress here that angular momentum in some cases does not produce very destructive influence. When fission barrier has an origin from the shell corrections in deformed nucleus, it should not be strongly reduced with the angular momentum growth. Experimental observation [7] of the rotational levels up to $I = 20$ in ^{254}No confirms that. The neutron emission can even be retarded due to the spin: in Ref. [8] there were given examples of high-spin isomers stable to neutron emission at excitation energy above binding B_n. Such peculiarities seem a little paradoxical, but we are going to discuss an even more paradoxical idea that Coulomb repulsion can play a positive role for the fusion of two heavy nuclei. The CN cross-section is normally decreasing with the growth of Coulomb parameter proportional to the product $Z_1 \cdot Z_2$ for interacting nuclei. However for very heavy nuclei, higher Coulomb barrier can be creative for formation of a potential well near the spherical CN shape and can accordingly promote fusion.

In the present work, we try, remaining within relatively simple phenomenological approach, to find new favourable possibilities for the synthesis of $Z_c = 110{-}118$ nuclei. The stages of a successful fusion and consequent survival of the SH residue are considered below separately, using simple approximations that reflect still (as we believe) some key points of the reaction mechanism. More developed theories lead normally to complications and uncertainties, while the reliable predictions are hardly achievable.

Heavy-ion physics has a future bound with the radioactive ion beam (RIB) facilities, and they are under construction at many laboratories today. Among them, most popular are apparently the projects for the fission-fragment acceleration. Such systems should be created in a few years in Germany, France, USA, Japan and Russia. Because of that, in the present article, we extend the set of available projectiles with inclusion of the radioactive neutron-rich fission fragments, in addition to stable ions. Remind that until now, all experiments aimed at the transfermium element synthesis were carried out using stable projectiles.

The most discouraging property of a RIB facility would be the beam intensity, much lower than the stable-ion beam current. Therefore, an application of RIB to a problem of the SHE production is directly dependent on the possibility to find the reactions and to choose the experimental conditions corresponding to high cross-sections, significantly higher than a level of about 10^{-36} cm^2 typical for SHE [1].

2. FORMATION OF QUASI-SPHERICAL CN

In collision of complex nuclei, the projectile can be elastically scattered or trapped after arrival to a contact point with the target. Then, the tangential motion, type of surface sliding, is going to be transformed to the rolling and sticking, as is discussed in [9]. The entrance orbital velocity partially dissipates with time, while the radial velocity is obviously damped from the beginning. The di-nuclear system may exist as a quasi-stable composite system during some period. Time scale and evolution of the system depending on the entrance parameters would be a challenge for extensive theoretical simulations.

Experimentally, fast break-up of the composite system is established with the fixation of reaction products in the channels of quasi-elastic, deep-inelastic and fast fission reactions. Recently, long-time scale of about $10^{-19}{-}10^{-17}$ s was obtained for fission and quasi-fission processes in the case of super-heavy systems after calculations [5] and experimental measurements [10]. Long-time evolution of a composite system is necessary but not enough for the CN formation. At some conditions, the system shape progresses spontaneously in the direction of a spherical CN shape. This is the most probable scenario for the medium-mass CN formation due to the relatively strong attracting forces between two nuclei.

However, for super-heavy systems, there is a question whether this would be possible at all, and if so, what conditions are required for the successful fusion with reasonable probability.

In Ref. [11] we described the balance between the centrifugal and contracting forces acting in two touched nuclei. The following equation was derived for the critical angular momentum of fusion:

$$\ell_{\rm cr} = 0.155 r_{\rm eff}(A_1^{1/3} + A_2^{1/3}) \left[\frac{A_1 A_2}{A_1 + A_2}(B - Q)\right]^{1/2}, \qquad (1)$$

where $r_{\rm eff}$ (fm) characterizes the size of system, B is a potential energy (MeV) for the figure of touched nuclei and the fusion threshold Q can be determined as a mass-defect difference $(M_c - M_1 - M_2)$ using tabulated nuclear masses. The potential energy B may be assigned as a Coulomb barrier of interaction, in accordance with the tradition. Numerical choice of the parameters $r_{\rm eff}$ and B allows some variation, but in the literature there exists enough data for calibration. The excitation functions for CN formation were measured in many cases for different nuclei species.

Logically, Ref. [11] and Eq. (1) do not contradict the approaches of other authors, as is clear from Ref. [12, 13]. In Ref. [14], relative position of the contact and CN points is also described. Eq. (1) and similar formulations characterize qualitatively the inherent linking between fusion cross-section and the potential energy difference $(B-Q)$. Fusion does not occur when $(B-Q) \leqslant 0$, because $\ell_{\rm cr}$ does not exist in this case. A physical reason for that is very clear. If spherical shape is placed at potential energy above the initial point of two touched nuclei, then there is negative gradient of potential for the path to fusion. As mentioned above, a higher Coulomb barrier may promote fusion due to positive $(B - Q)$ parameter. This is true only for very heavy CN when B and Q are almost equal in absolute values.

Potential surfaces for the composite systems were extensively calculated by different groups using sophisticated parametrizations and excellent mathematics tools. In contrast, Eq. (1) takes into account only two points at the deformation space: the CN and di-nuclear shapes, but they both are solid due to the experimental basis. It would also be important to specify that a top-hill position of the CN shape should strongly suppress the fusion probability. One may increase the collision energy significantly above B and assume the stabilization of a CN shape due to some additional barrier [14]. Nevertheless, the dissipation and friction force will cross a path to fusion without attracting potential forces. So, the fusion is eventually forbidden. On the contrary, the potential energy gain (if exists) will allow a fusion trajectory to reach the CN shape, if not directly, then after shape fluctuations. In such an approach, the $(B - Q)$ parameter defines, at least qualitatively, whether conditions are favourable for fusion in some projectile–target combination, or not.

The numerical $(B-Q)$ values are given in Table 1. A barrier of interaction B is taken according to R. Bass, Ref. [12], because this is the most popular choice in the literature devoted to the analysis of experimental excitation functions. For the discussion of barriers B, see also Ref. [15]. Table of nuclear masses [16] contains regularized values, both experimentally measured and predicted for nuclei far from stability, including the SH elements. Thus, Q values for the reactions of interest can be figured out using Tables [16].

Three groups of the reactions are characterized in Table 1:

I. Typical cold fusion reactions of the ^{208}Pb target with the most neutron-rich stable isotopes available as projectiles;

II. Reactions of the ^{208}Pb target with radioactive neutron-rich isotopes produced in fission; and

III. Reactions of heaviest stable W, Os, Pt targets with fission fragments. In principle, all reactions may be classified as cold fusion reactions because of low excitation at barrier.

Table 1. **Classification of the reactions and $(B-Q)$ values for the super-heavy element synthesis with stable and radioactive ion beams**

Group	Reaction	CN	B, MeV	$B-Q$, MeV	Class
I	^{48}Ca + ^{208}Pb	^{256}No	175.9	22.0	A
	^{50}Ti + ^{208}Pb	^{258}Rf	193.2	24.2	A
	^{54}Cr + ^{208}Pb	^{262}Sg	209.6	23.1	A
	^{58}Fe + ^{208}Pb	^{266}Hs	225.8	21.9	A
	^{64}Ni + ^{208}Pb	^{272}Ds	241.0	18.3	A
	^{70}Zn + ^{208}Pb	^{278}112	256.0	13.6	A
	^{76}Ge + ^{208}Pb	^{284}114	270.9	10.9	C
	^{82}Se + ^{208}Pb	^{290}116	285.6	5.0	C
	^{86}Kr + ^{208}Pb	^{294}118	301.1	0.2	C
II	^{72}Ni + ^{208}Pb	^{280}Ds	237.6	13.0	B
	^{78}Ni + ^{208}Pb	^{286}Ds	235.4	16.2	B
	^{78}Zn + ^{208}Pb	^{286}112	252.7	10.2	C
	^{84}Ge + ^{208}Pb	^{292}114	267.6	10.8	C
	^{90}Se + ^{208}Pb	^{298}116	282.4	10.1	C
	^{94}Kr + ^{208}Pb	^{302}118	297.8	4.3	C
III	^{94}Kr + ^{186}W	^{280}Ds	272.8	21.3	B
	^{94}Kr + ^{192}Os	^{286}112	279.0	19.6	B
	^{94}Kr + ^{198}Pt	^{292}114	285.1	16.9	B
	^{100}Sr + ^{186}W	^{286}112	286.1	21.2	B
	^{100}Sr + ^{92}Os	^{292}114	292.6	19.6	B
	^{100}Sr + ^{198}Pt	^{298}116	299.1	13.8	B
	^{104}Zr + ^{198}Pt	^{302}118	313.6	6.4	C

A general tendency is definitely visible that $(B-Q)$ decreases with a growth of the element atomic number Z_c. This corresponds to the experimental fall down of the production cross-sections with Z_c, as is observed in Ref. [1] for the group I reactions. The calculated $(B-Q)$ parameters are steeply decreasing at groups I and II, but this is not as drastic for the group III reactions. Surprizingly, group II is not better than I, despite change to the radioactive neutron-rich projectiles. Only with targets from W to Pt, the $(B-Q)$ values are significantly improved. Thus, group III should be more promising for the successful fusion and for higher yields of SH elements than the other reactions. With the reactions of group I, the heaviest $Z=113$ element has been recently detected in Japan, Ref. [17], using the ^{70}Zn + ^{209}Bi reaction but with extremely low cross-section, of about 0.06 pb.

With the radioactive neutron-rich projectiles, the fusion-evaporation products are more neutron-rich than in standard cold fusion, either even in hot fusion reactions with stable isotopes. For instance, in the ^{208}Pb(^{82}Se, $1n$) reaction the produced $Z_c=116$ element has a mass number $A=289$; in the ^{248}Cm(^{48}Ca, $4n$) reaction, $A=292$; and in ^{198}Pt(^{100}Sr, $2n$), $A=296$. As discussed earlier, this would be the most important advantage of using the radioactive beams, because heavier isotopes of SHE should be more stable, longer lived, and more convenient for exploration.

We have found an additional advantage that the group III reactions are favourable in respect to the fusion cross-sections correlated with $(B-Q)$ parameter. Following Table 1, one can deduce that the cross-section should not be drastically decreasing from $Z_c=110$ to $Z_c=116$ in group III, unlike group I. Such a prediction supports the idea of the SHE synthesis at RIB facilities constructed for the fission-fragment acceleration.

In Fig. 1, the correlation between σ and $(B-Q)$ parameter is shown in a graphic mode, it is plotted by known cross-sections for the group I reactions [1]. One can see that odd-Z elements are produced in reactions with ^{209}Bi target with lower cross-sections than even-Z elements with ^{208}Pb target, but a general trend is similar for both odd and even Z in Fig. 1. For the synthesis of $Z=114$ element with the group III reaction, such systematics predict much higher cross-section, as compared to the group I reaction.

It is clear from Fig. 1 that detectable cross-sections are observed unless the $(B-Q)$ parameter is decreased to be lower than 12 MeV. Then, we may assume that the inequality

$$(B-Q) \geqslant 12 \text{ MeV} \tag{2}$$

may play a role of the *necessary condition* for the SHE synthesis with cross-section $\sigma > 10^{-37}$ cm^2. The latter value is near the detection limit at modern technical possibilities. Using the criterion (2), the reactions listed in Table 1 could be differentiated among three classes: experimentally observed — class A; not yet tested, but with detectable cross-section, in expectation — class B; and with

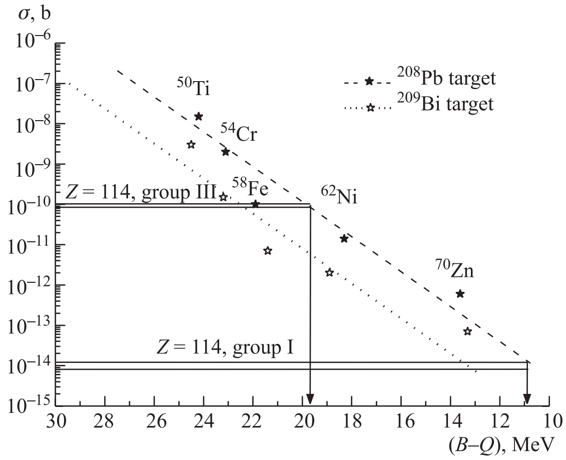

Fig. 1. Illustration of the correlation between SHE production cross-section σ and $(B-Q)$ parameter, discussed in the text. Experimental σ values are taken according to S. Hofmann et al., Ref. [1], and to recent K. Morita's result [17]

expected low cross-section — class C. Most of the group III reactions belong to class B, and their study would be a challenge for new experiments in the near future.

One has to realize that inaccuracy in estimation of $(B - Q)$ may be as high as 5 MeV, or even a little higher. The best nuclear mass tables predict unknown masses with standard deviation of about 1–2 MeV. The inaccuracy for the SHE mass prediction is probably above 2 MeV. Another uncertainty is due to the choice of the barrier B values, there is some freedom, a choice is not unique. But some regular deviation of the estimated $(B - Q)$ values from «correct» quantities does not cancel the properties of reactions discussed above. The differentiation of reactions among classes may be without changes despite the parameters variation. Our criterion (2) is deduced under definite choice of masses and barriers. At another choice, whole set of $(B - Q)$ values may drift a little, but general logics and, probably, final conclusions are still valid. The predictions based on experimental results in phenomenological approach are normally stable, unlike the calculations from first principles.

3. GAMMA-ASSISTED SHE SURVIVAL

In statistical approach, the absolute rates of fission and neutron emission are defined by the decay width, Γ_f and Γ_n, values. A product of the $\Gamma_n/(\Gamma_n + \Gamma_f)$ ratios for all steps of the multi-neutron emission should be combined with the

CN cross-section σ_c in order to get the residual production cross-section σ_{xn}. In this way, low survival probability σ_{xn}/σ_c for strongly fissile CN is naturally explained. In the cold fusion method, only one or two neutrons are needed for the CN de-excitation, because E^* is typically as low as 15–25 MeV. This means sharp increase in the survival probability, because only one or two steps of the neutron/fission competition influence the final product cross-section. However, the nature of fission barrier in the case of SHE leads to some peculiarities reducing the survival probability.

Full height $B_f \approx 5{-}6$ MeV has been deduced in [18] from the analysis of experimental excitation functions that does not contradict a value calculated in the macroscopic-microscopic theory by the authors of [19]. In general, fission barrier has a two-component nature: the macroscopic liquid drop (droplet) part and microscopic shell correction part. But for SHE, the macroscopic $B_f(\mathrm{LD})$ should be near zero at $Z^2/A \approx 44{-}45$, [19–20]. The main contribution from shell correction reduces with the nuclear temperature growth and the fission barrier height at some excitation E^* can be expressed [21] as follows:

$$B_f(E^*) = B_f(\mathrm{LD}) + B_f(\mathrm{SC}) \exp\left(-\frac{E^*}{\delta}\right). \qquad (3)$$

For SHE we choose numerically $B_f(\mathrm{LD}) = 0$ and $B_f(\mathrm{SC})$ of about 5 MeV. Damping parameter δ defines the effective energy of the shell correction melting, and it is taken now to be $\delta = 15$ MeV, instead of 20 MeV in [21]. The stabilization of a nucleus against fission due to the $N = 126$ shell closure was anticipated, but it was not visible at $E^* \geqslant 15$ MeV in experiments [22, 23]. One may deduce the melting of shell corrections at such energies. There exist other variants of explanation, for instance, the effect of collective modes in the level density [22] or reduced viscosity for near-magic nuclides [23]. But yet, it would not be wrong to reduce a little the δ parameter value, taking into account a fragile nature of fission barrier at the SHE range, in general.

Decreasing $B_f(E^*)$ function (3) influences the survival probability because of reduced Γ_n/Γ_f ratio at higher energies. But now, let us stress that the survival depends not only on the n/f competition. In Ref. [24], we investigated the important role of gamma emission for the fusion-evaporation products in the cases of fissile or non-fissile CN.

For strongly fissile nucleus, when $B_f < B_n$, neutrons can be emitted with some (little) probability at $E^* > B_n$, but at $B_f \leqslant E^* \leqslant B_n$ the fission probability reaches 100% explicitly. Respectively, survival probability $(1 - P_f)$ equals zero at this range. For the (xn) residue survival, one needs not only the successful emission of x neutrons, but also a requirement that remaining excitation E_r^* should be well below B_f to stop fission past neutron emission. This restricts significantly the excitation function width and the maximum cross-section for individual (xn) channels.

A numerical example of the survival probability has been calculated, which is given below for the $^{94}\mathrm{Kr} + {}^{192}\mathrm{Os} \rightarrow xn + {}^{(286-x)}112$ reactions. Standard statistical model equations were used for Γ_n, Γ_f, Γ_γ widths taking the level density by Gilbert–Cameron [25] with $a_c = a_n = A/10$ and $a_f = 1.02a_n$. Mean binding energy $\bar{B}_n = 6.4$ MeV should correspond to this neutron evaporation cascade according to [16]. Odd-even B_n variation is averaged and this is equivalent to the account of a zero-point variation for level density. Γ_n was calibrated via inverse process cross-section for the black nucleus with a radius parameter of 1.4 fm. The Γ_γ absolute values are linked to the known ones for neutron resonances of heavy nuclei. More detail of the calculation scheme can be found in [23].

At excitations below B_n, a competition between gamma and fission channels defines the residual nucleus fate. The Γ_γ magnitude is normally much lower as compared to Γ_f, and respectively, fission still dominates at some window of E^* near and under barrier B_f. For strongly fissile actinide nuclei, the near barrier fission was studied in [26] and the sub-barrier shelf of fission probability was revealed. In the present simulations, the fission width near the barrier is calculated with the account of a barrier-penetration probability using the known equation:

$$\Gamma_f(U) = \frac{1}{2\pi\rho_c(U)} \int_0^U \frac{\rho_f(\varepsilon)d\varepsilon}{\{1 + \exp[-\frac{2\pi}{\hbar\omega}(U - B_f(E^*) - \varepsilon)]} \tag{4}$$

with thermal energy $U = E^* - E_R$ and the barrier curvature parameter $h\omega = 1$ MeV. Rotational energy E_R could be neglected because of relatively low spins and due to high momentum of inertia for SH nuclei. Eq. (3) with $B_f(\mathrm{SC}) = 5$ MeV and $\delta = 15$ defines the $B_f(E^*)$ function.

Viscosity of a nuclear matter flow was assumed to be zero under the barrier and linearly increasing at $E^* > B_f$:

$$\eta = 0.1[E^* - B_f(E^*)]. \tag{5}$$

The dimensionless composite parameter η [27] reduces the fission width, and the corresponding Kramers factor $(\sqrt{1 + \eta^2} - \eta)$ was included in calculation of Γ_f at $E^* > B_f$. The moderate viscosity retards the fission lifetime by a factor of 4 at $E^* = 20$ MeV. The level density rotational enhancement should not change much the calculated Γ_f values, if an axial symmetry characterizes both the shape of statically deformed nucleus in ground state and the saddle point shape.

The described method allows one to calculate a fission probability $P_f = \Gamma_f/(\Gamma_f + \Gamma_n + \Gamma_\gamma)$ and the survival probability $(1 - P_f)$ as well. Results for the $^{286}112$ CN are shown in Fig. 2. At low E^*, a successive γ-emission in competition with fission is productive for the survival, and above B_n neutron emission supplies a new chance for the survival. Mean decay time could be defined for the CN as $\tau_c = \hbar/(\Gamma_n + \Gamma_f + \Gamma_\gamma)$, and the $\tau_c(E^*)$ function is also shown in Fig. 2.

A probability of neutron emission is not very low at $E^* \geqslant 15$ MeV, despite decreasing $B_f(E^*)$ function. The integral survival probability σ_{xn}/σ_c could be obtained with the calculated $(1 - P_f)$ function as follows:

$$\frac{\sigma_{xn}}{\sigma_c} = \left\{ \int_0^{B_{nx+1}} W(U_x)\,[1 - P_f(U_x)]\,dU_x \right\} \prod_{i=1}^{x} \left(\frac{\Gamma_n}{\Gamma_n + \Gamma_f} \right)_i, \qquad (6)$$

where $W(U_x)$ is a distribution of the residual excitation energy after successful emission of x neutrons, B_{nx+1} is a binding energy of the $(x+1)$ neutron. The $\Gamma_n/(\Gamma_n + \Gamma_f)$ ratios correspond to the neutron emission steps from 1 to x.

Numerical results of the calculations using Eq. (6) are given in Fig. 3 for $(1n)$ and $(2n)$ evaporation channels. Peak value is relatively high for $(1n)$ channel, but the width of maximum is small; $(2n)$ maximum is wider. Narrow

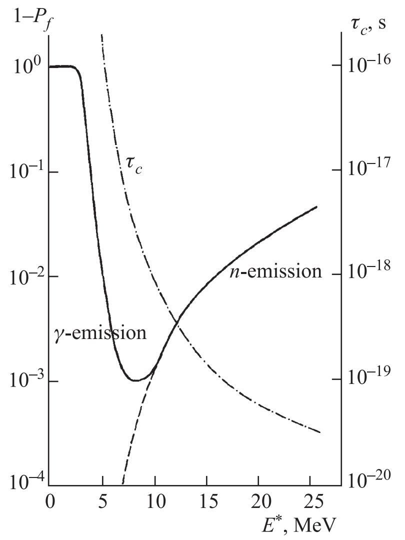

Fig. 2. The CN survival probability $(1-P_f)$ versus excitation energy calculated with the parameters: $\bar{B}_n = 6.4$ MeV and $B_f(E^*)$ — in accordance with Eq. (3). The $\tau_c(E^*)$ function is shown with the dash-dot curve

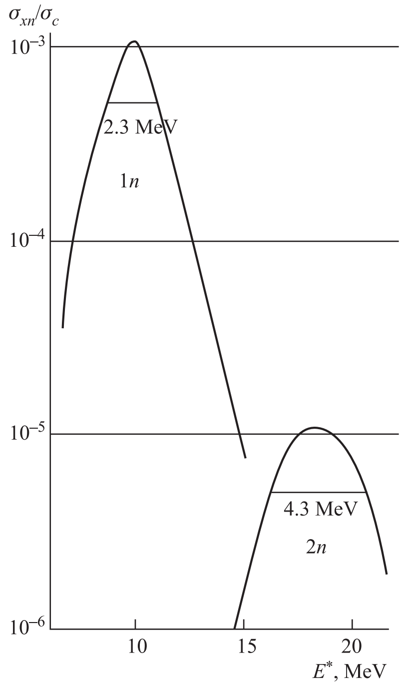

Fig. 3. Excitation functions of the $(1n)$ and $(2n)$ evaporation channels for the $^{286}112$ compound nucleus formed in the $^{94}Kr + {}^{192}Os$ reaction

excitation functions are mostly due to the dip in the survival probability between 4 and 9 MeV in Fig. 2. When σ_{xn}/σ_c is multiplied by strongly increasing $\sigma_c(E)$ function, both reactions may get a comparable cross-section σ_{xn} at a maximum. Peaks should be even more narrow and still separated by some interval $\Delta E^* \sim 7$ MeV along the horizontal axis. A conclusion follows that the production cross-section is reduced to very low level $\leqslant 1$ pb mostly due to the suppressed fusion cross-section, while the survival probability is not extremely low.

The above calculations are carried out for the ^{192}Os(^{94}Kr, $xn)^{(286-x)}112$ reaction with the radioactive fission-fragment ^{94}Kr nuclide as a projectile. More or less similar results are expected for the typical cold fusion reactions with stable projectiles, for instance for the ^{208}Pb(^{70}Zn, $xn)^{(278-x)}112$ reaction tested experimentally. If the value B_f at $E^* = 0$ is varied only within 1–1.5 MeV, then one may expect comparable (within one order of magnitude) the σ_{xn}/σ_c quantities for the whole group of reactions leading to $Z = 110-114$ elements. At the same time, the fusion cross-section can be very different, in particular due to the $(B - Q)$ parameter variation.

Excitation functions $\sigma_{1n}(E^*)$ and $\sigma_{2n}(E^*)$ have been measured in Ref. [1] for the cold fusion group I reactions listed in Table 1. However, the fusion $\sigma_c(E)$ function is still hidden because σ_{xn} contains also the survival probability. It would be important to get reliable σ_c values, and there is a possibility to deduce those combining experimental results [1] with our calculation of the survival probability. In a schematical approach, one can use the results shown in Fig. 3 as a survival probability for all projectile–target combinations independently of the atomic number Z. Then, estimated σ_c should be about 20 μb for $Z_c = 104$ and about 0.5 nb for $Z_c = 112$ at an energy corresponding to the maximum of $(1n)$ excitation function. As high value as $\sigma_c = 1.8$ mb follows from the peak cross-section measured [1] for the ^{208}Pb(^{50}Ti, $2n$) reaction. An accuracy of such estimates may be very low, which is also combined with poor statistics collected in experiments [1]. Nevertheless, this is a positive result because the important parameter previously hidden from direct observation is now estimated.

The ^{94}Kr + ^{186}W reaction may have high cross-section because the corresponding $(B-Q)$ value is not much different from that known for the ^{48}Ca + ^{208}Pb reaction, see Table 1. Fusion cross-section (correlated with $(B - Q)$ parameter) should be comparable for those two reactions and even for the synthesis of $Z_c = 112, 114$ nuclei with the fission-fragment beams using group III reactions. Expected cross-section of about 10^{-32}–10^{-33} cm^2 must be sufficient for the SHE production at RIB facilities, despite restricted beam current of the accelerated fission fragments.

It should be very important to test the above-discussed correlation between σ and $(B - Q)$ values in additional experiments looking for a confirmation of new possibilities for higher cross-sections of SHE production. For that, the production cross-sections of No and Rf isotopes in standard reactions of group I may be compared with the yield of more exotic ^{82}Se + ^{170}Er and ^{82}Se + ^{176}Yb reactions. In Table 2, the calculated $(B - Q)$ parameter values for ^{82}Se induced reactions seem to be almost similar as compared to the studied reactions with ^{48}Ca and ^{50}Ti ions. One may expect the comparable cross-sections as well, and if proved, it would strongly support the discussed systematics for very heavy projectiles such as ^{82}Se and eventually for fission fragment ions as well. The test experiment should not be very expensive because the cross-sections are expected on a level of 10^{-31}–10^{-32} cm^2.

Table 2. **Parameter comparison for reactions leading to the No and Rf isotopes. The reactions with ^{48}Ca and ^{50}Ti ions were experimentally investigated [1] and the ^{82}Se ion induced ones are now proposed as promising**

Reaction	CN	xn	Product	$T_{1/2}$	Decay mode	Cross-section	B, MeV	$B - Q$, MeV
^{82}Se + ^{170}Er	^{252}No	$1n$	^{251}No	0.75 s	α	—	243.3	22.7
^{48}Ca + ^{208}Pb	^{256}No	$1n$	^{255}No	3.1 min	α, EC	$3 \cdot 10^{-31}$	175.9	22.0
^{82}Se + ^{176}Yb	^{258}Rf	$1n$	^{257}Rf	4.3 s	α, EC	—	249.4	21.9
^{50}Ti + ^{208}Pb	^{258}Rf	$1n$	^{257}Rf	4.3 s	α, EC	$1.5 \cdot 10^{-32}$	193.2	24.2

4. CORRELATION BETWEEN LONGTIME FISSION AND THE CN SURVIVAL

The cold fusion reactions have been only discussed above. For hot fusion, a survival probability past 4–5 neutrons emission becomes very low, and in addition not very definite, because the parameter choice strongly influences the Γ_n/Γ_f ratios. Respectively, the CN cross-section remains hidden even in the best case, when the product cross-section is measured. One can try a reverse procedure calculating the CN cross-section in order to specify then a survival probability. However, the discussed restrictions due to the strong Coulomb repulsion and due to quasi-fission of a composite system make such a procedure not reliable as well.

Some light on the problem may be thrown after observation of the longtime fission component ($t_f > 10^{-18}$ s) for super-heavy CN in reaction $^{238}\mathrm{U} + \mathrm{Ni} \to {}^{(296)}120$ [10]. The crystal blocking method was applied in Ref. [10]. The longtime fission for excited nuclei with $E^* > 50$ MeV was found many years ago in Dubna experiments [28] on the blocking effect studies with heavy ion beams. Extended results were reported by other groups [29–31] and confirmed by other methods, for instance by the «atomic-clock» method [32]. Theoretical understanding was found in assumption that many neutrons are emitted before the successful fission, with significant reduction of the excitation energy. The lifetime is naturally increased when E^* is going down. Such an explanation was satisfactory for the moderate-fissility nuclei with $\Gamma_n/\Gamma_f \geqslant 1$. However, the experimental result of the French Collaboration [10] appears unexpected, and it confirms the surprising behavior of a superheavy composite system: a) high cross-section for the true CN formation, and b) high probability of its survival past 3–4 neutrons emission. More detail on the latter reaction is given below.

With the CN excitation energy $E^* = 67$ MeV, as given in Ref. [10], one deduces the ^{238}U projectile energy to exceed the Bass barrier by 24 MeV in c.m. system. The parameter of $(B-Q) = 43$ MeV is figured out as well. Estimated total reaction cross-section σ_R should be about 0.4 barn. The maximum entrance angular momentum $I_{\max} \approx 90$ can be found. From longtime component observed in [10], one deduces that true CN cross-section σ_c is not lower than 15% of the composite system quasi-fission yield. Assuming in addition that quasi-elastic processes take 2/3 of the total σ_R, the σ_c value can be estimated as follows: $\sigma_c \sim 20$ mb. The corresponding $I_{\max}$ must also be reduced, and a value of $I_{\max}(CN) = 25-30$ may be realistic.

In Section 3, we have found $\sigma_c = 1.8$ mb near the Bass barrier energy from the excitation function of the ^{208}Pb(^{50}Ti, $2n$) reaction. Unlike that, the ^{238}U + Ni reaction was studied at the energy above the barrier by 24 MeV. Respectively, the $\sigma_c = 20$ mb value does not look like very high cross-section accounting the actual energy position. Thus, the first surprising conclusion deduced above from the results [10] becomes not very surprising after such estimates. Finally, it confirms that a CN formation is not forbidden by strong Coulomb repulsion, when the $(B-Q)$ parameter is positive and not very low, even at $Z_1 \cdot Z_2 = 2576$. Angular momenta up to 30 also do not destabilize the superheavy CN in agreement with the preliminary expectations.

Another wonderful result of Ref. [10] on the survival of strongly fissile nucleus past several neutrons emission should be explained. Being understood, this may be productive for optimization of the SH element synthesis. Indeed, the successful emission of many neutrons indicates also a survival of the SH residual nucleus with a reasonable probability. In Fig. 2, the CN lifetime $\tau_c(E^*)$ function is shown, and long time $\tau_c > 10^{-18}$ s appears only at low excitations $E^* \leq 10$ MeV. The initial $E^* = 67$ MeV of the CN in $^{238}\mathrm{U} + \mathrm{Ni}$ reaction should be essentially decreased to reach the longtime range. Assuming even maximum rotational energy $E_R = 5$ MeV, one concludes that four neutrons are necessary for the removal of more than 40 MeV from the CN. In Fig. 1, the Γ_n/Γ_f ratio is also shown and the mean value is lower than 0.1 at the range of enegy corresponding to emission of four neutrons. Respectively, the probability of such a process should be as low as 10^{-4}–10^{-5}. But in Ref. [10] the longtime fission appears with high probability. How to explain such a dicrepancy by orders of magnitude?

The moderate viscosity parameter value has been used in our calculations illustrated by Fig. 2. Comparing it with the experiment, one can say that much higher viscosity, strongly dependent on E^*, is required for reproducing results [10]. This is not impossible, because data available in the literature is not enough to specify a viscosity parameter for definite reaction. Here we only intend to stress the contradictions and promising consequences that should be solved and confirmed in future studies.

One additional possibility exists that the quasi-fission and the CN fission events were not well-selected in the experiment [10]. But an assumption of the longtime-scale process for quasi-fission seems exotic as well.

5. SUMMARY

Cross-sections of the massive nuclei fusion with formation of the SH nuclei correlate with the parameter $(B-Q)$ characterizing a potential energy gradient on the path from the di-nuclear contact point to the quasi-spherical CN configuration. Possible reactions for the SHE synthesis with stable and radioactive heavy ions are classified on the basis of the $(B-Q)$ values defined with attraction of the generalized experimental systematics. A new conclusion is deduced that the fusion of stable W–Pt target nuclides with radioactive fission-fragment projectiles may promise an improved cross-section for the synthesis of $Z_c = 110{-}116$ nuclei, as compared to the studied reactions. Thus, new extension of the cold fusion method for the synthesis of elements with $Z \geqslant 113$ can be proposed.

After fusion, the competition between neutron emission and fission reduces significantly a product cross-section. Survival of the evaporation residue is also defined by the successful gamma-emission in competition with fission at the final step of the reaction. The corresponding factors are taken into account, and excitation functions for survival of the $(1n)$ and $(2n)$ products are numerically calculated for the ^{94}Kr + ^{192}Os reaction. There was found that the survival probabilities for isotopes of element 112 and neighboring elements are not extremely low, despite the fission dominance. Combining it with the reasonable fusion cross-section, one deduces the appropriate conditions for the SHE production with accelerated fission-fragment beams, even at restricted beam intensities. Experimental observation of the longtime fission in the crystal blocking experiments indicates a significant delay of fission due to the nuclear matter viscosity growing up with E^*. The latter result supports a possibility of $Z \geqslant 110$ elements synthesis in reactions with different projectiles.

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