CHIN.PHYS.LETT. Vol. 24, No. 10 (2007) 2796

The Average Lifetime of Giant Composite Systems Formed in Strongly Damped Collisions *

TIAN Jun-Long(田俊龙)[1**], WU Xi-Zhen(吴锡真)[1***], OU Li(欧立)[1], LI Zhu-Xia(李祝霞)[1,2]
[1] China Institute of Atomic Energy, Beijing 102413
[2] Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080

(Received 28 February 2007)

The dynamic, adiabatic and diabatic entrance potentials in strongly damped reactions of ^{238}U+^{238}U, ^{232}Th+^{250}Cf *are calculated and compared. The feature of the dynamical potential implies that it is possible for the composite systems to stick together for a period of time. By means of the improved quantum molecular dynamics model the time evolution of the density and charge distributions of giant composite systems and their fragments for reactions* ^{238}U+^{238}U, ^{232}Th+^{250}Cf *are investigated, from which the lifetimes of giant composite systems at different energies are obtained. The longest average lifetime of* ^{238}U+^{238}U *is found when the incident energy is about* $E_{\rm c.m.}$=1080 MeV, *which is about 1200 fm/c.*

PACS: 25.70.−z, 24.10.−i, 25.60.Je

Superheavy nuclei obtained in “cold” fusion reactions with Pb or Bi target[1] and in “hot” fusions with actinides[2] are still far from the centre of the predicted island of stability formed by the neutron closed shell around $N = 184$. In order to approach this region of island of stability, other ways in addition to the complete fusion reaction must be searched for. The strongly damped reactions between very massive nuclei, like U+U could be one of possible approaches, which was studied in the 1970s and the early 1980s at the energies near the Coulomb barrier.[3−9] Only very recently, the study on this kind of reactions is renewed.[10−12] In Ref. [10] the dissipative reaction of ^{197}Au+^{197}Au was studied by the constrained molecular dynamics model, and it was found that the superheavy composite system formed in the reaction might survive for a long time. In Ref. [11], the dependence of the production probability of primary superheavy fragments on incident energies and combinations of projectile and target was studied within the improved quantum molecular dynamics model. In Ref. [12] the low energy collisions of ^{238}U+^{238}U and ^{232}Th+^{250}Cf etc. were studied within multi-dimensional Langevin equations, in which the mass and charge distributions of primary and survived fragments formed in the reactions were mainly concerned. However, for microscopical understanding the mechanism of low energy collisions between massive nuclei there are still many works required. Among them, the studies about the formation of the giant composite system and its properties are essentially important. In this Letter, we firstly study the time evolution of configuration and lifetime of the composite systems at different incident energies. Further, it is also useful to investigate the orientation of elongation axis of the systems with respect to the beam direction, i.e. the angular distribution of re-separated fragments for understanding the behaviour of the formed composite systems. Those studies can provide us with very useful information about the mechanism of strongly damped reactions between very massive nuclei and will help us to search for a possible pathway for synthesis of more neutron-rich superheavy nuclei. Furthermore, they are also of a great significance for discovery of spontaneous positron emission from super-strong electric field by a static QED process[13] (transition from neutral to charged QED vacuum).

The improved quantum molecular dynamics (ImQMD) model is employed[14] in this work. For reader’s convenience we briefly describe the model. The effective interaction potential energy includes the nuclear local interaction potential energy and Coulomb interaction potential energy,

$$U = U_{\rm loc} + U_{\rm Coul}. \tag{1}$$

$U_{\rm loc}$ is obtained from the integration of the nuclear local interaction potential energy density functional. The same nuclear local interaction potential energy density functional $V_{\rm loc}(\rho(\boldsymbol{r}))$ is taken as that in Ref. [14], which reads

$$V_{\rm loc} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{C_s}{2\rho_0}(\rho^2 - \kappa_s(\nabla\rho)^2)\delta^2 + g_\tau\frac{\rho^{\eta+1}}{\rho_0^{\eta}}. \tag{2}$$

Here ρ, ρ_n, ρ_p are the nucleon, neutron, and proton density, respectively, and $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry. The first three terms in the above expression can be obtained from the potential energy functional of Skyrme force directly. The fourth term is the symmetry potential energy where both the bulk and the surface symmetry potential energy are included. The surface symmetry potential energy term modifies the symmetry potential in the surface region and it is important to have a correct neutron skin and neck dynamics in heavy ion collisions. The last term in the potential energy functional is a small correction

---

* Supported by the National Natural Science Foundation of China under Grant Nos 10235030 and 10675170.
** Email: tianjl@ciae.ac.cn
*** Email: lizwux9@ciae.ac.cn

term. From the integration of $V_{\rm loc}$, we obtain the local interaction potential energy:

$$U_{\rm loc} = \frac{\alpha}{2}\sum_i\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0} + \frac{\beta}{\gamma+1}\sum_i\Big(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\Big)^{\gamma} + \frac{g_0}{2}\sum_i\sum_{j\neq i}f_{sij}\frac{\rho_{ij}}{\rho_0} + \frac{C_s}{2}\sum_i\sum_{j\neq i}t_it_j\frac{\rho_{ij}}{\rho_0} \cdot (1-\kappa_s f_{sij}) + g_\tau\sum_i\Big(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\Big)^{\eta}, \qquad (3)$$

where

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

$$f_{sij} = \frac{3}{2\sigma_r^2} - \Big(\frac{\boldsymbol{r}_i-\boldsymbol{r}_j}{2\sigma_r^2}\Big)^2, \qquad (5)$$

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

The Coulomb energy is written as a sum of the direct and the exchange contribution, and the latter is taken into account in the Slater approximation,

$$U_{\rm coul} = \frac{1}{2}\int\rho_p(\boldsymbol{r})\frac{e^2}{|\boldsymbol{r}-\boldsymbol{r}'|}\rho_p(\boldsymbol{r}')d\boldsymbol{r}d\boldsymbol{r}' - e^2\frac{3}{4}\Big(\frac{3}{\pi}\Big)^{1/3}\int\rho_p^{4/3}d\boldsymbol{R}. \qquad (6)$$

The parameters used are as the same as Ref. [11] (see Table 1).

Table 1. The model parameters.

α (MeV)	β (MeV)	γ	g_0 (MeV fm^2)	g_τ (MeV)	η	C_S (MeV)	κ_s (fm^2)	ρ_0 (fm^{-3})
-356	303	7/6	7.0	12.5	2/3	32.0	0.08	0.165

Now let us apply the model to study the strongly damped reactions of ^{238}U+^{238}U, ^{232}Th+^{250}Cf at energies of $E_{\rm c.m.} = 680-1880$ MeV. Only central collisions are studied in this work because those reactions are most important for the purpose of this study. The initial nuclei of projectile and target are prepared by the same procedure in Refs. [11,14,17].

Firstly, we study the entrance channel potential energy, which is defined as

$$V_b(R) = E_{12}(R) - E_1 - E_2, \qquad (7)$$

where R is the distance between centres of mass of projectile and the target. $E_{12}(R)$, E_1 and E_2 are the total energy of the whole system, the energies of projectile (like) and target (like) part, respectively. Figure 1 shows the characteristics of $V_b(R)$ for ^{238}U+^{238}U. The long-dashed curve represents the potential obtained with the frozen density, which is repulsive everywhere. In the real reactions, the densities of the reaction partners should evolve with time. Consequently, the realistic potential experienced by the reaction partners should be different from that calculated by frozen density. The potential obtained from the realistic time-dependent density is known as a dynamical potential. The solid curve in Fig. 1 shows the dynamic potential. For comparison we also show the adiabatic potential calculated by the two center shell model (liquid drop energy plus shell correction), which is popularly used in the low energy collisions. The adiabatic potential is shown by the dotted line, which is found to be very close to the dynamic potential in the contacting configuration of two nuclei. Both the dynamic and adiabatic potential in the contacting configuration are flat with respect to variation of the distance of centers of mass between reaction partners. Thus it seems that it is possible for the composite system to exist for a period of time.

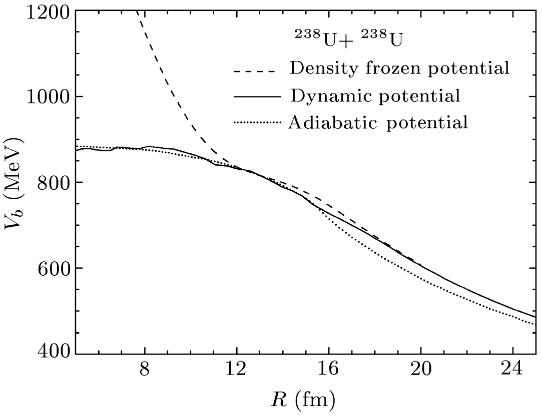

Fig. 1. Entrance channel potential energy of the system of ^{238}U+^{238}U as a function of distance between centres of mass of projectile and target.

Now we study the formation of giant composite system. The pre-prepared initial nuclei are required to have binding energy of 7.57±0.05 MeV/nucleon and rms radius of 7.36 ± 0.2 fm for ^{238}U and binding energies 7.62 ± 0.05, 7.48 ± 0.05 MeV/nucleon and rms radii 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 the pre-prepared nuclear systems evolve for at least 3000 fm/c. If the pre-prepared nuclei satisfy the following requirements, i.e. their binding energies and rms charge radii remain to be constant with a very small fluctuation in this period of time and within the nuclei evolve stably without spurious emission. The pre-prepared nuclei will be taken as the initial nuclei. They are stored for usage in the following simulating reactions. Since we are mainly interested in the average behaviour of composite system, the deformation of projectile and target nuclei is not considered in this work for simplicity. The study of the effect of the orientation of deformed initial nuclei on the formation of giant composite nuclei is in progress. One thousand of collision events are performed for each energy and each impact parameter. Figure 2 shows the time evolution of density for a typical reaction event of ^{238}U+^{238}U at $E_{\rm c.m.}$ = 780 MeV. At the time of about 400 fm/c the interacting nuclei begin to stick together and form a composite system. When t = 600 fm/c the system turns into a quite deformed mononuclear composite system, it keeps in such a shape for almost 400 fm/c, after about t = 1000 fm/c the deformed mononuclear system again turns into dinuclear system with strong necking in, since then the dinuclear system still keeps about 250 fm/c, finally at about 1250 fm/c it re-separates again. Thus the lifetime of this composite system is more than 850 fm/c. One can find from this figure that there seems to exist a three-cluster configuration in the time evolution of the system, which may result in an asymmetric re-separation into one superheavy fragment and one lanthanide fragment. We find that this kind configuration is about 10% of total events.

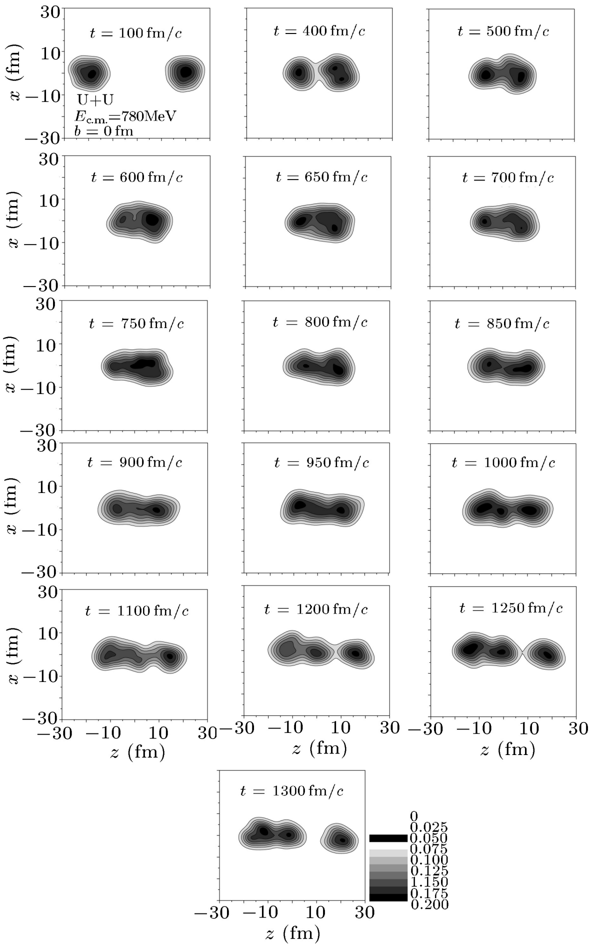

Fig. 2. Time evolution of density distribution for a typical event of the ^{238}U+^{238}U head on collisions at 780 MeV c.m. energy.

Figure 3 shows the charge distributions of fragments in the reaction ^{238}U+^{238}U at 830 MeV and $b = 1$ fm at 1000, 1300, and 1600 fm/c, respectively. We can see that at the time $t = 1000$ fm/c the giant composite systems with $Z \sim 184$ are dominant and the number of fragments is very small. With the time up to 1300 fm/c, the number of survived giant composite systems decreases to the same order of magnitude with that of fragments, and at $t = 1600$ fm/c the fragments are dominant and only a few of giant composite systems survive. The decay behaviour of the giant composite systems depends on the incident energy and the combination of projectile and target, which will be studied elsewhere. Here we will first estimate the lifetime of giant composite system according to the time evolution of the charge distribution at different incident energies. Figure 4 presents the distributions of the lifetime of the composite systems of ^{238}U+^{238}U and ^{232}Th+^{250}Cf at $E_{\text{c.m.}} = 1080$ MeV and $E_{\text{c.m.}} = 1180$ MeV, respectively. The lifetimes distribute from more than 400 fm/c to about 1900 fm/c. For most of reaction events, the lifetimes of giant composite systems are between 900–1300 fm/c. The average lifetime of the composite systems is about 1140 fm/c for ^{238}U+^{238}U at $E_{\text{c.m.}} = 1080$ MeV and 1110 fm/c for ^{232}Th+^{250}Cf at $E_{\text{c.m.}} = 1180$ MeV.

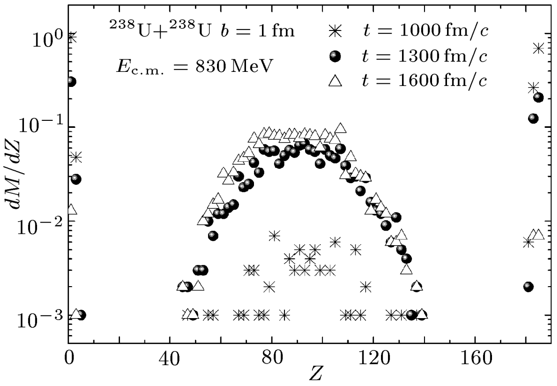

Fig. 3. Charge distributions of fragments in the reaction ^{238}U+^{238}U at the c.m. energy 830 MeV and $b = 1$ fm at different times.

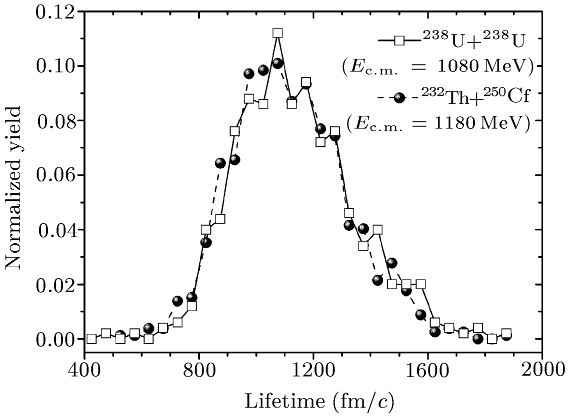

Fig. 4. Distributions of lifetime of the composite system with $Z \geq 170$ at incident energy $E_{\text{c.m.}} = 1080$ MeV for ^{238}U+^{238}U(square) and at incident energy $E_{\text{c.m.}} = 1180$ MeV for ^{232}Th+^{250}Cf (circle) with impact parameter $b = 1$ fm.

Figure 5 shows the energy dependence of the average lifetime of composite systems ($Z \geq 170$) for two reactions of ^{238}U+^{238}U and ^{232}Th+^{250}Cf at energies $E_{\text{c.m.}} = 680 - 1880$ MeV. One can find that the behaviour of the energy dependence of lifetime of the composite system for both the reactions is quite similar and the pronounced feature of the average lifetime is such that there is a peak at a certain energy for both the reactions. The longest average lifetime of the composite system is reached when $E_{\text{c.m.}} = 1080$ MeV, which is about 1140 fm/c for ^{238}U+^{238}U. Whereas the longest lifetime for ^{232}Th+^{250}Cf is 1110 fm/c when $E_{\rm c.m.} = 1180$ MeV which is shorter than that of the ^{238}U+^{238}U. This is due to the larger total charge of ^{232}Th+^{250}Cf compared with ^{238}U+^{238}U. Thus, to suitably select the incident energy is of crucial importance for obtaining the long-lifetime giant composite system in strongly damped reactions.

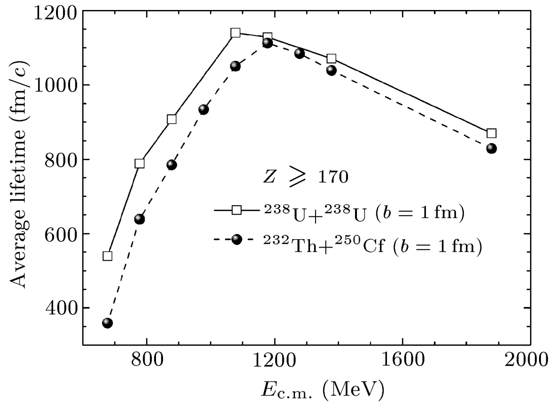

Fig. 5. Energy dependence of average lifetime of composite systems with $Z \geq 170$. The lines with full square and full circles are for the systems of ^{238}U+^{238}U and ^{232}Th+^{250}Cf, respectively.

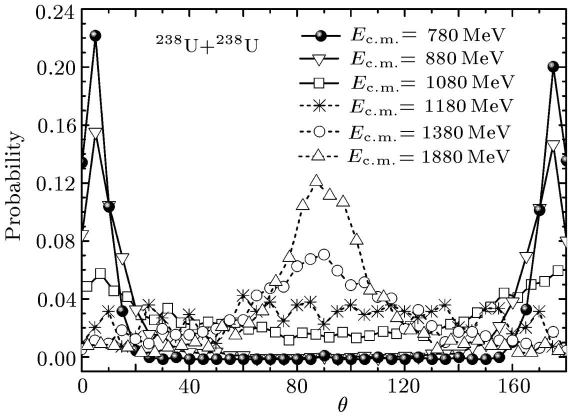

Fig. 6. Distribution of orientation angles for 1000 heads on ^{238}U+^{238}U reaction events at different incident energies.

Since the composite systems formed in head-on collisions are generally in a deformed shape, it is necessary to investigate how the elongation axis orientates in reaction space. Therefore, we define an angle between the elongation axis (i.e. re-separation direction) of the system and beam direction as the orientation angle θ. We investigate the dependence of the orientation angle on the incident energy and find that at the relatively low energies, for example at $E_{\rm c.m.} = 780$ MeV, the elongation axis of the composite system of ^{238}U+^{238}U is always along the beam direction, i.e. $\theta = 0°$ or $180°$ (see Fig. 2). However, with the increasing incident energies the orientation angle θ will deviate from 0° or 180°. In order to clearly show the feature of orientation angles as a function of incident energies, in Fig. 6 we present the distributions of the orientation angles for 1000 heads on ^{238}U+^{238}U reaction events at different incident energies. One sees that at the energies of $E_{\rm c.m.} = 780$ and 880 MeV the peaks of distributions of orientation angles are located at about 0° and 180°. With the energy increasing up to 1080 MeV, the peak in the distribution is less pronounced. When $E_{\rm c.m.} = 1180$ MeV the peak disappears and the distribution becomes very flat. This indicates that at this energy the orientation angles are isotropically distributed in the reaction plane, thus the angular distribution of re-separated fragments is isotropic. This is just one of characteristics of compound nuclei. When the incident energy further increases up to $E_{\rm c.m.} = 1380$ and 1880 MeV the peak in orientation angles distribution appears again but at $\theta = 90°$.

In summary, we have studied the properties of the composite systems formed in the strongly damped collisions of ^{238}U+^{238}U and ^{232}Th+^{250}Cf at different energies by means of the ImQMD model. The feature of the dynamical potential implies that it is possible for composite systems to survive for a period of time. We find that the average lifetime of the formed composite systems depends on the incident energies and that the composite systems with the average lifetime as long as about 1140 fm/c can be formed at the suitably choosing incident energies around $E_{cm} = 1080 - 1180$ MeV. Based on the ImQMD model the distributions of the orientation angles of elongation axis with respect to the beam direction, i.e. the angular distributions of the re-separated fragments at different energies are investigated. The results tell us that at a suitably choosing incident energy the formed composite system in strongly damped reactions seems to have a characteristic of compound-like state within a relatively long period of time. This kind of study on the behaviour of the composite systems is certainly helpful to search for a possible pathway for the synthesis of more neutron-rich superheavy nuclei and to find spontaneous positron emission from super-strong electric field by a static QED process.

References

[1] Hofmann S et al 2000 *Rev. Mod. Phys.* **72** 733
[2] Oganessian Y T et al 2004 *Phys. Rev.* C **70** 064609
[3] Herrmann G 1979 *Nature* **280** 543
[4] Seaborg G T et al 1979 *Scince* **203** 711
[5] Maruhn J A et al 1980 *Prog. Part. Nucl. Phys.* **4** 257
[6] Riedel C and Nörenberg W 1979 *Z. Phys.* **290** 385
[7] Gäggeler H et al 1980 *Phys. Rev. Lett.* **45** 1824
[8] Hildenbrand K D et al 1977 *Phys. Rev. Lett.* **39** 1065
[9] Schädel M et al 1978 *Phys. Rev. Lett.* **41** 469
Schädel M et al 1982 *Phys. Rev. Lett.* **48** 852
[10] Maruyama T et al 2002 *Eur. Phys. J.* A **14** 191
[11] Wang N et al 2005 *Mor. Phys. Lett.* A **20** 1
[12] Zagrebaev V I et al 2006 *Phys. Rev.* C **73** 031602(R)
[13] Greiner W 1983 *Quantum Electrodynamics of Strong Fields* (New York: Plenum)
[14] Wang N et al 2004 *Phys. Rev.* C **69** 034608
[15] Feldmeier H and Schnack J 2000 *Rev. Mod. Phys.* **72** 655
[16] Papa M et al 2001 *Phys. Rev.* C **64** 024612
[17] Wang N et al 2002 *Phys. Rev.* C **65** 064608