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# Superheavy nuclei and quasi-atoms produced in collisions of transuranium ions

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Low energy collisions of very heavy nuclei ($^{238}$U+$^{238}$U, $^{232}$Th+$^{250}$Cf, and $^{238}$U+$^{248}$Cm) have been studied within the realistic dynamical model based on multidimensional Langevin equations. Large charge and mass transfer was found to result from the "inverse quasi-fission" process leading to the formation of the surviving superheavy long-lived neutron-rich nuclei. In many events, the lifetime of the composite system consisting of two touching nuclei turns out to be rather long; sufficiently long for the spontaneous formation of positrons to occur from a super-strong electric field—a fundamental QED process.

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Superheavy (SH) nuclei obtained in "cold" fusion reactions with a Pb or Bi target [1] occur along the proton drip line and are very neutron-deficient with a short half-life. In the fusion of actinides with $^{48}$Ca, more neutron-rich SH nuclei are produced [2] with much longer half-lives. But they are still far from the center of the predicted "island of stability" formed by the neutron shell around $N = 184$. In cold fusion, the cross sections of SH nuclei formation decrease very fast with increasing charge of the projectile and become less than 1 pb for $Z > 112$. The heaviest transactinide, Cf, which can be used as a target in the second method, leads to the SH nucleus with $Z = 118$ being fused with $^{48}$Ca. Using the next nearest elements instead of $^{48}$Ca (e.g., $^{50}$Ti, $^{54}$Cr, etc.) in fusion reactions with actinides is expected to be less encouraging, though experiments of such kind are being planned. In this regard, other ways to produce SH elements in the region of the island of stability should be searched for.

About 20 years ago, transfer reactions of heavy ions with a $^{248}$Cm target were evaluated for their usefulness in producing unknown neutron-rich actinide nuclides [3,4]. The cross sections were found to decrease very rapidly with increasing atomic number of the surviving targetlike fragments. However, Fm and Md neutron-rich isotopes were produced at the level of 0.1 $\mu$b. Theoretical estimations for the production of primary superheavy fragments in the damped U+U collision have also been performed, this time within the semiphenomenological diffusion model [5]. In spite of the high probabilities obtained for the yields of superheavy primary fragments (more than $10^{-2}$ mb for $Z = 120$), the cross sections for the production of heavy nuclei with low excitation energies were estimated to be very small. The authors concluded, however, that "fluctuations and shell effects not taken into account may considerably increase the formation probabilities."

In this Rapid Communication, we study the processes of low energy collisions of very heavy nuclei (such as U+Cm) within the recently proposed model of fusion-fission dynamics [6]. The purpose is to determine the influence of the nearest closed shells $Z = 82$ and $N = 126$ (formation of $^{208}$Pb as one of the primary fragments) on nucleon rearrangement between primary fragments. We try to estimate how large the charge and mass transfer could be in these reactions and what the cross sections are for the production of surviving neutron-rich SH nuclei. Direct time analysis of the collision process allows us to estimate also the lifetime of the composite system consisting of two touching heavy nuclei with total charge $Z > 180$. Such "long-lived" configurations may lead to spontaneous positron emission from the super-strong electric field of quasi-atoms by a static QED process (transition from neutral to charged QED vacuum) [7,8]. The lifetime of SH composites formed in Au+Au collisions at above barrier energies was estimated recently within the molecular dynamics model [9] and found to be rather long.

Besides the distance between the nuclear centers $R$, the mass transfer $\alpha = (A_1 - A_2)/(A_1 + A_2)$ and dynamic deformations of nuclear surfaces $\beta$ play a most important role in fusion-fission and deep inelastic processes of low energy heavy ion collisions. The corresponding multidimensional adiabatic potential energy surface was calculated here within the semi-empirical two-core approach [10] based on the two-center shell model [11]. Projections onto the $R$-$\alpha$ and $R$-$\beta$ planes of the three-dimensional potential energy are shown in Fig. 1 for the nuclear system formed in the collision of $^{232}$Th+$^{250}$Cf. There is no potential pocket typical for lighter systems; the potential is repulsive everywhere. However, the potential energy is not so steep in the region of contact point, and two nuclei may keep in contact for a long time, increasing their deformations and transferring nucleons to each other (see below).

We studied the whole dynamics of such a nuclear system by numerical solution of the coupled Langevin-type equations of motion, inertialess motion along the mass-asymmetry coordinate was derived from just the corresponding master equation for nucleon transfer [6]. The inertia parameters $\mu_R$ and $\mu_\beta$ were calculated within the Werner-Wheeler approach [13]. Parameters of the friction forces and nucleon transfer rate were taken from Ref. [6], where they were estimated from the successful description of experimental regularities of heavy ion deep inelastic scattering and fusion-fission reactions. Damping of the shell effects by the excitation energy was taken into account in the level density parameter both on the dynamic stage of the reaction and in statistical treatment of decay of the primary fragments.

 

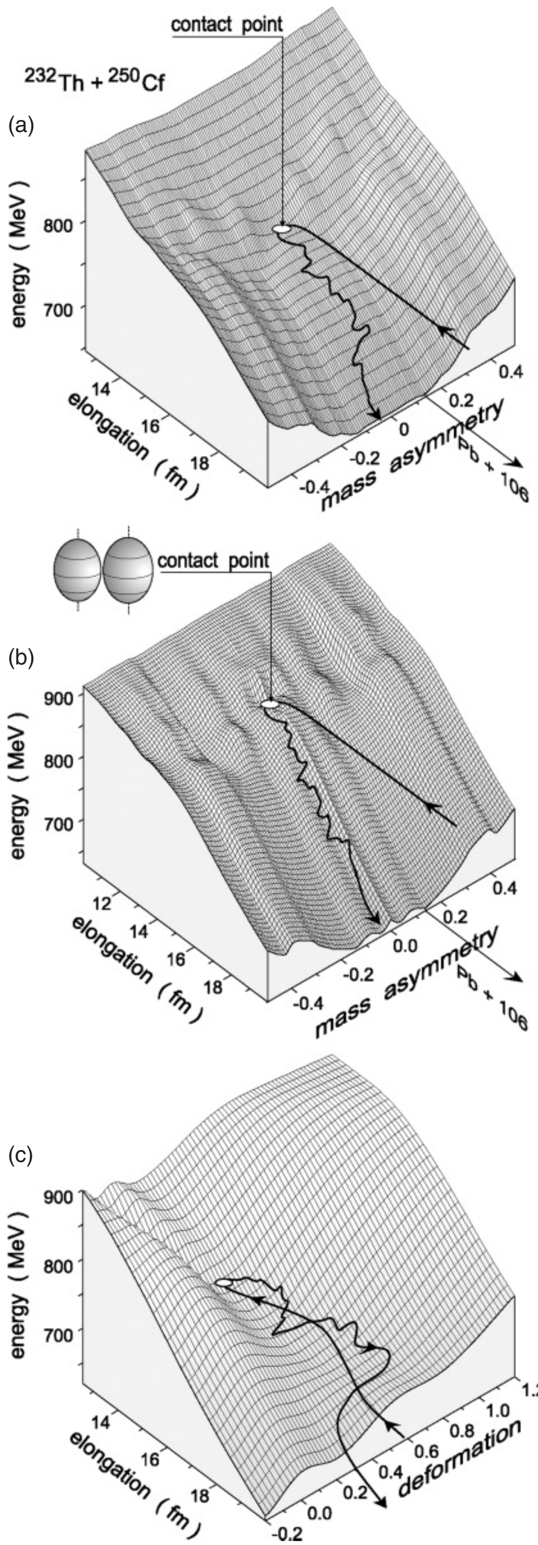


FIG. 1. Potential energy surface for the nuclear system formed by $^{232}$Th+$^{250}$Cf as a function of $R$ and $\alpha$ ($\beta = 0.22$) for nose-to-nose (a) and side-by-side (b) orientations, and as a function of $R$ and $\beta$ ($\alpha = 0.037$) (c). Typical trajectories are shown by the thick curves with arrows. Before nuclei reach the region of nuclear friction forces, they are in their ground states (zero temperature) and no fluctuations occur. However, when nuclei come in contact, they are already well excited and fluctuations play a significant role [12].

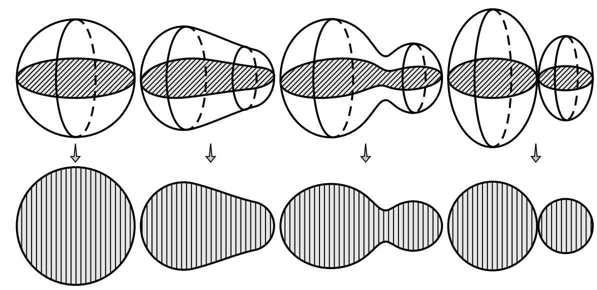

FIG. 2. Back and top views (upper and bottom figures) of subsequent shapes of the nuclear system evolving from the configuration of two equatorially touching statically deformed nuclei to the configuration of spherical CN.

The orientation effects play a rather important role in the subbarrier fusion of deformed nuclei. However, it is not so easy to define the adiabatic potential energy for the case of two touching arbitrary oriented deformed nuclei. The main difficulty here is a determination of unknown subsequent intermediate shapes of the nuclear system and a calculation of the macroscopic and microscopic parts of the total energy for these shapes. Moreover, additional degrees of freedom are definitely needed to describe these complicated shapes. The standard two-center shell model, as well as other macromicroscopic models, deal only with axially symmetric shapes.

Within the two-core model, we may calculate the adiabatic potential energy also for the side-by-side initial orientation assuming that on the way to compound nucleus (CN) only the equatorial dynamic deformations of both fragments may change, whereas the static deformations of the cores (along axes perpendicular to the line connecting two centers) gradually relax to zero values with increasing equatorial deformation and mass transfer, see schematic Fig. 2. This assumption seems quite reasonable because there are no forces which may change the "perpendicular" deformations of the fragments. In that case, we need no additional degrees of freedom. The same variables $\beta_1$ and $\beta_2$ may be used for dynamic deformations along the axis between nuclear centers ($\beta_{1,2} = 0$ at contact). We assume that the static deformations of the nuclei just gradually disappear with increasing mass transfer and dynamic equatorial deformations: $\beta^{\perp}_{1,2} = \beta^{\perp}_{1,2}(0)\exp[-(\frac{\alpha-\alpha_0}{\Delta_\alpha})^2]\exp[-(\frac{\beta_{1,2}}{\Delta_\beta})^2]$. Thus, they are not independent variables. Here $\alpha_0$ is the initial mass asymmetry, $\beta^{\perp}_{1,2}(0)$ are the static deformations of the projectile and target, and $\Delta_\alpha \sim 10/A_{\rm CN}$ and $\Delta_\beta \sim 0.2$ are the adjusted parameters which do not much influence the whole dynamics. Found in such a way, the potential energy surface for the side-by-side initial configuration is shown in Fig. 1(b). It is rather difficult (if possible at all) to derive adiabatic potential energy of the nuclear system evolving from the configuration of arbitrary oriented touching deformed nuclei. In contrast, the diabatic potential energy is calculated easily in that case by using the double folding procedure, for example. To take into account the orientation effect in the cross sections, we just averaged the results obtained for the two limiting orientations.

The cross sections are calculated in a natural way. A large number of events (trajectories) are tested for a given

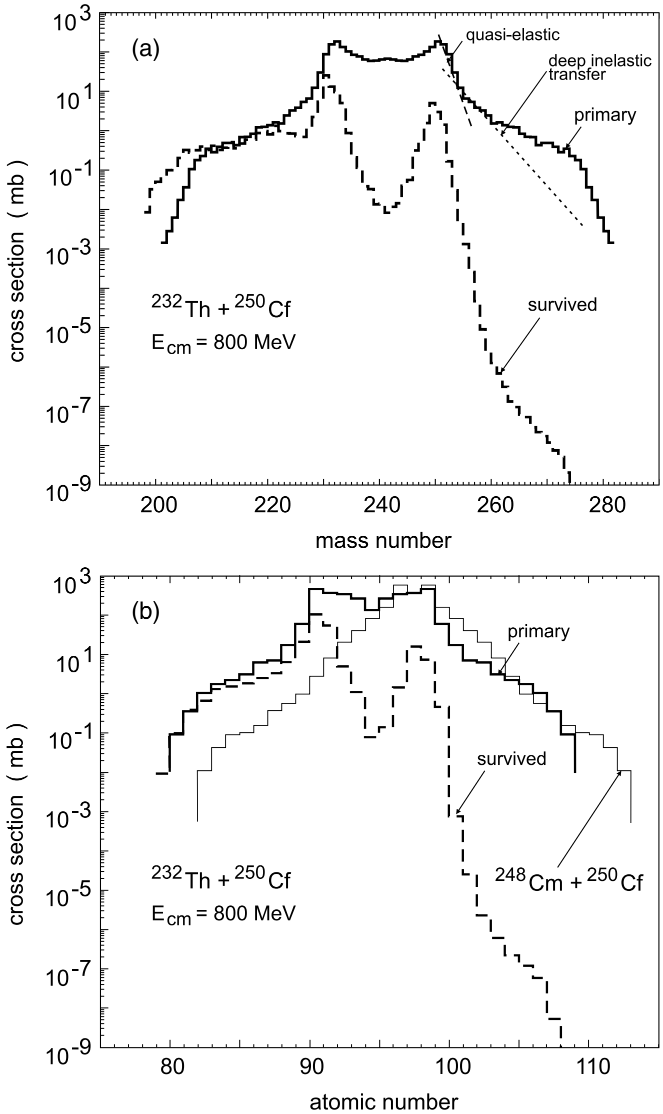


FIG. 3. Mass (a) and charge (b) distributions of primary (solid histograms) and survived (dashed histograms) fragments in the $^{232}$Th+$^{250}$Cf collision at c.m. energy of 800 MeV. Thin solid histogram in (b) shows the primary fragment distribution in the hypothetical reaction $^{248}$Cm+$^{250}$Cf.

impact parameter. Each event in studied reactions ends in the exit channel with two excited primary fragments. The corresponding double differential cross section is calculated as follows:

$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \frac{\Delta N_\alpha(b,E,\theta)}{N_{\rm tot}(b)} \frac{1}{\sin(\theta)\Delta\theta\Delta E}. \quad (1)$$

Here, $\Delta N_\alpha(b, E, \theta)$ is the number of events at a given impact parameter $b$ in which the system enters into the channel $\alpha$ with kinetic energy in the region $(E, E + \Delta E)$ and the center-of-mass outgoing angle in the region $(\theta, \theta + \Delta\theta)$, and $N_{\rm tot}(b)$ is the total number of simulated events for a given value of impact parameter.

The expression (1) describes the energy, angular, charge, and mass distributions of the *primary* fragments formed in the reaction. Subsequent deexcitation of these fragments via fission or emission of light particles and $\gamma$ rays was taken into account within the statistical model leading to the *final* fragment distributions. The sharing of the excitation energy between the primary fragments was assumed to be proportional to their masses. These fragments also possess some definite deformations at scission configuration. We assumed that the dynamic deformation relaxed rather fast to the ground state deformation (faster than neutron evaporation) and simply added the deformation energy to the total excitation energy of a given nucleus. Neutron emission during an evolution of the system was also taken into account. However, we found that the preseparation neutron evaporation does not influence significantly the final distributions.

Found in that way, mass and charge distributions of the primary and surviving fragments formed in the $^{232}$Th+$^{250}$Cf collision at 800 MeV center-of-mass energy are shown in Fig. 3. The pronounced shoulder can be seen in the mass distribution of the primary fragments near the mass number $A = 208$. It could be explained by existence of noticeable valley on the potential energy surface [see Fig. 1(a)], which corresponds to the formation of the doubly magic nucleus $^{208}$Pb ($\alpha = 0.137$). The emerging of the nuclear system into this valley resembles the well-known quasi-fission process and may be called "inverse (or antisymmetrizing) quasi-fission" (the final mass asymmetry is larger than the initial one). For $\alpha > 0.137$ (one fragment becomes lighter than lead), the potential energy sharply increases and the mass distribution of the primary fragments falls down rapidly at $A < 208$ ($A > 274$). The same is true for the charge distribution at $Z < 82\,(Z > 106)$. As a result, in the charge distribution of the heavy fragments that survived, Fig. 3(b), a shoulder also occurs at $Z = 106$, and the yield of nuclei with $Z > 107$ was found in this reaction at the level of less than 1 pb. This result differs sharply from those obtained within the diffusion model [5], where the yield of heavy primary fragments decreases slowly and monotonically with increasing charge number.

In Fig. 4, the available experimental data on the yield of SH nuclei in collisions of $^{238}$U+$^{238}$U [14] and $^{238}$U+$^{248}$Cm [3] are compared with our calculations. In these experiments, thick targets were used, which means that the experimental

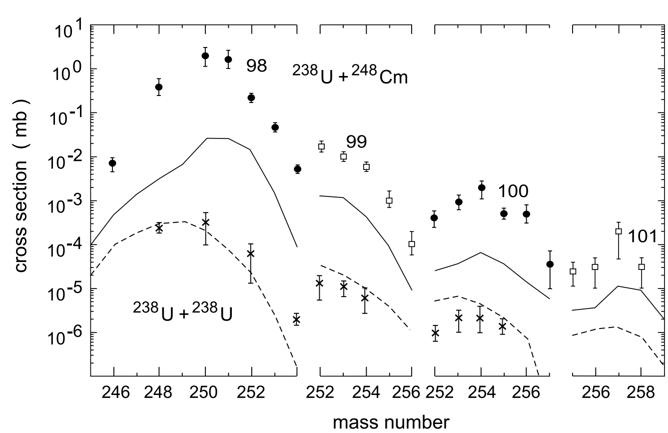


FIG. 4. Isotopic yield of the elements 98–101 in the reactions $^{238}$U+$^{238}$U (crosses) [14] and $^{238}$U+$^{248}$Cm (circles and squares) [3]. Curves show the results of our calculations.

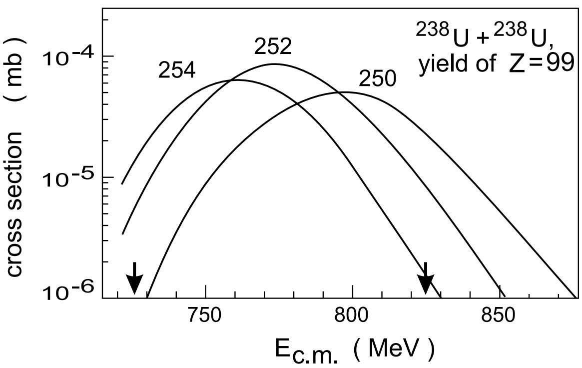


FIG. 5. Excitation functions for the yields of Es isotopes (numbers near the curves) for the $^{238}$U+$^{238}$U reactions. The arrows indicate potential energy of two nuclei in contact ($r_0 = 1.16$ fm) for tip (left) and side (right) configurations.

data were, in fact, integrated over the energy in the region of about 750–850 MeV [3,14]. The estimated excitation functions for the yield of heavy surviving nuclei, shown in Fig. 5, demonstrate not so sharp dependence on beam energy as in fusion reactions but still rather strong one. In spite of that, the agreement of our calculations with experimental data is quite acceptable (worse for few-nucleon transfer and better for massive transfer processes).

The estimated isotopic yields of SH nuclei in the $^{232}$Th+$^{250}$Cf, $^{238}$U+$^{238}$U, and $^{238}$U+$^{248}$Cm collisions at 800 MeV c.m. energy are shown in Fig. 6. Thus, there is a real chance for production and chemical study of the long-lived neutron-rich SH nuclei up to $^{274}_{107}$Bh produced in the reaction $^{232}$Th+$^{250}$Cf. As can be seen from Figs. 5 and 6, the yield

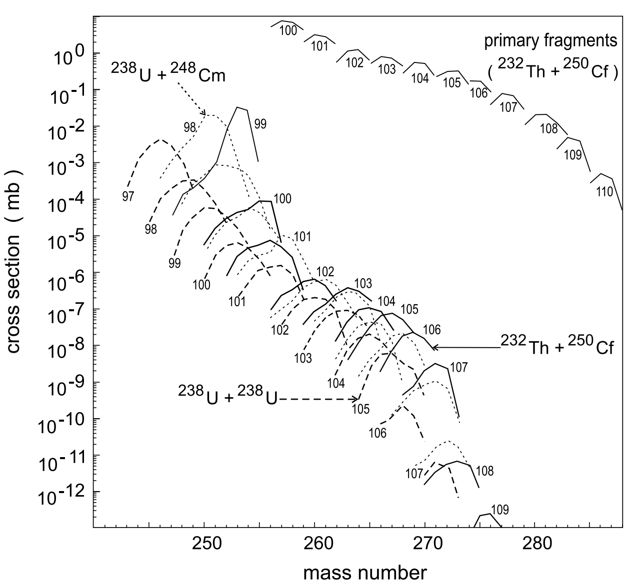


FIG. 6. Yield of superheavy nuclei in collisions of $^{238}$U+$^{238}$U (dashed), $^{238}$U+$^{248}$Cm (dotted), and $^{232}$Th+$^{250}$Cf (solid lines) at 800 MeV c.m. energy. Solid curves in upper part show isotopic distribution of primary fragments in the Th+Cf reaction. In the case of U+Cm, only the upper curve is marked by $Z$ number ($Z = 98$); curves for the other reactions are marked one by one up to $Z = 107$.

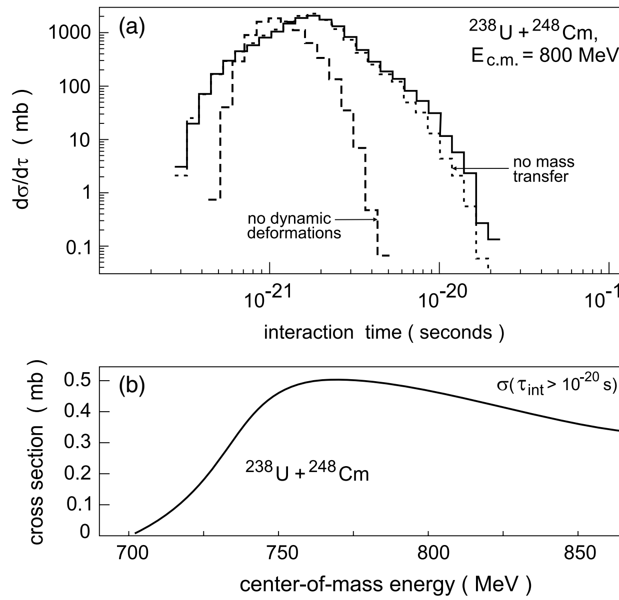


FIG. 7. (a) Reaction time distribution for the $^{238}$U+$^{248}$Cm collision at 800 MeV c.m. energy. Dashed and dotted histograms show the effect of switching off dynamic deformations or mass transfer, respectively. (b) Cross section for events with interaction time longer than $10^{-20}$ s depending on beam energy.

of SH elements in damped reactions depends strongly on beam energy and on nuclear combination, which should be chosen carefully. In particular, Fig. 3 shows the estimated yield of the primary fragments obtained in the hypothetical reaction $^{248}$Cm+$^{250}$Cf (both constituents are radioactive), demonstrating a possibility for production of SH neutron-rich nuclei up to the element 112 (complementary to lead fragments in this reaction).

The time analysis of the reactions studied shows that in spite of a nonexisting attractive potential pocket, the system consisting of two very heavy nuclei may hold in contact rather long in some cases. During this time, it moves over a multidimensional potential energy surface with almost zero kinetic energy (result of large nuclear viscosity); a typical trajectory is shown in Fig. 1. The total reaction time distribution, $\frac{d\sigma}{d\log(\tau)}$ ($\tau$ denotes the time after the contact of two nuclei), is shown in Fig. 7 for the $^{238}$U+$^{248}$Cm collision. We found that the dynamic deformations were mainly responsible for the time delay of the nucleus-nucleus collision. Ignoring the dynamic deformations in the equations of motion significantly decreases the reaction time, whereas the nucleon transfer has less influence on the time distribution, see Fig. 7(a).

As mentioned above, the lifetime of a giant composite system more than $10^{-20}$ s is quite enough to expect for spontaneous $e^+e^-$ production from the strong electric field as a fundamental QED process ("decay of the vacuum") [7,8]. The absolute cross section for long events ($\tau > 10^{-20}$ s) was found to be maximal just at the beam energy ensuring two nuclei to be in contact, see Fig. 7(b). Note that the same energy is also optimal for production of the most neutron-rich SH nuclei (Fig. 5). Of course, there are some uncertainties in the parameters

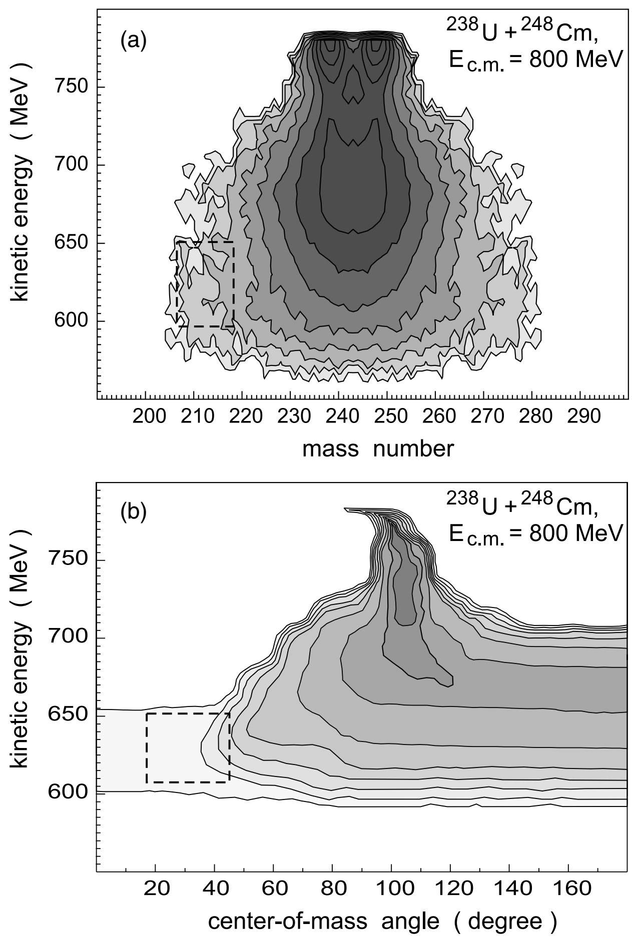


FIG. 8. Energy-mass (a) and energy-angular (b) distributions of primary fragments in the $^{238}$U+$^{248}$Cm collision at 800 MeV ($E_{\text{loss}} >$ 15 MeV) and logarithmic landscape of the corresponding double differential cross sections. Lines are drawn over each half order of magnitude. Dashed rectangles show regions of longest events.

used, mostly in the value of nuclear viscosity. However, we found only a linear dependence of the reaction time on the strength of nuclear viscosity, which means that the obtained reaction time distribution is rather reliable; see the logarithmic scale on both axes in Fig. 7(a).

Formation of the background positrons in these reactions forces one to find some additional trigger for the longest events. Such long events correspond to the most damped collisions with formation of mostly excited primary fragments decaying by fission. However, there is also a chance for production of primary fragments in the region of doubly magic nucleus $^{208}$Pb, which could survive against fission because of nucleon evaporation, see Figs. 8(a) and 3. The number of the longest events depends weakly on impact parameter up to some critical value. On the other hand, in the angular distribution of all the excited primary fragments (strongly peaked at the c.m. angle slightly larger than 90°), there is the rapidly decreasing tail at small angles, see Fig. 8(b). Thus the detection of the surviving nuclei in the lead region at c.m. angles less than 60° could be a definite witness of a long reaction time.

In summary, the production of long-lived neutron-rich SH nuclei in collisions of transuranium ions seems to be quite possible because of the large mass and charge rearrangement in the "inverse quasi-fission" process caused by the $Z = 82$ and $N = 126$ nuclear shells. Radiochemical identification of $^{267,268}$Db isotopes, produced in the U+Cm or Th+Cf reactions, could be performed, for example, to test this conclusion. If the found cross section were to be higher than 10 pb, then the subsequent experiments with such reactions could be aimed at the production of SH nuclei just in the region of the island of stability. A parallel search for spontaneous positron emissions from a supercritical electric field of long-lived quasi-atoms formed in these reactions is also quite promising.

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[1] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
[2] Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, 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, A. A. Voinov, G. V. Buklanov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, D. A. Shaughnessy, J. M. Kenneally, P. A. Wilk, R. W. Lougheed, R. I. Il'kaev, and S. P. Vesnovskii, Phys. Rev. C **70**, 064609 (2004).
[3] M. Schädel, W. Brüchle, H. Gäggeler, J. V. Kratz, K. Sümmerer, G. Wirth, G. Herrmann, R. Stakemann, G. Tittel, N. Trautmann, J. M. Nitschke, E. K. Hulet, R. W. Lougheed, R. L. Hahn, and R. L. Ferguson, Phys. Rev. Lett. **48**, 852 (1982).
[4] K. J. Moody, D. Lee, R. B. Welch, K. E. Gregorich, G. T. Seaborg, R. W. Lougheed, and E. K. Hulet, Phys. Rev. C **33**, 1315 (1986).
[5] C. Riedel and W. Nörenberg, Z. Phys. A **290**, 385 (1979).
[6] V. Zagrebaev and W. Greiner, J. Phys. G **31**, 825 (2005).
[7] J. Reinhard, U. Müller, and W. Greiner, Z. Phys. A **303**, 173 (1981).
[8] *Quantum Electrodynamics of Strong Fields*, edited by W. Greiner (Plenum, New York, 1983); W. Greiner, B. Müller, and J. Rafelski, *QED of Strong Fields*, 2nd ed. (Springer, Berlin, 1985).
[9] T. Maruyama, A. Bonasera, M. Papa, and S. Chiba, Eur. Phys. J. A **14**, 191 (2002).
[10] V. I. Zagrebaev, Phys. Rev. C **64**, 034606 (2001); in *Tours Symposium on Nuclear Physics V*, AIP Conf. Proc., No. 704, edited by M. Arnould *et al*. (AIP, New York, 2004), p. 31.
[11] U. Mosel, J. Maruhn, and W. Greiner, Phys. Lett. **B34**, 587 (1971); J. Maruhn and W. Greiner, Z. Phys. **251**, 431 (1972).
[12] C. Shen, G. Kosenko, and Y. Abe, Phys. Rev. C **66**, 061602(R) (2002).
[13] F. G. Werner and J. A. Wheeler (unpublished); K. T. R. Davies, A. J. Sierk, and J. R. Nix, Phys. Rev. C **13**, 2385 (1976).
[14] M. Schädel, J. V. Kratz, H. Ahrens, W. Brüchle, G. Franz, H. Gäggeler, I. Warnecke, G. Wirth, G. Herrmann, N. Trautmann, and M. Weis, Phys. Rev. Lett. **41**, 469 (1978).