

True ternary fission of superheavy nuclei

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True ternary fission with formation of a heavy third fragment is quite possible for superheavy nuclei because of the strong shell effects leading to a three-body clusterization with the two doubly magic tinlike cores. The simplest way to discover this phenomenon in the decay of excited superheavy nuclei is a detection of two tinlike clusters with appropriate kinematics in low-energy collisions of medium-mass nuclei with actinide targets. The three-body quasi-fission process could be even more pronounced for giant nuclear systems formed in collisions of heavy actinide nuclei. In this case a three-body clusterization might be proved experimentally by the detection of two coincident leadlike fragments in low-energy U + U collisions.

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I. INTRODUCTION

Today the term “ternary fission” is commonly used to denote the process of formation of light charged particle which accompanies fission [1]. This is a rare process (less than 1%) relative to binary fission (see Fig. 1). As can be seen, the probability of such a process decreases sharply with increasing mass number of the accompanied third particle. These light particles are emitted almost perpendicularly with respect to the fission axis (equatorial emission) [1]. It is interpreted as an indication that the light ternary particles are emitted from the neck region and are accelerated by the Coulomb fields of both heavy fragments.

In contrast to such a process, the term “true ternary fission” is used for a simultaneous decay of a heavy nucleus into three fragments of not very different mass [1]. Such decays of low excited heavy nuclei have not yet been unambiguously observed. The true ternary fission of atomic nuclei (below we omit the word “true”) has a long history of theoretical and experimental studies. Early theoretical considerations based on

the liquid drop model (LDM) [3] showed that, for heavy nuclei, ternary fission produces a larger total energy release in comparison to binary fission, but the actual possibility of ternary fission is decided, in fact, by barrier properties and not by the total energy release. It was found that the LDM ternary fission barriers for oblate (triangle) deformations are much higher compared to the barriers of prolate configurations [4], and it seems that the oblate ternary fission may be excluded from consideration. However, further study of this problem within the more sophisticated three-center shell model [5] showed that the shell effects may significantly reduce the ternary fission barriers even for oblate deformations of very heavy nuclei.

It is well known that for superheavy nuclei the LDM fission barriers are rather low (or vanish completely) and the shell correction to the total deformation energy is very important. First estimations of the binary and prolate ternary fission barriers of superheavy nucleus ²⁹⁸114, made in Ref. [6] with the shell corrections calculated in an approximate way, demonstrated that they are identical to within 10%. To our knowledge, since then there has not been any significant progress in the theoretical (or experimental) study of ternary fission. Meanwhile, today it has become possible to study the properties and dynamics of formation and decay of superheavy nuclei experimentally [7], for which ternary fission could be rather probable (see below).

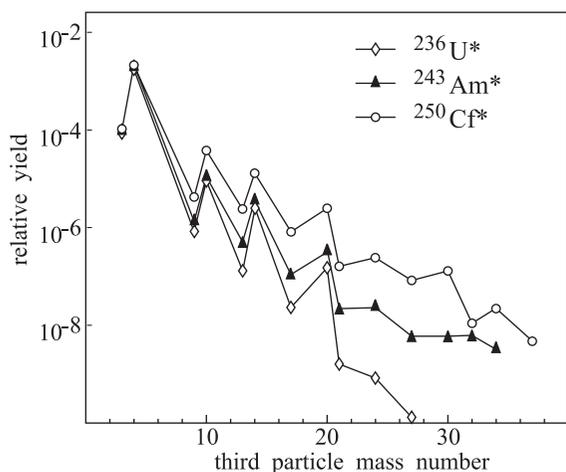


FIG. 1. Yields of ternary particles in the (n_{th}, f) reactions with thermal neutrons [2], relative to binary fission. The figure is a simplified version of Fig. 4 from Ref. [2] (kindly prepared by F. Gönnewein).

II. CLUSTERIZATION AND SHAPE ISOMERIC STATES OF HEAVY NUCLEI

The two-center shell model (TCSM) [8] looks most appropriate for calculation of the adiabatic potential energy of a heavy nucleus at large dynamic deformations up to the configuration of two separated fragments. The nuclear shape in this model is determined by five parameters: the elongation R of the system, which for separated nuclei is the distance between their mass centers; the ellipsoidal deformations of the two parts of the system, δ_1 and δ_2 ; the mass-asymmetry parameter $\eta = (A_2 - A_1)/(A_2 + A_1)$, where A_1 and A_2 are the mass numbers of the system halves; and

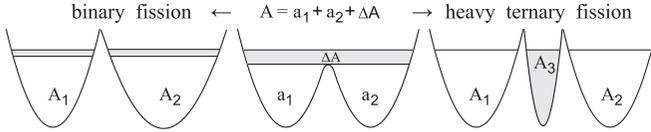


FIG. 2. Schematic view of binary and ternary fission.

the neck parameter ϵ , which smoothes the shape of overlapping nuclei.

Within the macro-microscopic approaches, the energy of the deformed nucleus is composed of the two parts: $E(A, Z; R, \delta, \eta, \epsilon) = E_{\text{mac}}(A, Z; R, \delta, \eta, \epsilon) + \delta E(A, Z; R, \delta, \eta, \epsilon)$. The macroscopic part, E_{mac} , smoothly depends on the proton and neutron numbers and may be calculated within the LDM. The microscopic part, δE , describes the shell effects. It is constructed from the single-particle energy spectra via the Strutinsky procedure [9]. The details of calculation of the single-particle energy spectra within the TCSM, the explanation of all the parameters used, as well as the extended and empirical versions of the TCSM may be found in Ref. [10].

Within the TCSM for a given nuclear configuration $(R, \eta, \delta_1, \delta_2)$, we may unambiguously determine the two deformed cores a_1 and a_2 surrounded with a certain number of shared nucleons: $\Delta A = A_{\text{CN}} - a_1 - a_2$ (see Fig. 2). During binary fission, these valence nucleons gradually spread between the two cores with the formation of two final fragments, A_1 and A_2 . Thus, the processes of compound nucleus (CN) formation, binary fission, and quasi-fission may be described both in the space of the shape parameters $(R, \eta, \delta_1, \delta_2)$ and in the space $(a_1, \delta_1, a_2, \delta_2)$. This double choice of equivalent sets of coordinates is extremely important for a clear understanding and interpretation of the physical meaning of the intermediate local minima appearing on the multidimensional adiabatic potential energy surface and could be used for extension of the model for description of three-core configurations appearing in ternary fission.

The adiabatic driving potential for the formation and decay of the superheavy nucleus $^{296}116$ at fixed deformations of both fragments is shown in Fig. 3 as a function of elongation and mass asymmetry and also as a function of charge numbers z_1 and z_2 of the two cores (minimized over neutron numbers n_1 and n_2) at $R \leq R_{\text{cont}}$. Following the fission path [dotted curves in Figs. 3(a) and 3(b)], the nuclear system passes through the optimal configurations (with minimal potential energy) and overcomes the multihumped fission barrier. The intermediate minima located along this path correspond to the shape isomeric states. These isomeric states are nothing but the two-cluster configurations with magic or semimagic cores surrounded by a certain amount of shared nucleons. In the case of binary fission of nucleus $^{296}116$, the second (after the ground state) minimum on the fission path arises from the two-cluster nuclear configuration consisting of tinlike ($z_1 = 50$) and kryptonlike ($z_2 = 36$) cores and about 70 shared nucleons. The third minimum corresponds to the mass-symmetric clusterization with two magic tin cores surrounded by about 30 common nucleons.

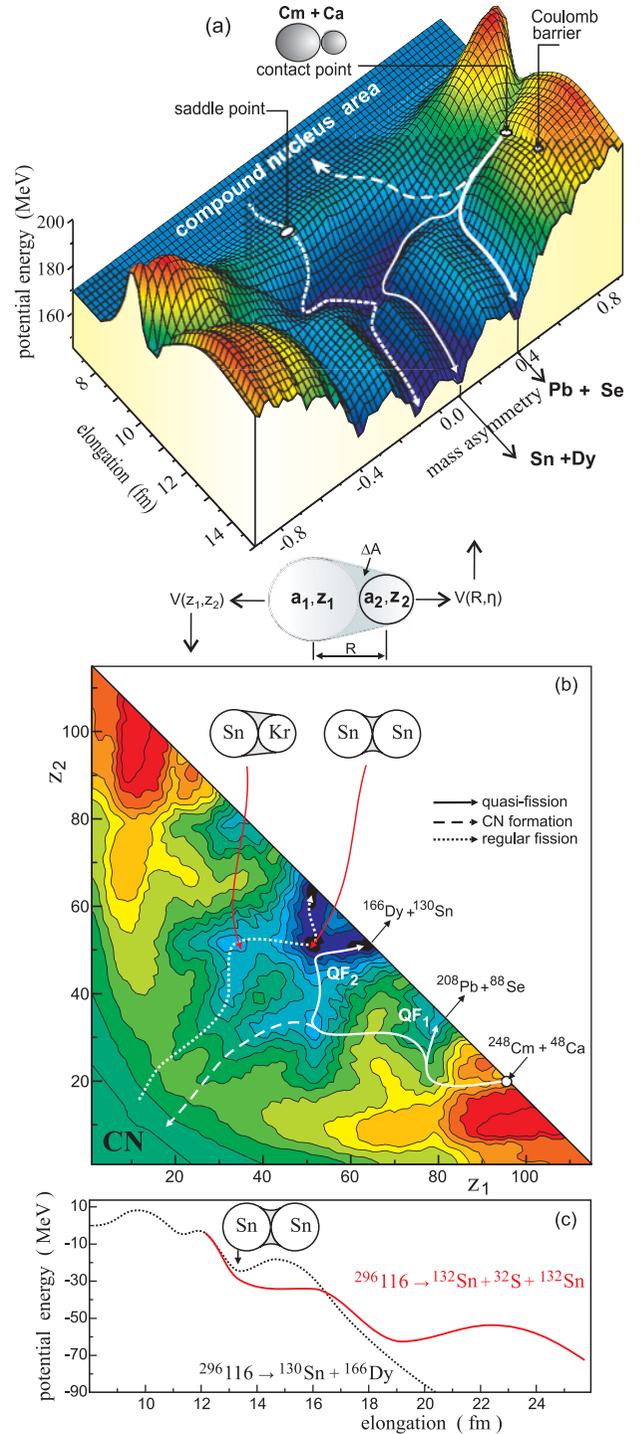


FIG. 3. (Color online) Adiabatic potential energy for nucleus $^{296}116$ formed in collision of ^{48}Ca with ^{248}Cm . (a) Potential energy in the “elongation-mass asymmetry” space. (b) Topographical landscape of the same potential in the (z_1, z_2) plane. Dashed, solid, and dotted curves show the most probable trajectories of fusion, quasi-fission, and regular fission, respectively. The diagonal corresponds to the contact configurations ($R = R_{\text{cont}}$, $z_1 + z_2 = Z_{\text{CN}}$, and $\Delta A = 0$). (c) Potential energy calculated for binary (dotted curve) and symmetric ternary fission of nucleus $^{296}116$.

A three-body clusterization might appear just on the path from the saddle point to scission, where the shared nucleons ΔA may form a third fragment located between the two heavy clusters a_1 and a_2 . In Fig. 2, a schematic view is shown for binary and ternary fission starting from the configuration of the last shape isomeric minimum of the CN consisting of two magic tin cores and about 30 extra (valence) nucleons shared between the two clusters and moving initially in the whole volume of the mononucleus. In the case of two-body fission of the $^{296}116$ nucleus, these extra nucleons gradually pass into one of the fragments with the formation of two nuclei in the exit channel (Sn and Dy in our case—see the fission path in Fig. 3; mass-symmetric fission of the $^{296}116$ nucleus is less favorable). However, there is a chance for these extra nucleons ΔA to concentrate in the neck region between the two cores and to finally form the third fission fragment.

III. TERNARY FISSION OF SUPERHEAVY NUCLEI

There are too many collective degrees of freedom needed for proper description of the potential energy of a nuclear configuration consisting of three deformed heavy fragments. We restricted ourselves by considering the potential energy of a three-body symmetric configuration with two equal cores $a_1 = a_2$ (and, thus, with two equal fragments $A_1 = A_2$ in the exit fission channels). Also we assumed equal dynamic deformations of all the fragments, $\delta_1 = \delta_2 = \delta_3 = \delta$, and used the same shape parametrization for axially symmetric ternary fission as in Ref. [11] (determined by three smoothed oscillator potentials).

The third fragment, a_3 , appears between the two cores when the total elongation of the system, described by the variable R (distance between a_1 and a_2), is sufficiently large to contain all three fragments; that is, $R \geq R(a_1) + 2R(a_3) + R(a_2)$. Finally, we calculated the three-dimensional potential energy $V(R, \delta, A_3)$, trying to find a preferable path for ternary fission and to estimate how much larger the barrier is for three-body decay compared to that for binary fission. For better visualization, the calculated potential energy $V(R, \delta, A_3)$ is plotted as a function of $(R/R_0 - 1) \cos(\alpha_3)$ and $(R/R_0 - 1) \sin(\alpha_3)$ at fixed dynamic deformation $\delta = 0.2$, where $\alpha_3 = \pi A_3/100$ and R_0 is the radius of a sphere of equivalent volume (CN).

The macroscopic (LDM) part of the potential energy for ^{248}Cm is shown in the upper panel of Fig. 4. The binary fission of ^{248}Cm evidently dominates because the potential energy is much steeper after the barrier just in the binary exit channel (bottom right corner, $A_3 \sim 0$). The emission of a light third particle is possible here but not the true ternary fission. The shell correction (which makes the ground state of this nucleus deeper by about 3 MeV) does not distinctively change the total potential energy (see the bottom panel of Fig. 4). The reason is quite simple. For nuclei with $Z < 100$ there is just not enough charge and mass to form two doubly magic tinlike nuclei plus a third heavy fragment. Nevertheless, experiments aimed at the observation of real ternary fission of actinide nuclei (with formation of a heavy third fragment) are currently in progress [12].

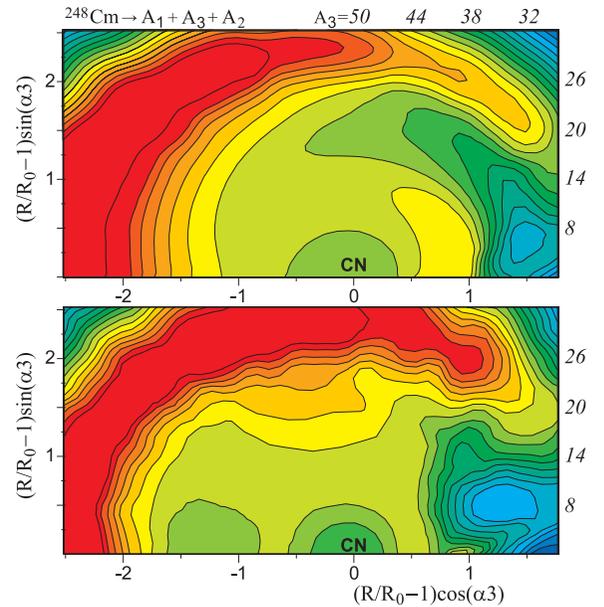


FIG. 4. (Color online) Potential energy for ternary fission of ^{248}Cm . The macroscopic part of the potential energy and the total one (LDM plus shell corrections) are shown in the upper and lower panels, respectively, depending on elongation and mass of the third fragment (italic numbers). Contour lines are drawn over 3 MeV.

In the case of superheavy nuclei, the macroscopic potential energy does not lead to any barrier at all (in neither the binary nor the ternary exit channel) and the stability of these nuclei is determined completely by the shell corrections. In Fig. 5, the calculated potential energy is shown for the superheavy nucleus $^{296}116$. In contrast with ^{248}Cm , in this case a real

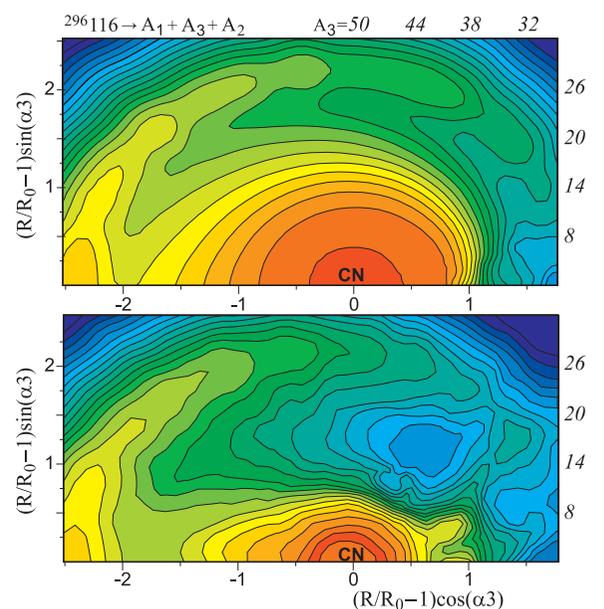


FIG. 5. (Color online) The same as Fig. 4 but for the superheavy nucleus $^{296}116$. Contour lines are drawn over 5 MeV.

possibility for ternary fission appears with formation of the third fragment, $A_3 \sim 30$, and two heavy fragments, $A_1 = A_2 \sim 130$. The ternary fission valley is quite well separated from the binary fission valley by the potential ridge. This means that ternary fission of the $^{296}116$ nucleus into the “tin-sulfur-tin” combination should dominate as compared with other true ternary fission channels of this nucleus.

A more sophisticated consideration of the multidimensional potential energy surface is needed to estimate the “ternary fission barrier” accurately. However, as can be seen from Fig. 5, the height of the ternary fission barrier is not immensely high. It is quite comparable with the regular fission barrier because the ternary fission in fact starts from the configuration of the shape isomeric state, which is located outside the first (highest) saddle point of the superheavy nucleus $^{296}116$ (see the solid curve on the bottom panel of Fig. 3).

IV. TERNARY QUASI-FISSION OF GIANT NUCLEAR SYSTEMS

A similar process of decay onto three doubly magic heavy fragments might also occur for giant nuclear systems formed in low-energy collisions of actinide nuclei, such as $U + U$. In this case, a compound nucleus may hardly be formed, and such decay is, in fact, a quasi-fission process. Conditions for the three-body decay are even better here, because the shell effects significantly reduce the potential energy of the three-cluster configurations with two strongly bound leadlike fragments. In Fig. 6, the landscape of the potential energy surface is shown for a three-body clusterization of the nuclear system formed in the $U + U$ collision. Here the potential energy was calculated as a function of three variables (Z_1 , Z_3 , and R) at fixed (equal) deformations of the fragments being in contact ($R_1 + 2R_3 + R_2 = R$). To make the result quite visible, we minimized the potential energy over the neutron numbers of the fragments, N_1 and N_3 .

As can be seen, the giant nuclear system, consisting of two touching uranium nuclei, may split into the two-body exit channel with formation of a leadlike fragment and complementary superheavy nucleus (the so-called antisymmetrizing quasi-fission process, which may lead to an enhanced yield of SH nuclei in multinucleon transfer reactions [13]). Besides

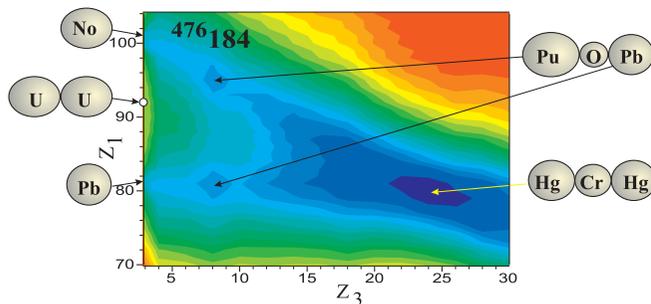


FIG. 6. (Color online) Landscape of potential energy of three-body configurations formed in collision of $^{238}\text{U} + ^{238}\text{U}$.

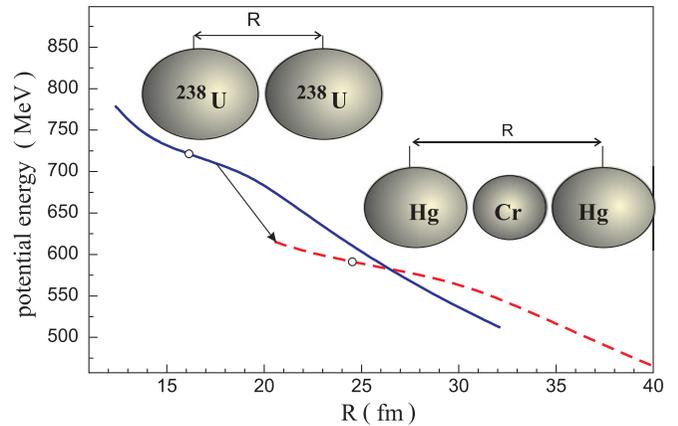


FIG. 7. (Color online) Radial dependence of the potential energy of two uranium nuclei (solid curve) and of the three-body nuclear configuration formed in the $^{238}\text{U} + ^{238}\text{U}$ collision (dashed curve).

the two-body Pb-No clusterization and the shallow local three-body minimum with formation of light intermediate oxygen-like cluster, the potential energy has a very deep minimum corresponding to the Pb-Ca-Pb-like configuration (or Hg-Cr-Hg) caused by the $N = 126$ and $Z = 82$ nuclear shells.

V. SUMMARY

Thus, we found that for superheavy nuclei the three-body clusterization (and, hence, real ternary fission with a heavy third fragment) is quite possible. The simplest way to discover this phenomenon is a detection of two tin- or xenon-like clusters in low-energy collisions of medium-mass nuclei with actinide targets, for example, in the $^{64}\text{Ni} + ^{238}\text{U}$ reaction. These unusual decays could also be searched for among the spontaneous fission events of superheavy nuclei [7]. In case it is discovered, it will be a new kind of radioactivity.

The extreme clustering process of formation of two leadlike doubly magic fragments in collisions of actinide nuclei is also a very interesting subject for experimental study. Such measurements, in our opinion, are not too difficult. It is sufficient to detect two coincident leadlike ejectiles (or one leadlike fragment and one calcium-like fragment) in $U + U$ collisions to conclude unambiguously about the ternary fission of the giant nuclear system. Greater flat radial dependence of the potential energy (as compared with a two-body system) is another feature of the three-body clusterization (see Fig. 7). This means that decay of a $(U + U)$ -like nuclear system into the energetically preferable (and more stable in some sense) three-body configurations may also significantly prolong the reaction time, which (among other things) could be important for spontaneous positron formation in a superstrong electric field.

ACKNOWLEDGMENTS

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