Fusion-Fission Dynamics of Super-Heavy Element Formation and Decay

V.I. Zagrebaev

Flerov Laboratory of Nuclear Reaction, JINR, Dubna, 141980, Moscow region, Russia

Abstract. The paper is focused on reaction dynamics of super-heavy nucleus formation and decay at beam energies near the Coulomb barrier. The aim is to review the things we have learned from recent experiments on fusion-fission reactions leading to the formation of compound nuclei with $Z \geq 102$ and from their extensive theoretical analysis. Main attention is paid to the dynamics of formation of very heavy compound nuclei taking place in strong competition with the process of fast fission (quasi-fission). The choice of collective degrees of freedom playing a principal role, finding the multi-dimensional driving potential and the corresponding dynamic equation regulating the whole process are discussed. Theoretical predictions are made for synthesis of SH nuclei up to $Z=120$ in the asymmetric “hot” fusion reactions basing on use of the heavy transactinide targets.

INTRODUCTION

The interest in the synthesis of super-heavy nuclei has lately grown due to the new experimental results [1, 2, 3] demonstrating a real possibility of producing and investigating the nuclei in the region of the so-called “island of stability”. The new reality demands a more substantial theoretical support of these expensive experiments which will allow most optimal choice of fusing nuclei and collision energies as well as a better estimation of the cross sections and unambiguous identification of evaporation residues.

CAPTURE, FUSION, AND EVR FORMATION CROSS SECTIONS

FIGURE 1. Schematic picture of super-heavy nucleus formation.

The process of a cold residual nucleus formation is shown schematically in Fig. 1. A whole process can be divided into three reaction stages. At the first stage, colliding nuclei overcome the Coulomb barrier and approach the point of contact. Quasi-elastic

and deep-inelastic reaction channels dominate at this stage leading to formation of projectile-like and target-like fragments (PLF and TLF) in the exit channel. At the second reaction stage the touching nuclei evolve into the configuration of an almost spherical compound mono-nucleus. After dynamic deformation and exchange by several nucleons, two touching heavy nuclei may re-separate into PLF and TLF or may go directly to fission channels without formation of compound nucleus. The later process is usually called quasi-fission. Denote a probability for two touching nuclei to form the compound nucleus as P_{CN} . This probability depends also on initial deformations and orientations of two touching nuclei (see below). At the third reaction stage an excited compound nucleus emits neutrons and γ rays lowering its excitation energy and forming finally a residual nucleus in its ground state. This process takes place in strong competition with a regular fission, and the corresponding survival probability $P_{xn}(l, E^*)$ is usually much less than unity even for a low-excited super-heavy nucleus.

The production cross section of a cold residual nucleus B , which is the product of neutron evaporation and γ emission from an excited compound nucleus C , formed in the fusion process of two heavy nuclei $A_1 + A_2 \rightarrow C \rightarrow B + xn + N\gamma$ at c.m. energy E close to the Coulomb barrier in the entrance channel, can be decomposed over partial waves and written as follows

$$\sigma_{ER}^{xn}(E) \approx \frac{\pi \hbar^2}{2\mu E} \sum_{l=0}^{\infty} (2l+1) \cdot \int_0^{\infty} f(B) P^{HW}(B, l, E) P_{CN}(B, l, E^*) dB \cdot P_{xn}(l, E^*). \quad (1)$$

Here P^{HW} is the penetration probability of the one-dimensional potential barrier given by the usual Hill-Wheeler formula [4] with the barrier height modified to include a centrifugal term. $f(B)$ is the “barrier distribution function”, which takes into account the multi-dimensional character of the realistic barrier given by dynamic deformations of nuclear surfaces and/or different orientations of statically deformed colliding nuclei. Integration over effective barrier B means, in fact, integration over such dynamic deformations and/or different orientations. Semi-empirical [5, 6] and/or channel coupling approaches [7, 8] may be used to calculate rather accurately a penetrability of the multi-dimensional Coulomb barrier and the corresponding capture cross section. The survival probability $P_{xn}(l, E^*)$ of an excited compound nucleus can be calculated within a statistical model [9] rather accurately also, if a realistic integration over neutron evaporation cascade and γ emission is performed and a realistic formula for the level density is used [6]. The most uncertain parameter here is the height of fission barrier of CN. Unfortunately, the fission barriers of super-heavy nuclei calculated within the different approaches differ by several MeV (see, e.g., [10]). The processes of the compound nucleus formation and quasi-fission are the least studied stages of heavy ion fusion reaction. Today there is no consensus for the mechanism of the compound nucleus formation itself, and quite different, sometimes opposite in their physics sense, models are used for its description.

TWO-CORE MODEL

To solve the problem of fusion-fission dynamics one has to answer very principal questions. What are the main degrees of freedom playing most important role at this

reaction stage? What is the corresponding driving potential and what is an appropriate equation of motion for description of time evolution of nuclear system at this stage? Until now quite different degrees of freedom and equations of motion are used for description of the fusion and fission processes. It is justified for not so heavy nuclear systems, when these two reaction stages are well separated in time by a long-lived compound nucleus. For heavy nuclear systems, when quasi-fission channels dominate, the fusion-fission dynamics has to be described as a common inseparable process. At the same time, we have to restrict ourselves to a small number of degrees of freedom to be able to solve numerically the corresponding equations of motion. However, any simplified one- or two-dimensional models hardly may be used for adequate description of the complicated reaction dynamics. Elongation of the system (distance between centers of fragments), mass-asymmetry (proton and neutron numbers of two separated nuclei), and deformations of the fragments are quite optimal degrees of freedom for description of fusion-fission process (see Fig. 2), and the two-center shell model [11] seems to be the best for calculation of the corresponding potential energy surface. However, the available numerical codes (being rather complicated) confront with some difficulties for large mass-asymmetry configurations and also for separated nuclei not giving the appropriate values of the Coulomb (fusion) barriers.

FIGURE 2. Optimal degrees of freedom to describe the fusion-fission dynamics.

In [5, 12] a new approach has been proposed for description of fusion-fission dynamics based on a semi-empirical version of the two-center shell model idea [11]. It is assumed that on a path from the initial configuration of two touching nuclei to the compound nucleus configuration and on a reverse path to the fission channels the nuclear system consists of two cores (z_1, n_1) and (z_2, n_2) surrounded with a certain number of common (shared) nucleons $\Delta A = A_{CN} - a_1 - a_2$ moving in the whole volume occupied by the two cores, see Fig. 3. The processes of compound nucleus formation, fission and quasi-fission take place in the space $(z_1, n_1, \delta_1; z_2, n_2, \delta_2)$, where δ_1 and δ_2 are the dynamic deformations of the cores. The compound nucleus is finally formed when the elongation of the system becomes shorter than a saddle point elongation of CN.

Within the two-core model the fusion-fission driving potential is defined as follows

$$V_{fus-fis}(R; z_1, n_1, \delta_1; z_2, n_2, \delta_2) = \tilde{V}_{12}(R, z_1, n_1, \delta_1; z_2, n_2, \delta_2) - [\tilde{B}(a_1) + \tilde{B}(a_2) + \tilde{B}(\Delta A)] + B(A_1^0) + B(A_2^0). \quad (2)$$

Here $\tilde{B}(a_1) = \tilde{\beta}_1 a_1$, $\tilde{B}(a_2) = \tilde{\beta}_2 a_2$ and $\tilde{B}(\Delta A) = 0.5(\tilde{\beta}_1 + \tilde{\beta}_1)\Delta A$ are the binding energies of the cores and of common nucleons. These quantities depend on the number of shared nucleons. If one defines the measure of the collectivization as $x = \Delta A / \Delta A_{CN}$, then $\tilde{\beta}_{1,2}$ can be roughly approximated as $\tilde{\beta}_{1,2} = \beta_{1,2}^{exp} \varphi(x) + \beta_{CN}^{exp} (1 - \varphi(x))$, where $\beta_{1,2}^{exp}$ and β_{CN}^{exp} are specific binding energies of the isolated (free) fragments, which can be derived from the experimental nuclear masses or calculated rather accurately within the macroscopic-microscopic model [13]. Note that $\Delta A < A_{CN}$ and CN formation does not mean $a_{1,2} = 0$ [5]. $\varphi(x)$ is an appropriate monotonous function satisfying the conditions $\varphi(x=0) = 1$, $\varphi(x=1) = 0$. Thus the specific binding energies of the cores $\tilde{\beta}_{1,2}$ approach the specific binding energy of CN with increasing ΔA . All the shell effects enter the total energy (2) by means of $\beta_{1,2}^{exp}$ and β_{CN}^{exp} . The interaction of two fragments $\tilde{V}_{12}$ is defined in usual way at $R \geq R_{cont}$ as a sum of the Coulomb and nuclear potentials (here proximity potential is used). This interaction weakens gradually with increasing the number of shared nucleons ΔA at $R_{CN} < R < R_{cont}$, i.e. with gradual dissolving the two cores in the compound mononucleus. The interaction energy transforms to the binding energy of CN. Thus, once the compound nucleus has been formed ($\Delta A = \Delta A_{CN}$), the total energy of the system $V_{fus-fis} = Q_{gg}^{fus} = B(A_1^0) + B(A_2^0) - B(A_{CN})$, as it should be if the energy of two resting at infinity initial nuclei (A_1^0 and A_2^0) is taken as zero.

FIGURE 3. Nuclear shape used in the two-core model of fusion-fission dynamics.

The fusion-fission driving potential is shown in Fig. 4 as a function of z_1 and z_2 at $R \leq R_{cont}$ (minimized over n_1, n_2) and as a function of elongation and mass-asymmetry. As can be seen, the shell structure, clearly revealing itself in the contact of two nuclei ($\Delta A = 0$, the diagonal in Fig. 4(b)), is also retained at $R < R_{cont}$ (see the deep minima in the regions of $z_{1,2} \sim 50$ and $z_{1,2} \sim 82$ in Fig. 4b). Following the fission path (dotted curves in Fig. 4b,d) the system overcomes the multi-humped fission barrier (Fig. 4c). It is well-known that the intermediate minima correspond to the shape isomer states. From analysis of the driving potential (see Fig. 4b) we may definitely conclude now that these isomeric states are nothing else but the two-cluster configurations with magic or semi-magic cores [14].

In Fig. 5 the driving potentials calculated within the two-center shell model (version of Ref. [15]) and within the two-core model are compared for the nuclear system formed in collision of $^{48}\text{Ca} + ^{248}\text{Cm}$ leading to compound nucleus $^{296}116$. As can be seen, the

FIGURE 4. Driving potential $V_{fus-fis}$ of the nuclear system consisting of 116 protons and 180 neutrons. (a) Potential energy of two touching nuclei at $a_1 + a_2 = A_{CN}$, $\Delta A = 0$, i.e., along the diagonal of the lower figure. (b) Topographical landscape of the driving potential on the plane (z_1, z_2) . The dashed, solid, and dotted curves with arrows show fusion, quasi-fission, and regular fission paths, respectively. (c) Three humped fission barrier calculated along the fission path (dotted curves). (d) Three dimensional plot in the “mass-asymmetry - elongation” space.

FIGURE 5. Fusion-fission driving potential as a function of mass-asymmetry calculated at two fixed distances between nuclei: in vicinity of the Coulomb barrier, $R = 12$ fm, and for well separated nuclei, $R = 16$ fm. Dotted, dashed and solid curves correspond to the LDM, two-center shell model, and two-core model calculations, respectively.

results of two calculations are rather close. At the same time, there are several advantages of the proposed approach. The driving potential is derived basing on experimental binding energies of two cores, which means that the “true” shell structure is taken into account and, thus, for well separated nuclei (large values of R) $V_{fus-fis}$ gives *explicit* values of nucleus-nucleus interaction. The fusion-fission driving potential (2) is defined in the whole region $R_{CN} < R < \infty$, it is a continuous function at $R = R_{cont}$, it gives the realistic Coulomb barrier at $R = R_B > R_{cont}$, and may be used for simultaneous description of the whole fusion-fission process. At last, along with using the variables $(z_1, n_1; z_2, n_2)$, one may easily recalculate the driving potential as a function of mass-asymmetry $\alpha = (a_1 - a_2)/(a_1 + a_2)$ and elongation $R_{12} = r_0(a_1^{1/3} + a_2^{1/3})$ (at $R > R_{cont}$, $R_{12} = R = s + R_1 + R_2$, where s is the distance between nuclear surfaces). These variables along with deformations of the fragments δ_1 and δ_2 are commonly used for description of fission process.

FIGURE 6. Three-dimensional driving potential of formation and fission of ^{216}Ra nucleus. In the insets the fission fragment mass distributions are shown obtained in the $^{12}\text{C} + ^{204}\text{Pb}$ (a) and $^{48}\text{Ca} + ^{168}\text{Er}$ (b) fusion-fission reactions [16]. In the last case a contribution from the quasi-fission process can be clearly seen.

Deformations of the fragments were found to be very important both at fusion and fission paths. Deformation energies of the cores $\Delta E_i^{def}(\delta_{i=1,2})$ can be taken into account in (2) by replacement of β_i^{exp} with $\beta_i^{exp} - \Delta E_i^{def}/a_i$ and calculated as follows $\Delta E_i^{def}(\delta_i) = E_i^{LDM}(\delta_i) + W_i(\delta_i) - W_i^0(\delta_i^0)$. Here $E^{LDM}(\delta)$ is the liquid drop model deformation energy and $W(\delta)$ is the shell correction. $W^0(\delta^0)$ is the shell correction to the ground state of a given nucleus, and δ^0 is the quadrupole deformation of

the ground state. Thus, using the table of Ref. [13] for the values of $\delta^0(Z_1, A_1)$ and $W^0(Z_1, A_1)$ and knowing the value of the shell correction at zero deformation $W(\delta = 0)$ (if $\delta^0(Z_1, A_1) \neq 0$), one may easily and rather accurately estimate the deformation energy of a given fragment without performing microscopic calculation. It is clear that $\Delta E^{def}(\delta = \delta^0) = 0$ and $W(\delta \rightarrow \infty) \rightarrow 0$.

In Fig. 6 the calculated three-dimensional driving potential for formation and fission of ^{216}Ra is shown in the space of elongation, mass-asymmetry, and deformation of the fragments (here, for simplicity, the deformations are assumed to be equal to each other: $\delta_1 = \delta_2 = \delta$). In Ref. [16] the two reactions ($^{12}\text{C}+^{204}\text{Pb}$ and $^{48}\text{Ca}+^{168}\text{Er}$) were studied leading to formation of ^{216}Ra . In the insets of Fig. 6 the corresponding mass distributions of the detected fission fragments are shown. In the case of very asymmetric $^{12}\text{C}+^{204}\text{Pb}$ fusion reaction ($\alpha \sim 0.9$) the contact configuration is located behind the Businaro-Gallone maximum, and the nuclei form CN with a probability equal to unity. After formation, CN goes to fission channels along a normal fission path, here it locates preferably at low values of mass-asymmetry and leads to symmetric mass distribution of deformed fission fragments (see Fig. 6). In the case of $^{48}\text{Ca}+^{168}\text{Er}$ fusion reaction, from the contact configuration the system may evolve along two different paths, one of them leads to formation of CN, whereas another one leads the system to the quasi-fission channel without formation of CN (see Fig. 6). This quasi-fission valley is caused by the shell effect corresponding to the double-magic ^{132}Sn nucleus. Thus, for the $^{48}\text{Ca}+^{168}\text{Er}$ reaction the model predicts a formation of deformed symmetric fission fragments ($\delta_1 \sim \delta_2 \sim 0.3$) and spherical asymmetric quasi-fission fragments, which can be checked in principle by detecting the coincident neutrons and γ -rays.

EQUATIONS OF MOTION ?

The common dynamic equations of motion for the variables (R, α, δ) , which would be valid in the whole configuration space and could be applied for description of all the competing processes (deep-inelastic collision, fusion, quasi-fission, and fission, see Fig. 1), are still have to be derived. All these degrees of freedom are quite similar for more or less uniform mono-nucleus, and even the corresponding inertia parameters (M_R, M_α, M_δ) are very close to each other here. However, for contact configurations and for separated fragments these degrees of freedom are quite different. All them play an important role here. In particular, neutron transfer with positive Q -value (change of α) may significantly increase the sub-barrier penetrability in the entrance channel [17]. Dynamic deformations of the separated fragments are also very important both in the entrance and in exit channels. That is why the common dynamic equations coupling all the degrees of freedom are very desired. Nevertheless, until now the different considerations of the entrance channel and the processes of CN formation, quasi-fission and fission are commonly used. In [18, 19] the Langevin equations were used for description of evolution of the system after contact of two nuclei. In [5] the master equation was proposed and used in [12, 14] to describe approximately the overdamped evolution of the system in the $(z_1, n_1, \delta_1; z_2, n_2, \delta_2)$ space.

Solving the master equation for the distribution function $F(\vec{y} = \{z_1, n_1, \delta_1; z_2, n_2, \delta_2\}; t)$

one may determine the probability of the compound nucleus formation as an integral of the distribution function over the region $R \leq R_{saddle}^{CN}$. Similarly one can define the probabilities of finding the system in the different quasi-fission channels, i.e., the charge and mass distributions of fission fragments measured experimentally. In fact, it is not so easy to perform such realistic calculations due to a large number of the variables. To simplify the problem, we solve the master equation with restricted number of the variables. First, the deformations of the fragments are fixed (not obligatory to zero values). Then the potential energy is minimized over n_1 and n_2 and a two-dimensional driving potential $V_{fus-fis}(z_1, z_2)$ is calculated. Finally the master equation for the distribution function $F(y = \{z_1, z_2\}, t)$

$$\frac{\partial F}{\partial t} = \sum_{y'} \lambda(y, y') F(y', t) - \lambda(y', y) F(y, t) \quad (3)$$

is solved to determine the value of P_{CN}^0 at a given excitation energy E^* . The macroscopic transition probabilities $\lambda(y, y') \sim \exp\{[V_{fus-fis}(y') - V_{fus-fis}(y)]/2T(y)\}$ are used, where $T = \sqrt{[E_{cm} - V_{fus-fis}(y)]/a}$ is the local temperature and a is the level density parameter. Eq. (3) describes an overdamped evolution, when a potential energy of the nuclear system plays a major role. The sum over y' in (3) is extended only to nearest configurations $z_{1,2} \pm 1$ (no fragment transfer). Eq. (3) is solved up to the moment when the total flux comes to the compound nucleus configurations (dark area in Fig. 4b) and/or escapes into the quasi-fission channels, giving us the probability of the compound nucleus formation P_{CN}^0 and the charge distribution of quasi-fission fragments.

Mutual orientation of statically deformed colliding nuclei at their contact configuration is also very important for subsequent evolution of the system. There is a common opinion that the more compact “side-by-side” configuration of two touching nuclei is more favorable for CN formation comparing with the more elongated “nose-to-nose” configuration, which may easily re-separates into the quasi-fission channel (see, for example, [20]). Recently it has been also proved experimentally [21]. This effect is not included in P_{CN}^0 calculated with the simplified master equation (3). To take this effect into account, one may introduce the weight function $g(\theta)$, which turns to zero at $\theta = 0$ (tip orientation, lowest barrier B_1) and is close to unity at $\theta = \pi/2$ (side orientation, highest barrier B_2). Thus the probability of CN formation, being part of Eq. (1) for the cross section, may be written as $P_{CN}(B(\theta), l, E^*) = P_{CN}^0(l, E^*) \cdot g(\theta)$, and $g(\theta)$ is approximated here by the Fermi function $1/[1 + \exp\{(\theta_0 - \theta)/\Delta\theta\}]$, where $0 < \theta_0 < \pi/2$ and $\Delta\theta$ are free parameters. This function simulates somehow a decrease of fusion probability P_{CN} for very elongated “nose-to-nose” configurations of deformed heavy nuclei. Note that in the entrance channel such configurations increase the barrier penetrability due to decrease of the Coulomb barrier. This effect is well-known and can be described very accurately within the semi-empiric [5, 6] and/or CC approaches [7, 8].

CROSS SECTIONS OF SHE FORMATION

In Fig. 7 the calculated capture, fusion, and evaporation residue formation cross sections are shown for the ^{48}Ca induced fusion reactions leading to super-heavy nuclei with

$Z = 112 \div 116$. The shell corrections to the ground state energies of super-heavy nuclei proposed by P. Möller *et al.* [13] were used to estimate the corresponding fission barriers and calculate survival probability $P_{xn}(l, E^*)$. As can be seen, for the “hot” fusion reactions, the EvR cross sections decrease rather slowly with increasing Z and remain at the level of few picobarns. From obtained results one may conclude that the “hot” fusion reactions with the heavy transactinide targets can be successfully used even at existing facilities for a synthesis of super-heavy nuclei with Z up to 120 ($^{54}\text{Cr} + ^{248}\text{Cm}$ or $^{58}\text{Fe} + ^{244}\text{Pu}$ combinations). The preferable beam energy corresponds to about 40 MeV of CN excitation energy (with maximal yield of 3n and/or 4n evaporation products), i.e., it should be slightly higher than those used in previous experiments [1, 2].

FIGURE 7. Capture, fusion, and evaporation residue formation cross sections in the ^{48}Ca induced fusion reactions. Experimental data for the capture cross sections (left panel) are from [3]. Dashed curves on the left panel are obtained ignoring the orientation effects in the entrance channel (i.e., $f(B) = \delta(B - B_0)$ in (1)) or in CN formation (side orientations only). The dotted, dashed, solid and dash-dotted curves on the right panels (a-d) correspond to 2, 3, 4, and 5 neutron evaporation channels, respectively. The thin curves in (b) and (d) correspond to the fusion reactions with lighter isotopes: ^{242}Pu and ^{245}Cm . Experimental data for production of nuclei with $Z=112, 114$, and 116 are from [1, 2].

ACKNOWLEDGMENTS

I am indebted to Profs. M.G. Itkis and Yu.Ts. Oganessian for many fruitful discussions of the problem. The work was supported partially by INTAS under grant No. 00-655.

REFERENCES

1. Yu.Ts. Oganessian, A.V. Yeremin, A.G. Popeko, S.L. Bogomolov, G.V. Buklanov, M.L. Chelnokov, V.I. Chepigin, B.N. Gikal, V.A. Gorshkov, G.G. Gulbekian, M.G. Itkis, A.P. Kabachenko, A.Yu. Lavrentev, O.N. Malyshev, J. Rohac, R.N. Sagaidak, S. Hofmann, S. Saro, G. Giardina, K. Morita, *Nature* **400**, 242 (1999).
2. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdulin, A.N. Polyakov, I.V. Shirokovsky, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, B.N. Gikal, A.N. Mezentsev, S. Iliev, V.G. Subbotin, A.M. Sukhov, O.V. Ivanov, G.V. Buklanov, K. Subotic, M.G. Itkis, K.J. Moody, J.F. Wild, N.J. Stoyer, M.A. Stoyer, R.W. Loughheed, *Yad.Fiz.*, **63**, 1769 (2000) [*Physics of Atomic Nuclei* **63**, 1679 (2000)]; *Phys.Rev. C* **63**, 011301(R) (2001).
3. M.G. Itkis, Yu.Ts. Oganessian, A.A. Bogatchev, I.M. Itkis, M. Jandel, J. Kliman, G.N. Kniajeva, N.A. Kondratiev, I.V. Korzyukov, E.M. Kozulin, L. Krupa, I.V. Pokrovski, E.V. Prokhorova, B.I. Pustyl'nik, A.Ya. Rusanov, V.M. Voskresenski, F. Hanappe, B. Benoit, T. Materna, N. Rowley, L. Stuttge, G. Giardina, K.J. Moody, in *Proceedings on Fusion Dynamics at the Extremes*, Dubna, 2000, edited by Yu.Ts. Oganessian and V.I. Zagrebaev, World Scientific, Singapore, 2001, pp.93-109.
4. D.L. Hill, J.A. Wheeler, *Phys.Rev.* **89**, 1102 (1953).
5. V.I. Zagrebaev, *Phys.Rev. C* **64**, 034606 (2001).
6. V.I. Zagrebaev, Y. Aritomo, M.G. Itkis, Yu.Ts. Oganessian, and M. Ohta, *Phys.Rev. C* **65**, 014607 (2002).
7. K. Hagino, N. Rowley, A.T. Kruppa, *Comp.Phys.Commun.*, **123**, 143 (1999).
8. V.I. Zagrebaev and V.V. Samarin, JINR report No. P7-2003-32, Dubna, 2003 (to be published in *Yad.Fiz.*, 2004); CC fusion code of the NRV: <http://nrv.jinr.ru/nrv>.
9. A.V. Ignatyuk, *Statistical properties of excited atomic nuclei*, Energoatomizdat, Moscow, 1983.
10. M.G. Itkis, Yu.Ts. Oganessian, and V.I. Zagrebaev, *Phys.Rev. C* **65**, 044602 (2002).
11. U. Mosel, J. Maruhn, and W. Greiner, *Phys.Lett. B* **34**, 587 (1971); J. Maruhn and W. Greiner, *Z.Physik*, **251**, 431 (1972).
12. V.I. Zagrebaev, *J.Nucl.Radiochem.Sci.* **3**, No. 1, 13 (2002).
13. P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, *At.Data Nucl.Data Tables* **59**, 185 (1995).
14. V.I. Zagrebaev, M.G. Itkis, and Yu.Ts. Oganessian, *Yad.Fiz.*, **66**, No.6, 1069 (2003) [*Phys.At.Nucl.*, **66**, No.6, 1033 (2003)].
15. A. Iwamoto, S. Yamaji, S. Suekane, and K. Harada, *Prog.Theor.Phys.*, **55**, 115 (1976).
16. A.Yu. Chizhov, M.G. Itkis, I.M. Itkis, G.N. Kniajeva, E.M. Kozulin, N.A. Kondratiev, I.V. Pokrovski, R.N. Sagaidak, V.M. Voskresenski, A.V. Yeremin, L. Corradi, A. Gadea, A. Latina, A.M. Stefanini, S. Szilner, M. Trotta, A.M. Vinodkumar, S. Beghini, G. Montagnoli, F. Scarlassara, A.Ya. Rusanov, F. Hanappe, O. Dorvaux, N. Rowley, and L. Stuttge, *Phys.Rev. C* **67**, 011603(R)(2003).
17. V.I. Zagrebaev, *Phys.Rev. C* **67**, 061601(R) (2003).
18. Y. Aritomo, T. Wada, M. Ohta, Y. Abe, *Phys.Rev. C* **59**, 796 (1999) (and subsequent papers).
19. Y. Abe, C.W. Shen, G.I. Kosenko, and D. Boilley, *Yad.Fiz.*, **66**, No.6, 1093 (2003).
20. A. Iwamoto, P. Möller, J.R. Nix, H. Sagawa, *Nuc.Phys. A* **596**, 329 (1996).
21. K. Nishio, H. Ikezoe, S. Mitsuoka, and J. Lu, *Phys.Rev. C* **62**, 014602 (2000); S. Mitsuoka, H. Ikezoe, K. Nishio, and J. Lu, *Phys.Rev. C* **62**, 054603 (2000).