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Reviews

Long-Lived Superheavy Nuclei and Giant Quasi-Atoms Produced in Damped Collisions of Transactinides

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Damped collisions of tranactinide nuclei (^{238}U + ^{238}U, ^{232}Th + ^{250}Cf, and ^{238}U + ^{248}Cm) have been studied within the realistic model based on solution of multidimensional transport equations. Large charge and mass transfer was found in these reactions due to the inverse (anti-symmetrizing) quasi-fission process leading to formation of survived superheavy long-lived neutron-rich nuclei, suitable for subsequent chemical analysis. In many events lifetime of the composite system consisting of two touching nuclei (giant quasi-atoms) turns out to be rather long; sufficient for spontaneous positron formation from super-strong electric field, a fundamental QED process.

1. Introduction

Damped collisions between very heavy nuclei were studied extensively about twenty years ago. Among others, there had been a great deal of interest in the use of heavy-ion transfer reactions with actinide targets to produce new nuclear species in the transactinide region.[1–5] The cross sections were found to decrease very rapidly with increasing atomic number of surviving target-like fragments. However, Fm and Md neutron-rich isotopes have been produced at the level of 0.1 μb. Note that superheavy (SH) nuclei obtained in "cold" fusion reactions with Pb or Bi target[6] are along the proton drip line and very neutron-deficient with a short half-life. In fusion of actinides with ^{48}Ca more neutron-rich SH nuclei are produced[7] with much longer half-life. But they are still far from the center of the predicted first "island of stability" formed by the neutron shell around N=184 (see the nuclear map in Figure 1). In the "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. 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 less encouraging, though experiments of such kind are planned to be performed. In this connection another ways to the production of SH elements in the region of the "island of stability" should be searched for.

One more effect, which may be expected in the damped collisions of transactinides, is a formation of giant quasi-atoms with a nucleus consisting of two closely located heavy nuclei. If the lifetime of the composite nuclear system with total charge Z>173 is rather long (~10^{-20}s) we may expect a spontaneous positron emission from superstrong electric field of quasi-atoms by a static QED process (transition from neutral to charged QED vacuum)[8,9] (see Figure 2). About twenty years ago a search for such effect were carried out and narrow line structures in the positron spectra were first reported at GSI. Unfortunately these results were not confirmed later, neither in ANL,[10] nor in new experiments performed at GSI[11,12] (see also hierarchical references therein). Thus the situation remains unclear, while the experimental efforts in this field have ended. We hope that a new analysis, performed within a realistic dynamical model, may shed additional light on this problem and also answer the principal question: are there some reaction features (triggers) testifying to a long reaction delay? If they are, a new experiment could be planned to detect the positrons in the specific reaction channels.

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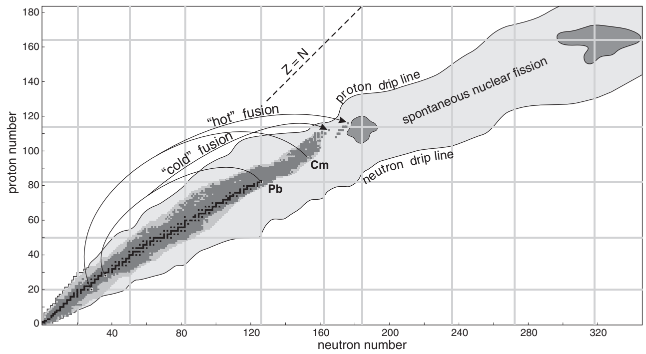

Figure 1. Nuclear map. Predicted islands of stability are shown around Z=114, N=184 and Z=164, N=318. Neither in "cold" nor in "hot" fusion reactions with stable nuclei these islands can be reached due to insufficient neutron number.

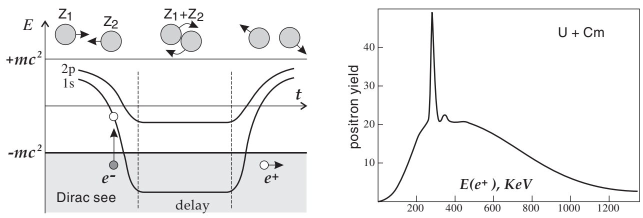

Figure 2. Schematic figure of spontaneous decay of the vacuum and spectrum of the positrons formed in supercritical electric field (Z_1 + Z_2 > 173), in which 1s-state of the quasi-atom finds itself in the Dirac's sea.

Recently a new model has been proposed[13] for simultaneous description of strongly coupled reaction channels of heavy ion collisions: deep inelastic (DI) scattering, quasi-fission (QF), fusion, and regular fission. Reasonable agreement of our first calculations with experimental data on low-energy DI and QF reactions induced by heavy ions[13] stimulated us to study the reaction dynamics of very heavy transactinide nuclei. The purpose is to find an influence of the shell structure of the driving potential (in particular, deep valley caused by the double shell closure Z=82 and N=126) on nucleon rearrangement between

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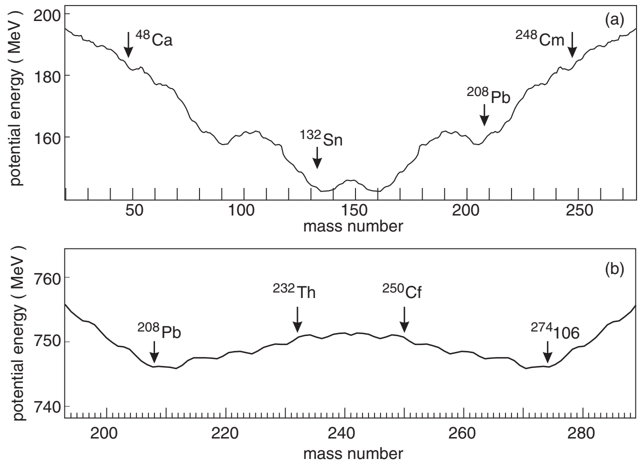

Figure 3. Potential energy at contact "nose-to-nose" configuration for two nuclear systems formed in ^{48}Ca + ^{248}Cm (a) and ^{232}Th + ^{250}Cf (b) collisions. Spheroidal deformation is equal 0.2.

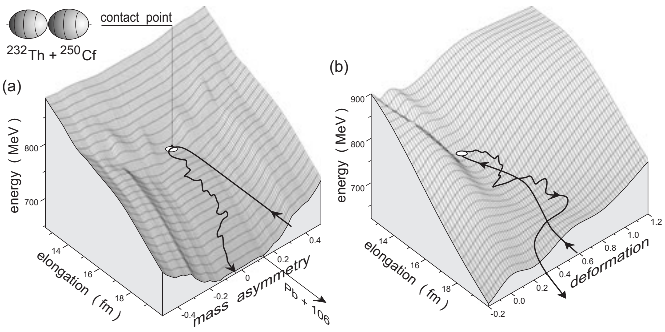

Figure 4. Potential energy surfaces for the nuclear system formed by ^{232}Th + ^{250}Cf as a function of R and α (β = 0.22) (a), and R and β (α = 0.037) (b). Typical trajectory is shown by the curves with arrows.

primary fragments. In Figure 3 the potential energies are shown depenting on mass rearrangement at contact configuration of the nuclear systems formed in ^{48}Ca + ^{248}Cm and ^{232}Th + ^{250}Cf collisions. In the first case (^{48}Ca + ^{248}Cm), discharge of the system into the lead valley (normal or symmetrizing quasi-fission) is the main reaction channel, which decreases significantly the probability of compound nucleus formation. In collisions of heavy nuclei (Th + Cf, U + Cm and so on) we expect that an existence of this valley may noticeably increase the yield of surviving neutron-rich superheavy nuclei complementary to the projectile-like fragments around ^{208}Pb ("inverse" or anti-symmetrizing quasi-fission process). 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 (if they exist) may lead to spontaneous positron emission from super-strong electric field of quasi-atoms by a static QED process.

2. Damped collisions of heavy ions

The distance between the nuclear centers R (corresponding to the elongation of a mono-nucleus), dynamic spheroidal-type surface deformations β_1 and β_2, mutual orientations of deformed nuclei φ_1 and φ_2, and mass asymmetry $\alpha = \frac{A_1 - A_2}{A_1 + A_2}$ are probably the relevant degrees of freedom to describe properly low-energy fusion-fission dynamics of heavy nuclear system. For the re-separation stage in the exit channel neck formation should be included to describe properly mass and energy distributions of the fission fragments. To avoid increasing the number of degrees of freedom the necking process was taken into account in a phenomenological way using different radial form-factors for the friction forces in the entrance and exit channel ($R^{\rm out}_{\rm scission} > R^{\rm in}_{\rm contact} = R_1(A_1, \beta_1, \varphi_1) + R_2(A_2, \beta_2, \varphi_2)$).

The corresponding multi-dimensional adiabatic potential energy surface was calculated here within the semi-empirical two-core approach[14] based on the two-center shell model.[15] Projections onto the $R - \alpha$ and $R - \beta$ planes of the three-dimensional potential energy are shown in Figure 4 for the nuclear system formed in 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 much steep in the region of contact point and two nuclei may keep in contact for a long time increasing their deformations and transfering 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 just from the corresponding master equation for nucleon transfer.[13] The inertia parameters μ_R and μ_β were calculated within the Werner-Wheeler approach.[16] Parameters of the friction forces and nucleon transfer rate were taken from Reference 13, where they have been estimated from successful description of experimental regularities of heavy ion deep inelastic scattering and fusion-fission reactions. Damping of the shell effects due to the excitation energy has been 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.

The cross sections are calculated in a natural way. A large number of events (trajectories) are tested for a given 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 α with kinetic energy in the region (E, $E + \Delta E$) and center-of-mass outgoing angle in the region (θ, $\theta + \Delta\theta$), and $N_{\rm tot}(b)$ is the total number of simulated events for a given value of impact parameter, b.

The expression (1) describes the energy, angular, charge, and mass distributions of the *primary* fragments formed in the reaction. Subsequent de-excitation 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. Neutron emission during an evolution of the system was also taken into account. However, it was found that the pre-separation neutron evaporation does not influence significantly the final distributions.

3. Superheavy nuclei produced in collisions of transactinides

In Figure 5 the available experimental data on the yield of SH nuclei in collisions of ^{238}U + ^{238}U [2] and ^{238}U + ^{248}Cm [3] are compared with our calculations. In these experiments thick targets have been used, which means that the experimental data were, in fact, integrated over the energy in the region of about 750–850 MeV.[2,3] The estimated excitation functions for the yield of heavy surviving nuclei demonstrate not so sharp as in fusion reactions but still rather strong dependence on beam energy. In spite of that, the agreement of our calculations with experimental data is quite acceptable (slightly worse for few-nucleon transfer and better for massive transfer processes).

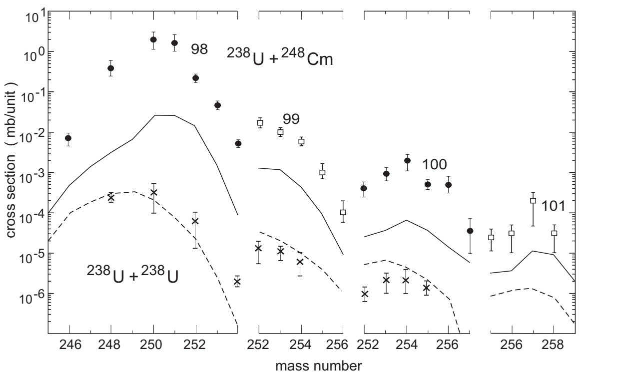

Figure 5. Isotopic yield of the elements 98−101 in the reactions $^{238}U+^{238}U$ (crosses)[2] and $^{238}U+^{248}Cm$ (circles and squares).[3] The curves show the result of our calculations.

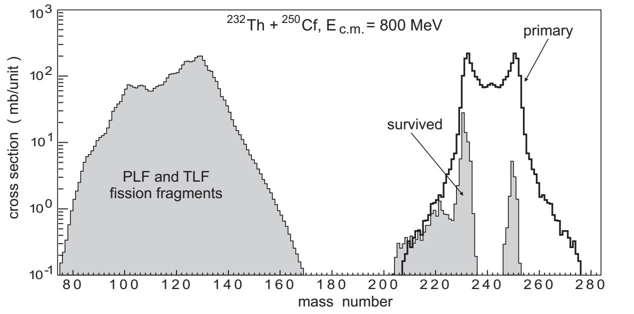

Figure 6. Mass distributions of primary (solid histograms), survived and sequential fission fragments (hatched areas) in the $^{232}Th+^{250}Cf$ damped collisions at 800 MeV center-of-mass energy.

Using the same parameters of nuclear viscosity and nucleon transfer rate we calculated the yield of primary and survived fragments formed in the $^{232}Th+^{250}Cf$ collision at 800 MeV center-of-mass energy. Low fission barriers of the colliding nuclei and of the most of reaction products conjointly with rather high excitation energies of them in the exit channel must lead to very low yield of survived heavy fragments. Indeed, sequential fission of the projectile-like and target-like fragments dominate in these collisions, see Figure 6. At first sight, there is no chances to get survived superheavy nuclei in such the reactions. However, as mentioned above, the yield of the primary fragments should be increased due to the QF effect (lead valley) comparing with gradual monotonic decrease typical for damped mass transfer reactions. Secondly, with increasing neutron number the fission barriers increase on average (also there is the closed sub-shell at N=162). Thus we may expect non-negligible yield (at the level of 1 pb) of survived superheavy neutron rich nuclei produced in these reactions.

Results of much longer calculations are shown in Figure 7, where the mass and charge distributions of survived fragments obtained in the $^{232}Th+^{250}Cf$ collision at 800 MeV are presented. The pronounced shoulder can be seen in the mass distribution of the primary fragments near the mass number A=208. It is obviously explained by existence of noticeable valley on the potential energy surface [see Figure 3 (b) and Figure 4 (a)], which corresponds to formation of doubly magic nucleus ^{208}Pb (α=0.137). The emerging of the nuclear system into this valley resembles the well-known quasi-fission process and may be called "inverse (or anti-symmetrizing) quasi-fission" (the final mass asymmetry is larger than initial one). For α> 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 for the charge distribution at Z< 82 (Z> 106). As a result, in the charge distribution of survived heavy fragments, see Figure 7 (b), there is also a shoulder at Z~106 and the yield of nuclei

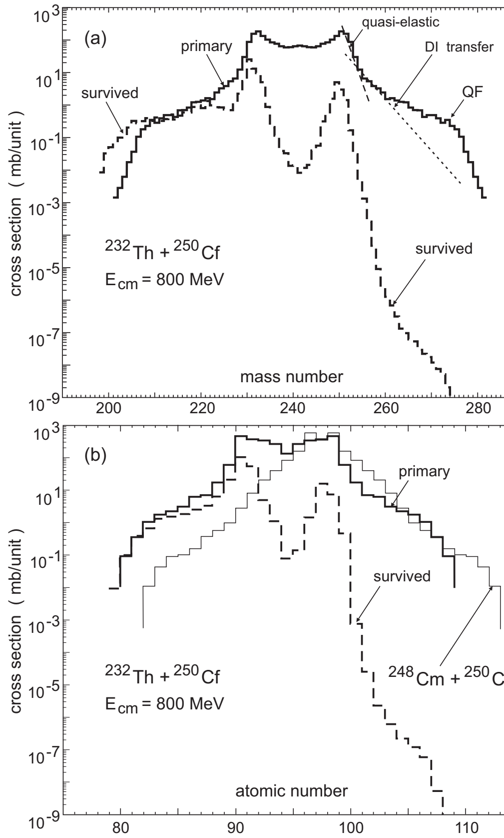

Figure 7. Mass (a) and charge (b) distributions of primary (solid histograms) and survived (dashed histograms) fragments in the $^{232}Th+^{250}Cf$ collision at 800 MeV center-of-mass energy. Thin solid histogram in (b) shows the primary fragment distribution in the hypothetical reaction $^{248}Cm+^{250}Cf$.

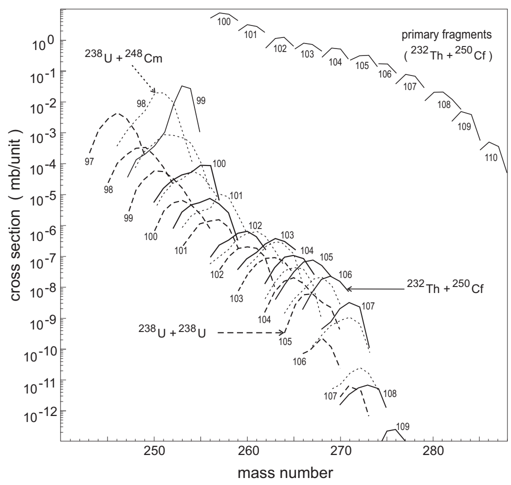

Figure 8. Yield of superheavy nuclei in collisions of $^{238}U+^{238}U$ (dashed), $^{238}U+^{248}Cm$ (dotted), and $^{232}Th+^{250}Cf$ (solid lines) at 800 MeV center-of-mass energy. Solid curves in upper part show isotopic distribution of primary fragments in the Th+Cf reaction. In the case of U+Cm the upper curve only is marked by Z-number (Z=98), the others are one by one up to Z=107.

with Z>107 was found in this reaction at the level of less than 1 pb. This result differs sharply from those obtained in Reference 17, where the reactions of such kind have been analyzed within the parameterized diffusion model and the yield of heavy primary fragments was found diminishing monotonically with increasing charge number. The authors of Reference 17 concluded, however, that the "fluctuations and shell effects not taken into account may considerably increase the formation probabilities". Such is indeed the case.

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 center-of-mass energy are shown in Figure 8. As can be seen, there is a

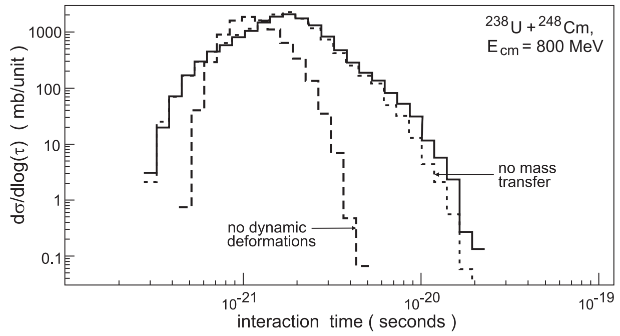

Figure 9. Reaction time distribution for the ^{238}U + ^{248}Cm collision at 800 MeV center-of-mass energy. Dashed and dotted histograms show the effect of switching-off dynamic deformations or mass transfer, respectively.

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. The yield of SH elements in damped reactions depends strongly on beam energy and on nuclear combination which should be chosen carefully. In particular, in Figure 7 the estimated yield of the primary fragments obtained in the hypothetical reaction ^{248}Cm + ^{250}Cf (both constituents are radioactive) is shown, demonstrating a possibility for production of SH neutron-rich nuclei up to the element 112 (complementary to lead fragments in this reaction).

4. Giant quasi-atoms and spontaneous positron formation

The time analysis of the reactions studied shows that in spite of non-existing 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 multidimensional potential energy surface with almost zero kinetic energy (result of large nuclear viscosity), a typical trajectory is shown in Figure 4. The total reaction time distribution, $\frac{d\sigma}{d\log(\tau)}$ (τ denotes the time after the contact of two nuclei), is shown in Figure 9 for the ^{238}U + ^{248}Cm collision. We found that the dynamic deformations are mainly responsible here 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 influences the time distribution not so strong. 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 vacuun").[8,9] 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. Note that the same energy is also optimal for production of the most neutron-rich SH nuclei. Of course, there are some uncertainties in the used parameters, 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 logarithmic scale on both axes in Figure 9.

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 the primary fragments in the region of doubly magic nucleus ^{208}Pb, which could survive against fission due to nucleon evaporation. 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

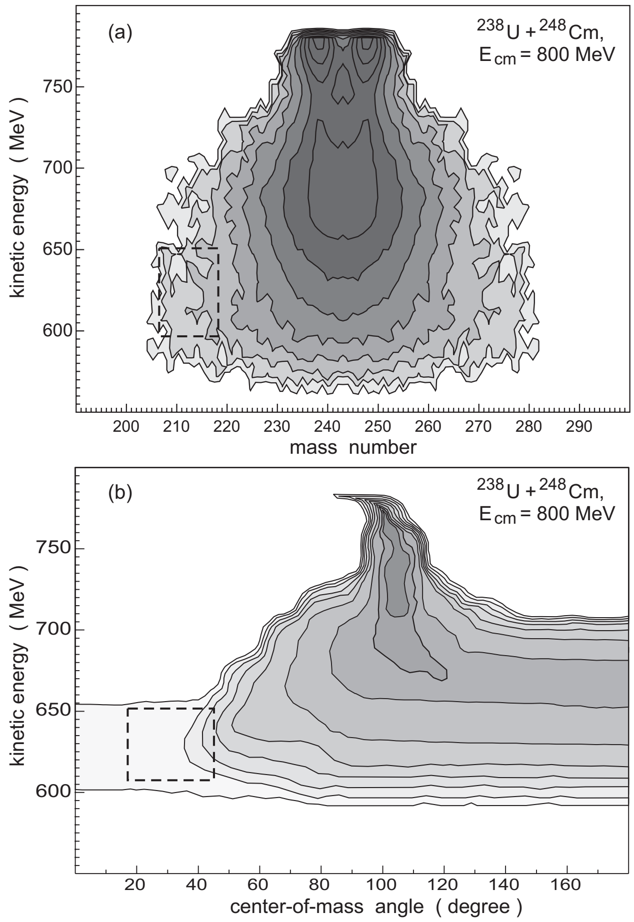

Figure 10. Energy-mass (a) and energy-angular (b) distributions of primary fragments in the ^{238}U + ^{248}Cm collision at 800 MeV (E_{loss} > 15 MeV). Logarithmic landscape of the corresponding double differential cross sections. Lines are drawn over each half order of magnitude. The dashed rectangles show the regions of the longest events.

(strongly peaked at the center-of-mass angle slightly larger than 90°) there is the rapidly decreasing tail at small angles. Thus the detection of the surviving nuclei in the lead region at the center-of-mass angles less than 60° could be a definite witness for a long reaction time (see Figure 10).

5. Conclusion

In summary, the production of long-lived neutron-rich SH nuclei in collisions of transuranium ions seems to be quite possible due to a large mass and charge rearrangement in the "inverse" (anti-symmetrizing) quasi-fission process caused by the $Z = 82$ and $N = 126$ nuclear shells. Radiochemical identification of neutron-rich Db, Sg, and even Bh isotopes, produced in the U + Cm or Th + Cf reactions, could be performed, for example, to test this conclusion. If the found cross sections will be higher than 1 pb, then the subsequent experiments with such reactions could be planned aimed to the production of SH nuclei just in the region of the first "island of stability". Parallel search for spontaneous positron emission from a supercritical electric field of long-lived giant quasi-atoms formed in these reactions is also quite promising.

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