Superheavy fragments produced in the asymmetric strongly damped collision*

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Abstract The strongly damped collisions of very heavy nuclei ^{232}Th+^{250}Cf at the energy range of 680—1880 MeV have been studied within the improved quantum molecular dynamics model. The production probability of primary superheavy fragments with $Z \geqslant 114$ (SHFs) for the asymmetric reaction ^{232}Th+^{250}Cf is higher than that for the symmetric reaction ^{244}Pu+^{244}Pu and ^{238}U+^{238}U. The calculated results show that the mass and charge distributions of primary fragments, the excitation energy distribution of SHFs depend on the incident energies strongly. Two stages of the decay process of composite systems are distinguished by very different decay slopes, which imply different decay mechanisms of the composite system. The first stage is for the decay of giant composite systems and the second one corresponds to the decay of fragments of giant composite systems including SHFs through emitting neutron, proton or other charged particles, and also through fission or fragmentation. The slow reduction of SHFs in the second stage seems to be helpful for the survival of primary superheavy fragments.

Key words strongly damped collision, superheavy fragments, ImQMD model

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In recent years, a great achievement in synthesis of superheavy elements (SHEs) has been made by the complete fusion reactions[1—4]. However, the further experimental extension of the region of SHEs to the central area of "Island of Stability" by means of those reactions is limited by the number of neutron available projectiles and targets, and also by the very low production cross section[2, 5]. In order to search new and more neutron-rich superheavy nuclei the radioactive ion beam will have to be utilized, but up to now the intensive radioactive ion beam is not available. An alternatively possible pathway to the production of superheavy elements is the strongly damped reaction between two very massive nuclei[6—8].

The strong damped collisions mean that two heavy interacting nuclei stick together for a period of time and during the time an amount of kinetic energy is transformed from the projectile into internal excitation and a number of protons and neutrons is also transfered between the interacting nuclei[9]. The symmetric strongly damped reactions of ^{197}Au+^{197}Au, ^{238}U+^{238}U and ^{244}Pu+^{244}Pu have been studied by Wang et al.[10] within the improved quantum molecular dynamics (ImQMD) model and it has been found that the production probability of SHFs for the ^{244}Pu+^{244}Pu reaction is higher than that for the ^{238}U+^{238}U reaction and no product of SHFs is found in the ^{197}Au+^{197}Au reaction. The study also explored that the production probability of SHFs strongly depends on the incident energy and is narrowly peaked at a certain energy. As an extention of that work, we will study the asymmetric strongly damped reactions, for example the reaction of ^{232}Th+^{250}Cf in this paper. We concerntrate our attention on: 1) the energy-depencence of the production probability of SHFs for ^{232}Th+^{250}Cf and comparison of it with symmetric reactions of ^{238}U+^{238}U and ^{244}Pu+^{244}Pu; 2) The mass and charge distributions of primary fragments produced in the reaction at different incident energies between 680 and 1880 MeV;

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3) The distribution of excitation energies of SHFs at different energies; and 4) The decay process of giant composite systems formed in the reaction.

The Improved Quantum Molecular Dynamics (ImQMD) model[11—13] is employed in this work. For reader convenience we briefly introduce the model. In the ImQMD model, the one-body phase space distribution function for N-distinguishable particles is given by:

$$f(\boldsymbol{r},\boldsymbol{p})=\sum_i \frac{1}{(\pi\hbar)^3}\exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_i)^2}{2\sigma_r^2}-\frac{2\sigma_r^2}{\hbar^2}(\boldsymbol{p}-\boldsymbol{p}_i)^2\right]. \tag{1}$$

For identical fermions, the effect of the Pauli principle has to be considered.

The propagation of nucleons under the self-consistently generated mean field is governed by the Hamiltonian equations of motion:

$$\dot{\boldsymbol{r}}_i=\frac{\partial H}{\partial \boldsymbol{p}_i}, \quad \dot{\boldsymbol{p}}_i=-\frac{\partial H}{\partial \boldsymbol{r}_i}. \tag{2}$$

The Hamiltonian H consists of the kinetic energy and the effective interaction potential energy:

$$H=T+U, \tag{3}$$

$$T=\sum_i \frac{p_i^2}{2m}. \tag{4}$$

The effective interaction potential energy includes the nuclear local interaction potential energy and the Coulomb interaction potential energy:

$$U=U_{\rm loc}+U_{\rm coul}. \tag{5}$$

Here $U_{\rm loc}$ is obtained from the integration of the nuclear local interaction potential energy density functional.

$$\begin{aligned}U_{\rm loc} =\ & \frac{\alpha}{2}\sum_i\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}+\frac{\beta}{\gamma+1}\sum_i\Big(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\Big)^{\gamma}+\\ & \frac{g_0}{2}\sum_i\sum_{j\neq i}f_{sij}\frac{\rho_{ij}}{\rho_0}+\\ & \frac{C_{\rm s}}{2}\sum_i\sum_{j\neq i}t_i t_j\frac{\rho_{ij}}{\rho_0}(1-\kappa_{\rm s}f_{sij})+\\ & g_\tau\sum_i\Big(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\Big)^{\eta},\end{aligned} \tag{6}$$

where

$$\rho_{ij}=\frac{1}{(4\pi\sigma_r^2)^{3/2}}\exp\left[-\frac{(\boldsymbol{r}_i-\boldsymbol{r}_j)^2}{4\sigma_r^2}\right], \tag{7}$$

$$f_{sij}=\frac{3}{2\sigma_r^2}-\left(\frac{\boldsymbol{r}_i-\boldsymbol{r}_j}{2\sigma_r^2}\right)^2, \tag{8}$$

and t_i=1 and −1 for proton and neutron, respectively.

The Coulomb energy can be written as a sum of the direct and the exchange contribution, and the latter being taken into account in the Slater approximation[14—16]

$$U_{\rm coul}=\frac{1}{2}\int\rho_{\rm p}(\boldsymbol{r})\frac{\boldsymbol{e}^2}{|\boldsymbol{r}-\boldsymbol{r}'|}{\rm d}\boldsymbol{r}{\rm d}\boldsymbol{r}'-\boldsymbol{e}^2\frac{3}{4}\left(\frac{3}{\pi}\right)^{1/3}\int\rho_{\rm p}^{4/3}{\rm d}\boldsymbol{R}. \tag{9}$$

The collision term plays a very small role in low energy heavy-ion collisions. The phase space occupation constraint method[17] and the system-size-dependent wave-packet width are adopted as those in the previous version of ImQMD[11]. The parameters used are the same as[10] (see Table 1).

Table 1. The model parameter.

α/MeV	β/MeV	γ	g_0/(MeV·fm^2)	g_τ/MeV	η	$C_{\rm s}$/MeV	$\kappa_{\rm s}$/fm^2	ρ_0/fm^{-3}
−356	303	7/6	7.0	12.5	2/3	32.0	0.08	0.165

Now we apply the model to study the reaction of ^{232}Th+^{250}Cf at energies of $E_{\rm c.m.}$ = 680—1880 MeV. The central collisions are mainly concerned in this work since those collisions are important for the production of superheavy fragments. To simulate the collision of two nuclei, the initial nuclei of projectile and target are prepared by the same procedure as in Refs. [11—13]. The ground states of nuclei are fixed to have a binding energy of 7.62 ± 0.05, 7.48 ± 0.05 MeV/nucleon and root mean square radius 7.34±0.2, 7.53 ± 0.2 fm for ^{232}Th and ^{250}Cf, respectively. To check the stability of the pre-prepared initial nuclei, we let those pre-prepared nuclear systems evolve for at least 3000 fm/c, and their binding energies and root-mean-square charge radii remain constant with a very small fluctuation and the bound nuclei evolve stably without spurious emission in this period of time. The pre-prepared nuclei satisfying all these requirements are selected as the "initial nuclei". They are stored for usage in simulating reactions. we put the initial distance between the projectile and target at 50 fm for each reaction event. Since we are mainly interested in the average behavior of composite system, the deformation of ground state of nuclei is omitted at this moment in the primary study for simplification. The study of the orientation effect in initial nuclei on the behavior of the composite systems is in progress. The simulation events are taken to be 1000 for every energy point and impact parameter.

Figure 1(a) shows the energy dependence of production probability of SHFs at the time t=6000 fm/c for ^{232}Th+^{250}Cf and ^{238}U+^{238}U. We can see that the production probability of SHFs for the asymmetric reaction of ^{232}Th+^{250}Cf is much higher than that for the symmetric reaction of ^{238}U+^{238}U. If comparing the production probability of SHFs for ^{232}Th+^{250}Cf with that for symmetric reaction of ^{244}Pu+^{244}Pu which appeared in Ref. [10], we find that for the composite systems with the same protons number the asymmetric case is better than that for the symmetric case for producing superheavy nuclei. Fig. 1(b) shows the production probability of SHFs for the same reaction of ^{232}Th+^{250}Cf with different impact parameters b=1 fm (line with full triangle) and b=3 fm (line with full square). The general behaviors of the energy dependence of production probability of SHFs are the same for different impact parameters. But the position of peak for the case with impact parameter b=3 fm is shifted to the high energy side compared to the case with impact parameter b=1 fm. The very pronounced feature we observed from the figure is the narrow peaks in the energy dependence of the production probability of SHFs. The peaks are at about $E_{\rm c.m.}$ = 880 and 830 MeV for the ^{232}Th+^{250}Cf and ^{238}U+^{238}U, respectively. The narrow peak means that it is of crucial importance for selecting the suitable incident energy in order to search superheavy elements experimentally by using the approach of the strongly damped massive reactions. At different incident energies we obtain the mass and charge distributions of the primary fragments.

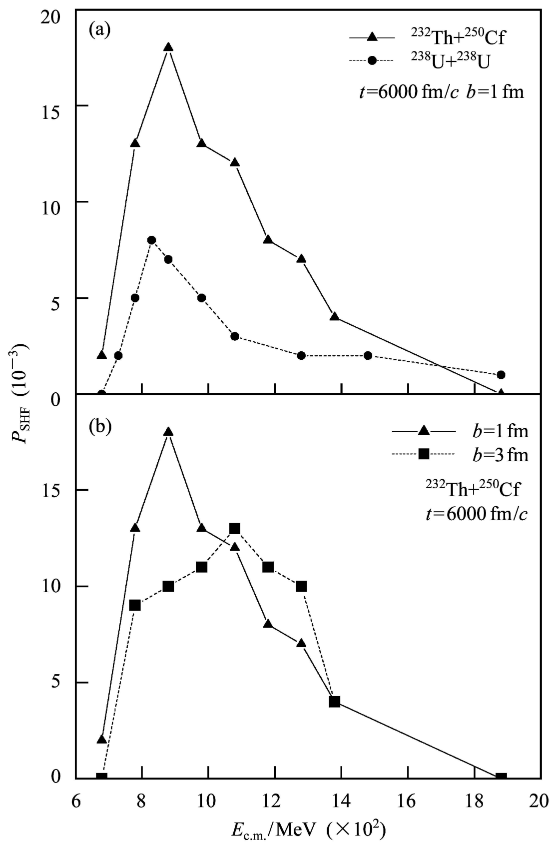

Fig. 1. The incident energy dependence of the production probability of SHFs at the time t= 6000 fm/c: (a) for the ^{238}U+^{238}U (line with full circle) and ^{232}Th+^{250}Cf (line with full triangle) with the impact parameter b=1 fm; (b) for the reaction ^{232}Th+^{250}Cf with different impact parameters b=1 fm (line with full triangle) and b=3 fm (line with full square).

Figure 2 shows the mass distributions of the primary fragments in the reaction ^{232}Th+^{250}Cf at the time t=2200 fm/c and incident energy $E_{\rm c.m.}$ = 680—1880 MeV with impact parameter b = 1 fm. At the incident energy of 680 MeV (Fig. 2(a)), there are two peaks in the mass distributions of primary fragments which just correspond to the mass of projectile (232) and target (250) nuclei, respectively. This means that the elastic and inelastic reactions are dominated and the probability of large mass transfer is very small. With the increase of incident energy, for example, when $E_{\rm c.m.}$ = 780 MeV, the mass distribution of primary fragments becomes one symmetric peak, which appears at the mass number of 240, as shown in Fig. 2(b). When the incident energy is further increased to $E_{\rm c.m.}$ = 880 MeV, the mass distribution is widened and the width of the distribution reaches 120, as shown in Fig. 2(c). In this case the reaction with a large mass transfer becomes important. For the cases of $E_{\rm c.m.}$ = 1080 to 1880 MeV, the mass distributions of primary fragments become even wider and the peaks of mass distributions shift gradually to low mass number side, and the asymmetric mass distributions replace the symmetric ones. Those results are shown in Fig. 2(d)—(f). In all these cases the large mass transfers are quite important, which may lead to the production of superheavy fragments. Here we pay a great attention to the fragments with the mass number larger than 300 (corresponding $Z\sim$114). We find that in the incident energy region between 1080 to 1380 MeV the production probability of those heavy fragments is relatively high. When the incident energy is even high, for instance, $E_{\rm c.m.}$ = 1880 MeV, the production probability of primary superheavy fragments decreases due to too large excitation energy resulting in an amount of heavy fragments breaking up.

The charge distributions of the primary fragments in the reaction are demonstrated in Fig. 3, from which we find the similar behavior with mass distributions, that is, at low incident energy again there are two peaks at around $Z\sim$90 and 98 and at $E_{\rm c.m.}$= 880 MeV large mass transfer becomes important (production of superheavy fragments becomes evident), and when $E_{\rm c.m.}$ = 1080 to 1380 MeV the relatively large production probability of SHFs seems to be presented. Then with the energy further increasing the production probability of those SHFs decreases. Since the main goal of this paper is to study the production of superheavy nuclei, we pay a great attention to searching for the favourable condition for producing SHFs.

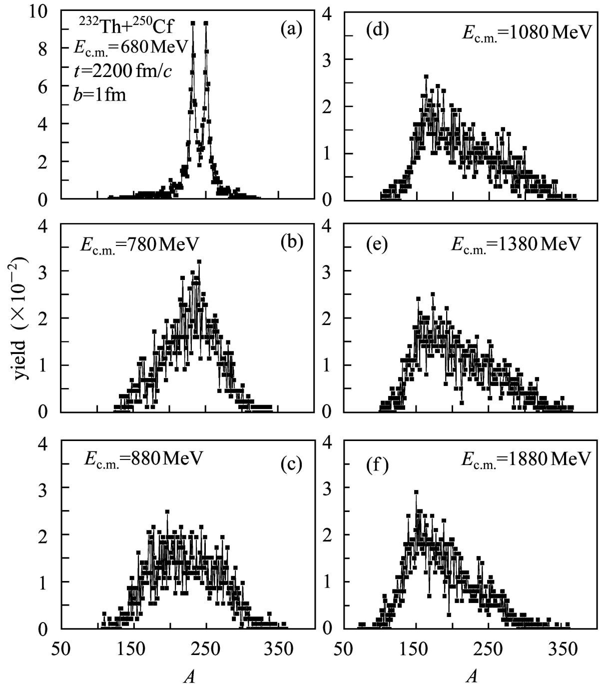

Fig. 2. The mass distribution of the primary fragments at t=2200 fm/c for the reaction ^{232}Th+^{250}Cf at different incident energies with the impact parameter b=1 fm.

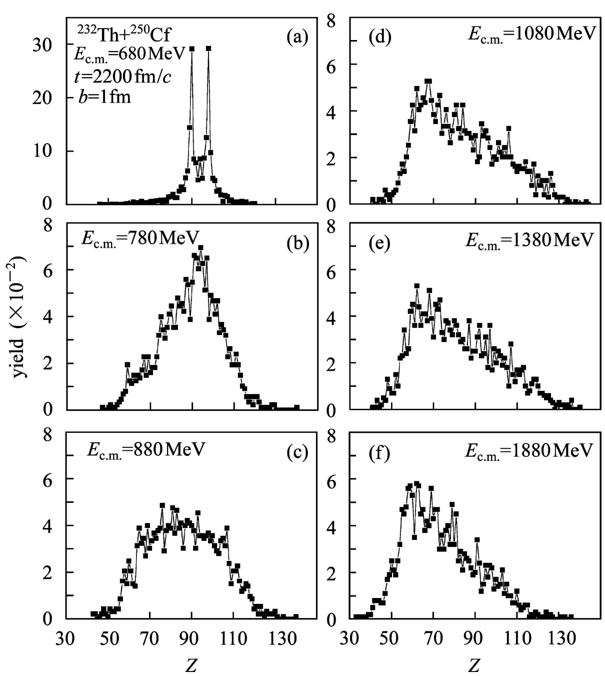

Fig. 3. The charge distributions of the primary fragments at t = 2200 fm/c in the reaction ^{232}Th+^{250}Cf at different incident energy with the impact parameter b = 1 fm.

In Fig. 4 we show the incident energy dependence of the production probability of SHFs at the different reaction time. One sees that at t = 2200 fm/c the maximum production probability of SHFs appears at incident energy $E_{\rm c.m.}$ = 1180 MeV (176 primary SHFs in 1000 ^{232}Th+^{250}Cf reaction events). With the reaction time increasing the peak of production probability of SHFs shifts to low energy side. For example, when t = 6000 fm/c, the peak of production probability of SHFs appears at 880 MeV. The shift of the peak is due to the fragmentation of SHFs resulting from high excitation at large incident energy. Thus one expects that the collisions at relatively low energy could produce more surviving SHFs.

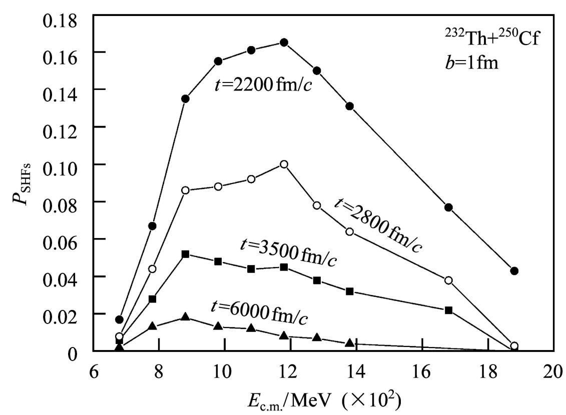

Fig. 4. The incident energy dependence of the production probability of SHFs in the ^{232}Th+^{250}Cf at different reaction time.

Further in Fig. 5 we show the distributions of excitation energy of SHFs at t = 2200 fm/c for different incident energies. The excitation energy $E^*(Z,A) = E_{\rm tot}(Z,A) - E_0(Z,A)$. In the QMD model, nuclear clusters (Z,A) are usually recognized by the coalescence model, i.e. nucleons are considered to be part of a cluster if in the end at least one other nucleon is closer than $r_{\rm min} \leqslant 3.5$ fm in coordinate space and $p_{\rm min} \leqslant 200$ MeV/c in which the particles with relative momentum smaller than 300 MeV/c and relative distance smaller than 3.5 fm are considered to belong to one cluster[18]. This mechanism has been extensively applied in transport theory for the cluster formation. Then $E_{\rm tot}(Z,A)$ can be calculated from Eqs. (3)—(9). $E_0(Z,A)$ is the ground state energy of nucleus (A,Z) taken from Ref. [19]. Considering that the stability of superheavy nuclei comes from the shell correction and the high excitation energy can make the shell effect disappear, here we pay an attention to the SHFs with low excitation energy, for example less than 60 MeV (about 3 times the 'damping' energy). For those superheavy fragments there is a possibility to be survived.

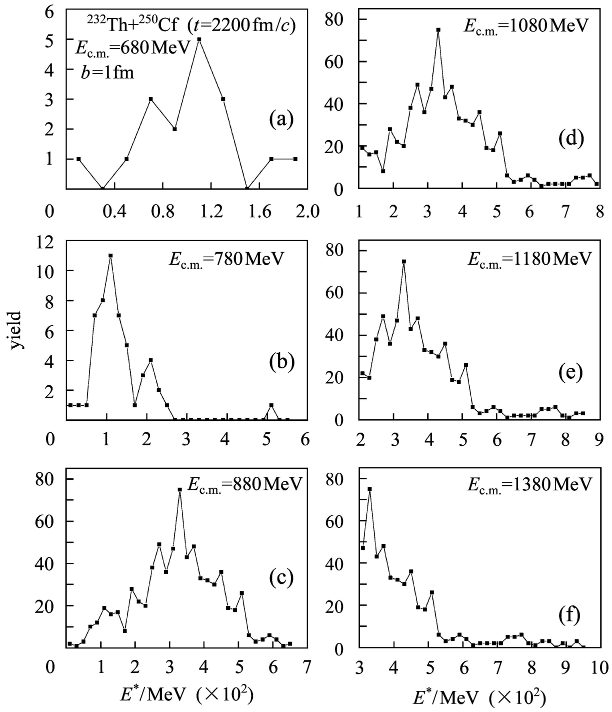

Fig. 5. The distributions of the excitation energy of SHFs in the reaction ^{232}Th+^{250}Cf at $t = 2200$ fm/c for different incident energies.

Now we come to Fig. 5. At the incident energy $E_{\rm c.m.} = 680$ MeV as shown in Fig. 5(a), there are totally 17 SHFs produced and among them there are only two SHFs with the excitation energy less than 60 MeV. With the incident energy increasing to 780 and 880 MeV (see Fig. 5(b) and 5(c)), the number of SHFs increases to 53 and 114, and there are 3 and 4 fragments with the excitation energy less than 60 MeV, respectively. When the incident energy continues to increase to 1080 till 1380 MeV (see Figs. 5(d)—(f)), we find that most parts of SHFs have an excitation energy more than 200 MeV. Such high excitation energy makes almost all fragments break up and almost no superheavy fragments survive. Therefore, from the point of view of synthesis of superheavy nuclei we should not only regard promoting the production probability of SHFs, but also pay a great attention to searching for the condition for producing SHFs with low excitation energy. In Fig. 6 we show the time evolution of the production probability of SHFs including the heavy residues of composite systems for 1000 ^{232}Th +^{250}Cf reaction events at $E_{\rm c.m.} =$ 880 and 1180 MeV. The impact parameter is taken to be $b = 1$ fm. From Fig. 6 one can see that two stages of the decay process can be distinguished by very different decreasing slopes, which implies different decay mechanisms of the composite systems. The first decay stage is for the decay of giant composite systems, which appears from about 1000 to 2000 fm/c. During this stage, the giant composite system quickly breaks up, in general, two pieces or three pieces for a very few cases since there is a very strong Coulomb repulsion interaction. The dashed lines in the figure represent this decay slope. The second decay stage appears after about 2000 fm/c. This stage corresponds to the decay of products during the first stage including SHFs. In this stage, the SHFs decrease slowly with time through emitting neutron, proton or other charged particles, and also through fission or fragmentation. The dotted lines represent the decay slope of this stage. The relatively slow reduction of SHFs seems to be helpful for the survival of SHFs.

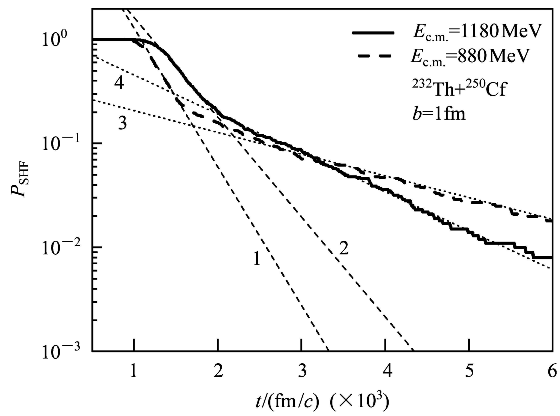

Fig. 6. The time evolution of the production probability of SHFs including the heavy residues of composite systems for the reaction of ^{232}Th+^{250}Cf at $E_{\rm c.m.} = 880$ and 1180 MeV with $b = 1$ fm.

In summary, we have studied the low energy collisions of very heavy system ^{232}Th+^{250}Cf within the improved quantum molecular dynamics model. It is found that the production probability of primary superheavy fragments with $Z \geqslant 114$ strongly depends on the reaction systems and incident energies. The production probability of SHFs for the asymmetric reaction ^{232}Th+^{250}Cf reaction is higher than that for the symmetric reaction ^{244}Pu+^{244}Pu (see Ref. [10]) and ^{238}U+^{238}U. The results show that the mass and charge distributions of primary fragments, the excitation energy distribution of SHFs also depend on the incident energy strongly. Two stages of the decay process of composite systems are distinguished by very different decay slopes, which imply different decay mechanisms of the composite system. The first stage is for the decay of giant composite systems and the second one corresponds to the decay of fragments of giant composite systems including SHFs through emitting neutron, proton or other charged particles, and also through fission or fragmentation. The slow reduction of SHFs in the second stage seems to be helpful for the survival of primary superheavy fragments.

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