Production probability of superheavy fragments at various initial deformations and orientations in the $^{238}U + ^{238}U$ reaction

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The dynamical effects of initial orientation and deformation (with and without β_4 deformation) of projectile and target on the $^{238}U + ^{238}U$ reaction have been investigated by using the improved quantum molecular dynamics model. The deformation of colliding nuclei at touching configuration is distributed with a wide width, especially for the nose-nose orientation case. The influence of different orientations and deformations on the average lifetime of the transient composite system and the production probability of superheavy fragments (SHF) with $Z > 110$ at incident energies 7–12 A MeV is studied. The average lifetime of the composite system as a function of incident energy peaks at about 9–10 A MeV for the side-side orientation and 11–12 A MeV for the nose-nose orientation, respectively. The inclusion of β_4 deformation in prolate uranium seems to enhance the production probability of SHF in the side-side case as the more stable structure of initial uranium effectively reduces the excitation energy of the composite system. It is suggested that the optimal initial condition for production of SHF in $^{238}U + ^{238}U$ could be the side-side orientation and prolate deformation with a small β_4 deformation (the ground state of uranium). Considering that the symmetry axis of the initial nuclei is oriented in an arbitrary direction with an equal probability, the lifetime of composite system and the SHF production probability are also studied with randomly selected orientation direction of initial nuclei.

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I. INTRODUCTION

Since the 1970s, the superheavy elements (SHEs) with $Z = 107$–118 have been synthesized by "cold fusion" reactions with lead and bismuth targets [1] and "hot fusion" reactions with actinide targets [2]. Note that for elements with $Z > 100$ only neutron-deficient isotopes (located to the left of the stability line) have been synthesized so far. As is well known, any further experimental extension of the region of SHEs to the center of the predicted first "island of stability" formed by the neutron shell around $N = 184$ by means of complete fusion is limited by the neutron number of available projectiles and targets and by the very low production cross section as well. Therefore, it is necessary to search for other ways, in addition to the complete fusion reaction, to approach the region of the island of stability. It is also expected to produce superstrong electric fields to test spontaneous positron-electron (e^+e^-) pair emission predicted by the quantum electrodynamics theory when the transient formed composite system has a long enough lifetime [3,4]. The strongly damped reactions between very heavy nuclei, such as U + U, could be one possible approach for those purposes [5–7]. The theoretical description of the strongly damped reactions between very heavy nuclei, such as U + U, is one of the most difficult problems in nuclear physics due to the extremely large number of degrees of freedom involved. This motivates the use of microscopic approaches. The quantum molecular dynamics type model is a microscopic n-body dynamical model which has been successful in describing the main features observed in nuclear collisions [8–11]. In Ref. [12], the properties of composite systems formed in $^{238}U + ^{238}U$ and $^{232}Th + ^{250}Cf$ reactions were studied and later in Ref. [13] the mass distribution of products in $^{238}U + ^{238}U$ at 7.0A MeV was studied by using the improved quantum molecular dynamics model (ImQMD). It was shown in Ref. [13] that the calculated mass distribution is to be roughly consistent with the experiment measurement of GANIL [14]. However, in these studies, the deformation of ^{238}U was not considered. A nucleus ^{238}U in its ground state exhibits a prolate deformation, which leads to different orientations of projectile and target at the initial time of the $^{238}U+^{238}U$ reaction. This may influence the reaction features, such as the lifetime of the composite system, the mass distribution of fragments, especially the production probability of superheavy nuclei. In recent years, the orientation effect on the potential energy surface was studied by Langevin-type equation approach [6,7] and dinuclear model [15–17]. It was pointed out that the orientation effect might play a rather important role in sub-barrier reactions of deformed nuclei. Recently, in Ref. [18] the TDHF theory was used to study collision dynamics of two ^{238}U atomic nuclei. In particular, the orientation effect on the lifetime of the composite system was emphasized. It was found that the lifetime of the composite system formed in the $^{238}U + ^{238}U$ reaction strongly depended on the orientation of initial two deformed ^{238}U. The calculated lifetime of the composite system as a function of incident energy for the side-side (S-S) and the nose-side (N-S) orientations had similar behaviors with that obtained in Ref. [12], but for the nose-nose (N-N) orientation case, the lifetime of the composite system exhibited a rather different behavior, i.e., a plateau with respect to incident energies, the value of which lowers to 2×10^{-21} s (due to the formed high density neck area leading to the third heavy fragment emission). This different behavior of the lifetime of composite

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system in the N-N orientation case is worth studying further. In addition to the lifetime of the composite system, the influence of the initial deformation and orientation of projectile and target on the interaction potential between them is of concern. To aim at the promotion of the production probability of superheavy nuclei by the strongly damped reaction between very heavy nuclei, the choice of an optimal initial condition of the reactions is much more desirable. For this purpose the study of the effect of initial deformation and orientation of projectile and target on the production probability of superheavy nuclei is of important significance.

In this work, we perform the ImQMD model calculations to study the effects of initial orientation and deformation of reaction partners on the reaction mechanisms of two ^{238}U, where many-body correlations and fluctuations can arise from the A-body dynamics [19,20]. We will mainly investigate the effects of orientation and deformation by considering the head-on reaction of ^{238}U $+^{238}$U. Since the touching configuration can be considered as a real entrance of the reaction, we first analyze the deformation change of reaction partners at touching time. Then we study the incident energy dependence of the lifetime of the transient composite system, the interaction potential between reaction partners, and the production probability of SHF under different initial orientations and shapes of projectile and target. For simplification, we only take nose-nose and side-side cases as initial orientations. Concerning the deformation of uranium, we take its ground state shape with $\beta_2 = 0.215$ and $\beta_4 = 0.093$ given by Ref. [21] as an initial deformation. In practice one also often simply takes the prolate shape with $\beta_2 = 0.215$ as an initial shape of uranium. Thus, in this paper we consider these two cases of deformation.

Considering that the symmetry axis of the initial nuclei is oriented in an arbitrary direction with an equal probability, we also perform the calculations of the average lifetime of the composite system and the average probability of producing SHF per event with randomly selected orientation directions of initial nuclei and briefly present the calculation results.

The paper is organized as follows. In Sec. II, we briefly introduce the theoretical model. In Sec. III we present the calculation results for the lifetime of the transient composite system and production probability of SHF, respectively. Finally, we give a brief summary in Sec. IV.

II. BRIEF DESCRIPTION OF THE IMQMD MODEL

In this work, the same model is adopted as in Refs. [12,13,22–24]. For the reader's convenience, we briefly introduce the ImQMD model. In the model, each nucleon is represented by a coherent state of a Gaussian wave packet. As is the same as in other transport models, the ImQMD model tracks the time evolution of a nuclear reaction and separately treats the nuclear equation of state through the mean field part and the nucleon-nucleon collision cross sections through the collision part. Within this model, the potential energy of the system reads

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

where $U_{\rm Coul}$ is the Coulomb energy, while the nuclear contribution can be represented in local form

$$U_{\rm loc} = \int V_{\rm loc} d\mathbf{r} \tag{2}$$

and the potential energy density $V_{\rm loc}$ can be derived directly from a zero-range Skyrme interaction:

$$\begin{aligned} V_{\rm loc} = {} & \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_0}{2\rho_0}(\nabla\rho)^2 \\ & + \frac{c_s}{2\rho_0}[\rho^2 - \kappa_s(\nabla\rho)^2]\delta^2 + g_\tau \frac{\rho^{\eta+1}}{\rho_0^{\eta}}, \end{aligned} \tag{3}$$

where ρ is the nucleon density. $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry, and ρ_n, ρ_p are neutron and proton densities, respectively. The same parameters are used as in [12,13], which are listed in Table I.

The Coulomb energy is written as a sum of the direct and the exchange contribution:

$$\begin{aligned} U_{\rm Coul} = {} & \frac{1}{2}\int\int \rho_p(\mathbf{r})\frac{e^2}{|\mathbf{r}-\mathbf{r}'|}\rho_p(\mathbf{r}')d\mathbf{r}d\mathbf{r}' - e^2\frac{3}{4}\left(\frac{3}{\pi}\right)^{1/3} \\ & \times \int \rho_p^{4/3} d\mathbf{R}. \end{aligned} \tag{4}$$

The isospin-dependent in-medium nucleon-nucleon scattering cross sections in the collision term are applied, and the Pauli blocking effects are described in Refs. [25,26]. The phase space occupation number constraint method and the system-size-dependent wave-packet width are adopted as those in previous works [12,13].

At the code level, the initialization of the reaction condition, such as the properties of projectile and target nuclei and the corresponding reaction geometry should be included in the code. To have a proper initial condition (with good properties of projectile and target nuclei) is of vital importance for studying low-energy heavy-ion reactions by means of the transport model description. As the aim of this work is to study the orientation and deformation effects on reaction dynamics of ^{238}U+ ^{238}U, we will pay special attention to the initial condition, especially the shape of initial nuclei and the orientation. As mentioned above we adopt two different deformations with (1) $\beta_2 = 0.215$ and $\beta_4 = 0$, named init-I and (2) $\beta_2 = 0.215$ and $\beta_4 = 0.093$, named init-II as initial shapes of the ^{238}U nucleus. The nucleons are sampled according to

TABLE I. 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	0.08	0.165

the density distribution (the Fermi distribution) which reads

$$\rho(r,\theta) = \frac{\rho_0}{1+\exp[\frac{r-R(\theta)}{a}]}. \tag{5}$$

Here,

$$R(\theta) = R_0\big[1+\beta_2 Y_{20}(\theta)+\beta_4 Y_{40}(\theta)\big] \tag{6}$$

and $R_0 = 1.16A^{1/3}$fm, $a = 0.5$ fm. In order to check the stability of initial deformed nuclei, the ratio $\beta = L_Z/L_X$ is used to characterize the deformation of a nucleus for simplicity. L_Z and L_X are the lengths of the z axis and x axis of the nucleus, respectively. In Fig. 1 we plot the equidensity distribution of the ^{238}U nucleus with the init-II condition as an example for illustration. We show the time evolution of (a) the binding energy, (b) the root-mean-square radius, and (c) the β value of initial nuclei in Fig. 2. In the figure, one can see that these three variables of initial nuclei remain constant with a small fluctuation within a time period of 1000 fm/c. In our work, only those sampled nuclei with good properties and stable enough feature without spurious emission are taken to be initial nuclei. For self-consistency, we adopt the same effective nuclear potential energy density in making initial nuclei and the simulation of the reaction process when solving the Hamiltonian equation. To investigate the orientation and deformation effect, we consider head-on collisions. For the head-on collisions, the orientations of nose-nose (N-N) and side-side (S-S) of two nuclei along the z axis in the x-z plane are considered and the initial distance between the centers of mass of the projectile and the target is taken to be 40 fm. Thus, we have four different initial conditions, namely, N-N orientation with init-I and init-II and S-S orientation with init-I and init-II. In addition, in the QMD model, fragments are formed due to A-body correlations caused by the overlapping wave packets. A cluster searching process should also be applied. In this work the method of cluster recognition is in terms of the conventional coalescence model [11], in which particles with relative momentum smaller than P_0 and relative distance smaller than $R_0$are considered to belong to one cluster. Here R_0 and P_0 are taken to be 3.5 fm and 300 MeV/c, respectively, the same as in Refs. [12,13]. At each time step of the time evolution of the reaction, fragments are searched,

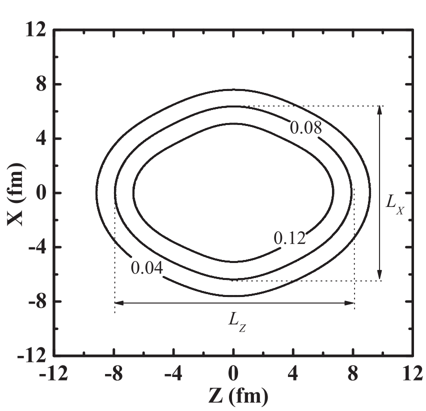

FIG. 1. Contour plot of the density distribution for the initial nuclei ^{238}U(the density unit is fm^{-3}).

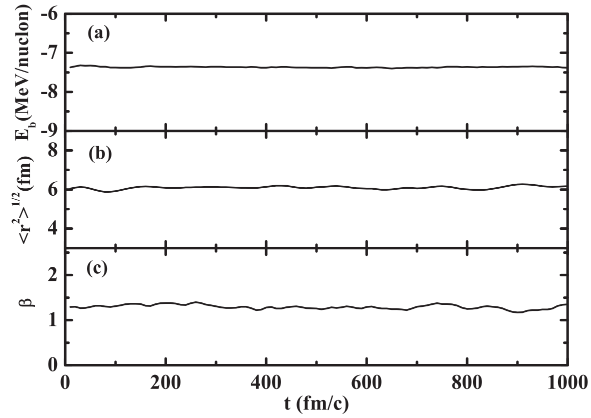

FIG. 2. The time evolution of (a) the binding energy, (b) the root-mean-square radius and (c) the deformation variable β of initial deformed nuclei ^{238}U.

by which we can find the touching time and the touching configuration as well as the fragments.

III. RESULT AND DISCUSSION

A. Behavior of touching configurations

Since the touching configuration can be considered as a real entrance of the reaction, we study the touching configuration in the S-S and the N-N orientation cases. Before nuclear interaction can take place, two nuclei are heated by a Coulomb interaction. The mutual Coulomb interaction between projectile and target may influence not only the distance between the two nuclei but also their shapes. Within a microscopic transport model one has first to define a nuclear surface by an equidensity surface based on the density distribution of the reaction system. In this work, this equidensity surface is taken to be at the half-normal density $\rho = 0.5\rho_{\rm nor} = 0.08$ fm^{-3}. The touching time is the time when the projectile and target merge into one transient composite system found by the cluster search and the density at the touching point is found to be around 0.05 fm^{-3} in the simulations. In order to study the shape change caused by the Coulomb interaction, in Fig. 3 we present the deformation distributions of the ^{238}U nucleus with the init-II deformation at the touching time at the incident energy 10A MeV for N-N and S-S orientations, respectively. Here, it should be noted that the β value is only a ratio between the lengths of axes parallel to the Z and X directions of projectile and target nuclei and therefore it can only roughly give us the information of deformation of two nuclei during the approaching process. The arrows in the figure indicate the initial β value of the ^{238}U nucleus. One can see from Fig. 3 that the β values of ^{238}U at the touching time are distributed over a wide range for both orientations. Moreover from the comparison between the left and right panels of Fig. 3 one sees that the spread width and the centroid shifting for the N-N orientation case are much larger than those for the S-S orientation. This means that the most probable deformation of the ^{238}U nucleus at the touching configuration remains almost unchanged for the S-S orientation case, while for the N-N orientation the

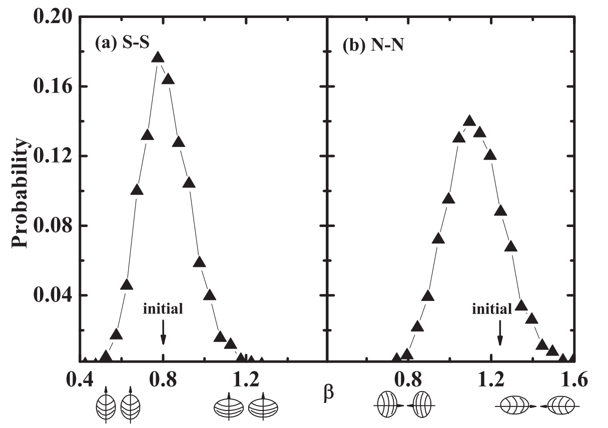

FIG. 3. The deformation distributions of ^{238}U with the init-II condition at touching configuration for (a) S-S orientation and (b) N-N orientation. The incident energy is taken to be $10A$ MeV and the initial deformation is indicated by the arrows.

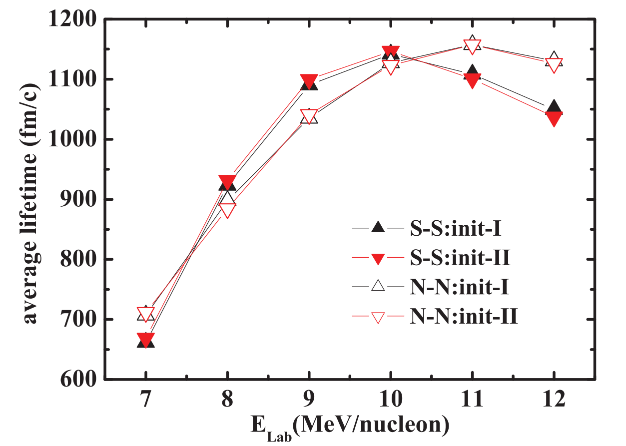

FIG. 4. (Color online) The energy dependence of the lifetime of the composite system for the head-on ^{238}U $+^{238}$U reaction for four different initial conditions. Lines serve to guide the eye.

most probable deformation at the touching configuration deviates from the initial one and moves towards a less prolate shape. For the init-I deformation case, the deformation distributions of ^{238}U nuclei at the touching configuration are quite similar with the case of the init-II. This means that the deformation distributions at the touching configuration are not very sensitive to the small β_4 deformation. In addition, the energy dependence of the deformations of projectile and target nuclei at the touching configuration is also studied. We find that as energy increases, the spread width of deformation distribution diminishes.

B. Lifetime of giant composite system

We define the lifetime of the composite system ($Z \geqslant 170$) as the time interval from the touching point of two nuclei to their reseparation. During this time interval, the reaction system experiences from the touching to the forming of a dinuclear system and further turning into a deformed mononuclear composite system, finally reseparating into two big fragments with light cluster emission. The lifetimes for different events could be quite different due to fluctuation (see Ref. [12]). In Fig. 4 we present the energy dependence of the average lifetime of the composite system for a head-on ^{238}U $+^{238}$U reaction for four different initial conditions. The general behavior of the average lifetimes for four different initial conditions is of a certain similarity, i.e., the lifetime first increases with energy and at a certain energy it reaches a maximum value and then decreases with energy. The maximum lifetime of a composite system is about 1100 fm/c which is consistent with those shown in Refs. [12,18]. The initial orientation of the projectile and target obviously influences the lifetime. One can see from the figure that the average lifetime of the composite system at low energy ($7A$ MeV) for the S-S orientation case is shorter compared with that for the N-N orientation case due to the stronger Coulomb repulsion in the S-S orientation case, but the lifetime for the S-S orientation case increases with energy faster than that for the N-N orientation case and quickly exceeds that for the N-N case. After reaching a maximum value the average lifetime for the S-S orientation also decreases faster than that for the N-N orientation. The maximum is located at about $E = 10A$ MeV for the S-S orientation and at $11A$ MeV for the N-N orientation. The effect of the initial deformation of the projectile and target on lifetime is relatively weak compared with the initial orientation. The inclusion of β_4 deformation in init-II only slightly enlarges the difference between the lifetime of a composite system with S-S and N-N orientations.

In Ref. [12], it was explored for a spherical initial ^{238}U that at low energies ($\leqslant 7A$ MeV) the formed mononuclear composite system normally elongates along the Z (beam) direction, and subsequently reseparates along this direction, while at higher energies ($\geqslant 11.5A$ MeV) the elongation and reseparation of the mononuclear composite system normally happen along the direction perpendicular to the beam direction. Only at a certain energy does the composite system reach a state close to a thermodynamic equilibrium state, and the distributions in momentum and coordinate space are close to the spherical one, which corresponds to the longest lifetime of the system. For deformed initial nuclei, it is obvious that for the the S-S orientation case, two nuclei have a shorter distance to reach the monosystem configuration but have stronger Coulomb repulsion compared with the N-N orientation. So the average lifetime of the composite system at low energy ($7A$ MeV) for the S-S case is shorter than that for the N-N case. But the touching surface area between two reaction partners increases faster for the S-S case than that for the N-N orientation case. Thus, for the S-S orientation case, it is favorable to make the composite system reach nearly spherical distributions in momentum and coordinate space at a lower energy of $10A$ MeV compared with the N-N orientation case. As the incident energy further increases, the S-S orientation is more favorable to form a deformed mononuclear composite system along the direction perpendicular to the beam direction than the N-N orientation is, and thus the lifetime of the composite system in this case decreases faster with energy increasing compared with the N-N orientation case. We notice that the energy dependence of the lifetime for the S-S orientation case is quite similar to Ref. [18], but the results for the N-N orientation show some different behavior with that in Ref. [18], where a flat energy dependence behavior with a lower lifetime of about 2×10^{-21} s (600 fm/c) was obtained for the N-N orientation due to the strong overlap of the two noses, producing a density in the neck region higher than the saturation density leading to the third heavy fragment emission. The dissipation and fluctuation effects are probably the cause for the different behaviors. One already sees from Fig. 3 that the two noses at the touching time for the N-N orientation already disappear or reduce a lot in the large part of the events due to the strong dissipation and fluctuation which exists during the period of two nuclei contacting [12], and thus the formation of the third heavy fragment is strongly suppressed.

In order to understand the effects from the different initial orientation and deformation of the projectile and target we further investigate the interaction potential energy between projectile and target at incident energy $E = 10A$ MeV for four initial conditions. In the ImQMD model, the nucleus-nucleus potential energy can be calculated by Refs. [12,27,28]:

$$V_{\rm pot}(R) = E_{\rm tot}(R) - E_1 - E_2, \quad (7)$$

where $E_{\rm tot}(R)$ is the total energy of the whole system, which is dependent on the dynamical density distribution of the system. E_1 and E_2 are the energies of individual projectile-like fragment and target-like fragments, respectively. In the dynamical description, the potential $V_{\rm pot}(R)$ and the relative distance R between two reaction partners evolve with time, and thus $V_{\rm pot}$ is also a function of time. In Fig. 5 we show the interaction potential as a function of R and the inserted figure shows the time evolution of potentials for a head-on $^{238}U + ^{238}U$ reaction at $10A$ MeV. For the S-S orientation case, two reaction partners approach each other quite closely and a pocket appears in the interaction potential, while for the N-N case the curve of the potential seems flatter and the pocket becomes shallower. Thus we can understand from Fig. 5 why at $10A$ MeV the lifetime of the composite system for the S-S case is longer than that for the N-N case, in a certain sense. Similar conclusions were also indicated in Ref. [29]. In addition, from Fig. 5 one can also see that the different initial deformations of nuclei, i.e., init-I and init-II, have only very little influence on the interaction potential.

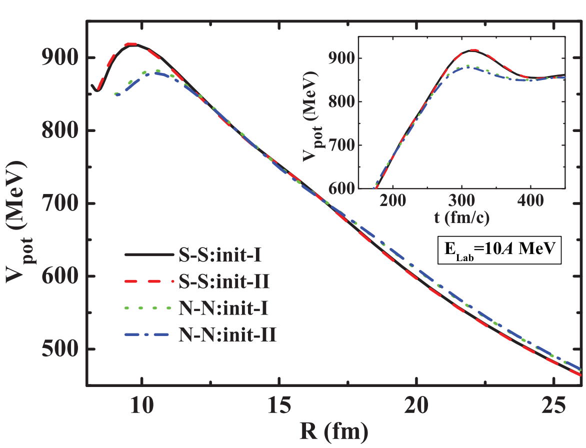

FIG. 5. (Color online) The interaction potential energies between the projectile-like fragment and target-like fragment for a head-on $^{238}U + ^{238}U$ reaction at $10A$ MeV.

C. Probability of producing super-heavy fragments

The superheavy fragments are defined as the fragments with $Z > 110$ in this work. In order to calculate the production of SHF a cluster searching process is applied. As mentioned in Sec. II the method of the conventional coalescence model [11] is adopted as in Ref. [13]. For each event, the time evolution of the reaction is tracked. The cluster searching process can check whether a SHF is produced or not in an event at any time. Then the number of events in which one SHF is produced can be obtained, which depends on the time of the cluster searching (see Ref. [13]). In this work, the cluster searching process is performed at reseparation time and at the time of 1000 fm/c after reseparation, respectively. Because only one SHF can be produced in one event at most, the average probability of producing SHF in one event can be calculated by the number of events in which one SHF is produced divided by the number of total events. The probability of producing SHF as a function of incident energy for a head-on $^{238}U + ^{238}U$ reaction for four initial conditions is presented in Fig. 6. Panels (a), (b), and (c) are calculated at the reseparation time, and (d), (e), and (f) show the results at the time of 1000 fm/c after reseparation of the composite system. One can find from (a), (b), (d), and (e) that the probability of producing SHF for the S-S case at about $7A$ MeV is lower than that for the N-N case for both initial init-I and init-II, and then the probability increases rapidly for the S-S case and exceeds that for the N-N case at about $8A$ MeV. With an incident energy increasing further, the probability of producing SHF increases further till reaching their maximum values. Then the probability of producing SHF decreases with a further increase of incident energy. At the time of 1000 fm/c after reseparation, the probability of producing SHF in one event for the S-S case reaches a maximum value at $9A$ MeV for the init-I case [see Fig. 6(d)] and at $10A$ MeV for the init-II case [see Fig. 6(e)]. One notices that for the init-II condition the maximum value of the probability of producing SHF for the S-S orientation case is obviously higher than that for the N-N case, as shown in Fig. 6(b) and (e). It is also interesting

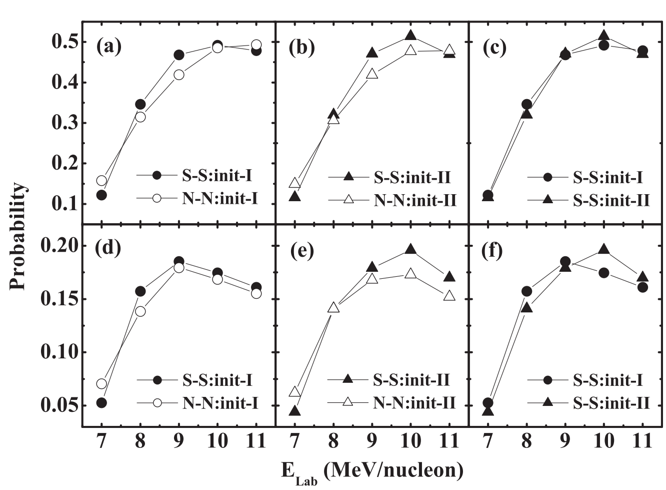

FIG. 6. The energy dependence of the probability of producing SHF for a head-on $^{238}U + ^{238}U$ reaction for four initial conditions. (a), (b), and (c) are calculated at reseparation time and (d), (e), and (f) at the time of 1000 fm/c after reseparation.

to find from Fig. 6(c) and (f) that for the S-S orientation case the maximum probability of producing SHF is enhanced obviously for the init-II case compared to the init-I case at the time of 1000 fm/c after reseparation [see Fig. 6(f)] but is only slightly enhanced at reseparation time [see Fig. 6(c)]. It implies that the inclusion of β_4 deformation in the initial uranium nucleus might effectively reduce the excitation energy of the composite system due to the more stable structure of uranium and thus obviously enhances the probability of producing SHF at the time of 1000 fm/c after reseparation. This study suggests that S-S orientation and init-II deformation are probably the most beneficial conditions for the production of SHF.

However, the symmetry axis of the initial nuclei is oriented in an arbitrary direction with an equal probability. Therefore, we further calculate the lifetime of the composite system and probability of producing SHF with randomly selected orientation directions and the init-II deformation of initial nuclei. Figures 7 and 8 show the incident energy and impact parameter dependence of the lifetime of the composite system and the probability of producing SHF, respectively. Figure 8(a) is calculated at the reseparation time and (b) is obtained at the time of 1000 fm/c after reseparation. 1500 events of the ^{238}U $+^{238}$U reaction are applied for each energy and each impact parameter. One sees from Fig. 7 that the lifetimes of the composite systems for all impact parameters are roughly similar in their tendency of the energy dependence, but their magnitudes decrease with impact parameter quickly. At $b = 1.5$ fm, the peak of the lifetime of the composite system is located at $E = 10A$ MeV, similar to the S-S orientation case shown in Fig. 4. As the impact parameter increases the peak of the lifetime of the composite system moves to higher energy. If we compare the results in Fig. 7 with previous work in [12,13] where the initial ^{238}U was taken to be spherical shape, it can be found that for low incident energies (for example at $E = 7.0A$ MeV) the lifetime of the composite system becomes shorter but the general behavior and the maximum value of the energy dependence of the lifetime of the composite system

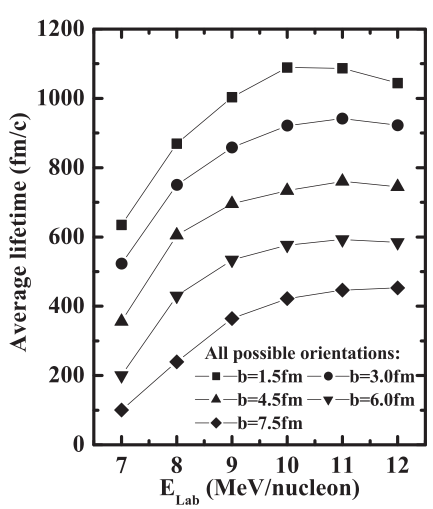

FIG. 7. The energy and impact parameter dependence of the lifetime of composite system for the ^{238}U $+^{238}$U reaction when the orientation directions of initial nuclei are selected randomly.

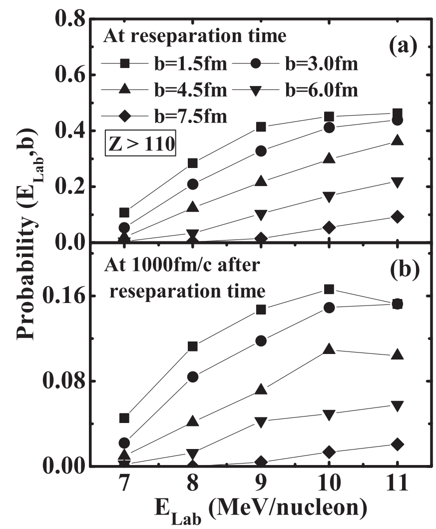

FIG. 8. The energy and impact parameter dependence of the probability of producing SHF for the ^{238}U $+^{238}$U reaction when the orientation directions of initial nuclei are selected randomly.

do not change much when the deformation of the initial ^{238}U nucleus is taken into account. From Fig. 8 we find that the SHF production probabilities first increase with energy for all impact parameters then they decrease or further increase with energy depending on the impact parameter. The magnitudes of SHF production probabilities drop quickly with an increasing impact parameter. In the previous work [13], the excitation energy distribution of the transuranic fragments with $Z \geqslant 100$ for ^{238}U $+^{238}$U at incident energy $7.0A$ MeV was studied and it was found that for central collisions the excitation energy could be very high but for intermediate impact parameter region $b = 5$–7 fm, the excitation energy distribution had a tail extending to the low excitation energy which was meaningful for producing superheavy nuclei. However, the production of final products, such as SHEs in ^{238}U $+^{238}$U, strongly depends on the excitation energy of fragments and the decay process of these fragments, which need to be studied further.

IV. SUMMARY

In this work the effects of initial deformation and orientation in the ^{238}U + ^{238}U reaction were studied by using the ImQMD model. We find that the deformation of ^{238}U at the touching point spreads over a wide range for both S-S and N-N orientations. Moreover, the spread width and the centroid shifting (to a smaller β value) for the N-N orientation case are much larger than those for the S-S orientation case for both init-I and init-II deformation conditions. For the S-S orientation case, a pocket appears in the interaction potential, while for the N-N case the curve of the potential seems flatter and the pocket becomes shallower. Our results show that the effects of the initial orientation on the average lifetime of the composite system and the average probability of SHF production per event are much stronger than that from initial deformation (with and without β_4 deformation). The energy dependence of the general behaviors of the average lifetime and the production probability of SHF at reseparation time are strongly correlated. Both first increase with increasing energy and at a certain energy they reach their individual maximum values, and then decrease with energy. The location of the maximum in the average lifetime is at $10A$ MeV for the S-S orientation case and $11A$ MeV for the N-N orientation case, respectively. The maximum value of the average lifetime of the composite system is about 1100 fm/c for four different initial conditions. The production probability of SHF calculated at the time of 1000 fm/c after the reseparation for the S-S case reaches a maximum value at $9A$ MeV for init-I and at $10A$ MeV for init-II, respectively, and in the latter case the maximum value of the production probability of SHF is obviously higher than that for the N-N and init-II cases [Fig. 6(e)]. The inclusion of β_4 deformation in prolate uranium seems to enhance the production probability of SHF in the side-side case as the more stable structure of initial uranium might effectively reduce the excitation energy of the composite system. From these studies it is suggested that the fluctuation and dissipation play important roles in the reaction dynamics of two ^{238}U and the optimal initial condition for production of SHF is probably the S-S orientation and init-II deformation.

Considering that the symmetry axis of the initial nuclei is oriented in an arbitrary direction with an equal probability, the lifetime of the composite system and the average probability of producing SHF are also studied with randomly selected orientation directions of initial nuclei. We find that the average lifetime of the composite system becomes shorter at low incident energies but the general behavior and maximum value of the energy dependence of the lifetime do not change much compared with the results obtained when initial ^{238}U is taken to be spherical shape studied in previous work.

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