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The Role of Neck Evolution in the Synthesis of Superheavy Element 112 *

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The coupled and uncoupled Langevin equations in two-dimensional collective space are used to study the neck dynamics of the mass asymmetric system $^{48}Ca+^{238}U$ at the above barrier energy. The results show that the coupling between the neck and radial degrees of freedom delays the transition from dinucleus to mononucleus, and correspondingly increases the lifetime of the dinucleus system. The lifetime of the dinucleus for the asymmetric system $^{48}Ca+^{238}U$ is about 11.6 and 13.0×10^{-22} s, obtained with uncoupled and coupled Langevin equations. We calculate the evaporation residue (ER) cross sections for the 3n and 4n evaporation channels in the $^{48}Ca+^{238}U$ reaction leading to the formation of $^{283}112$ and $^{282}112$ isotopes in three different approaches, i.e., coupled, uncoupled and frozen approximation, and compare them with the experimental data. It is found that the results of the uncoupled and frozen approximation are in close similarity, while the coupling between the radial and neck degrees of freedom reduces the ER cross section by about 30%, compared with the case of frozen approximation.

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It has been commonly accepted for many years that the fusion of heavy nuclear systems is hindered, compared with that of lighter systems. The mechanism responsible for fusion hindrance is that for a system with fissility, where parameter x exceeds about 0.7, the saddle-point shrinks into the position behind the contact configuration of the projectile and target combination. In a collision involving such nuclei, after contact the rapid growth of the neck between the target and the projectile changes the system from a dinuclear regime to a mononuclear one. Accompanying this process, the heavy composite system is injected from the fusion valley into an asymmetric fission valley, which is located outside the saddle-point (the inner barrier). Hence, the fusing system must overcome the inner barrier to reach the compound nuclear configuration, resulting in the formation probability of the compound nucleus being greatly reduced.

Recently, it has been realized that for very heavy systems, the injection-point configuration has a critical influence on the fusion process.[1] Boilley *et al.*[2] have shown the severe hindrance effects of the neck growth process on the fusion of heavy symmetric systems due to a dynamic coupling between the radial and neck degrees of freedom. However, they made several approximations in their work. For instance, in their calculations the inertia term was neglected and the friction tensor γ was assumed to be independent of the radial and neck degrees of freedom. The relative and neck motions were also studied for symmetric systems by Zhao *et al.*[3] with an improved quantum molecular dynamics model, and it was found that the mass parameters obtained from their microscopic transport model are larger than the ones deduced from the hydrodynamic model we used here. Very recently, Liang *et al.*[4–6] investigated the neck evolution for asymmetric systems with coupled Langevin equations in the two- and three-dimensional collective space, and found that the coupling brings the system into a somehow elongated shape when the injection into the asymmetric fission valley takes place, and hence decreases the fusion probability and the relevant evaporation residue (ER) cross sections. In this Letter, we make a close inspection of the role of neck evolution in the production of superheavy nuclei for the asymmetric system ^{48}Ca+^{238}U by comparing the results of three different approaches, *i.e.*, coupled, uncoupled and frozen approximation.[7] Moreover, the lifetime of the dinuclear system ^{48}Ca+^{238}U is deduced, which is meaningful for the theoretical study of superheavy elements.

The orientation effects of deformed nuclei play an important role in subbarrier fusion. However, it is not so easy to define the potential energy of deformation for the case of two touching arbitrary-oriented deformed nuclei. The main difficulty here stems from the lack of knowledge about the subsequent evolution of the nuclear shapes after two nuclei contact each

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other. In addition, we deal with the fusion reactions at the above barrier energies. Hence, the effects of the target deformation should be relatively less important. For simplicity, target deformation is not taken into account in the dynamic simulations, and the shape of the system is specified in terms of two spheres with radii R_1 and R_2 smoothly connected by a hyperboloidal neck. Let L stand for the total length of the system, $s = L - 2(R_1 + R_2)$ for the surface separation between two spheres, and n is the radius of the neck. In the present work only the neck and radial degrees of freedom are concerned. The mass asymmetry degree of freedom is not taken into account in the calculations because its influence on neck growth is limited. The coupled Langevin equations of motion in two-dimensional collective space have the form

$$\begin{aligned}\frac{dq_i}{dt} &= \mu_{ij}p_j,\\ \frac{dp_i}{dt} &= -\frac{1}{2}p_jp_k\frac{\partial\mu_{jk}}{\partial q_i} - \frac{\partial V(q)}{\partial q_i}\\ &\quad -\gamma_{ij}\mu_{jk}p_k + \theta_{ij}\xi_j(t),\end{aligned} \tag{1}$$

where $q_i \equiv s, n$ represents the collective coordinates, p_i its conjugate momenta, $V(q)$ is the nuclear deformation potential energy calculated in the framework of the finite range liquid drop model (FRLDM),[8,9] μ_{ij} $(i, j \equiv s, n$, the same for the other quantities in the following) denotes the inverse matrix elements of the inertia tensor m_{ij}, and γ_{ij} is the friction tensor calculated with the one-body dissipation model.[10−14] The normalized random variables ξ_j are assumed to be independent white noises. The strength θ_{ij} of the random force is given by $\theta_{ik}\theta_{kj} = T\gamma_{ij}$, with T being the temperature of the heat bath. The inertia tensor m_{ij} was evaluated under the Werner–Wheeler approximation[15,16] for incompressible and irrotational flow.

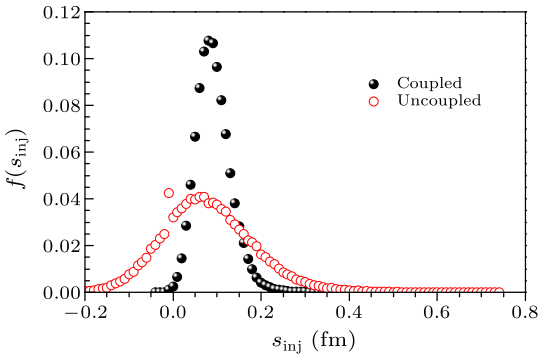

Fig. 1. The probability distributions of s_{inj} calculated with the coupled (solid circles) and uncoupled (open circles) Langevin equations for the ^{48}Ca+^{238}U system at $E_{\rm c.m.} = 200$ MeV.

The initial conditions for the radial and neck motions were defined in Refs. [17,10]. Similar to the criterion suggested by Swiatecki,[18] we define $n = \sqrt{0.5}R_i$ with $R_i = min(R_1, R_2)$ to be the boundary between the dinuclear and mononuclear regimes. By solving these dynamic equations, the probability distributions of the radial degree of freedom at the injection point $s_{\rm inj}$, which is the distance between the surfaces of two approaching nuclei where injection into an asymmetric fission valley takes place, are obtained. As an example, the resultant distributions $f(s_{\rm inj})$ are plotted in Fig. 1 for the ^{48}Ca+^{238}U system at the center-of-mass energy $E_{\rm c.m.} = 200$ MeV.

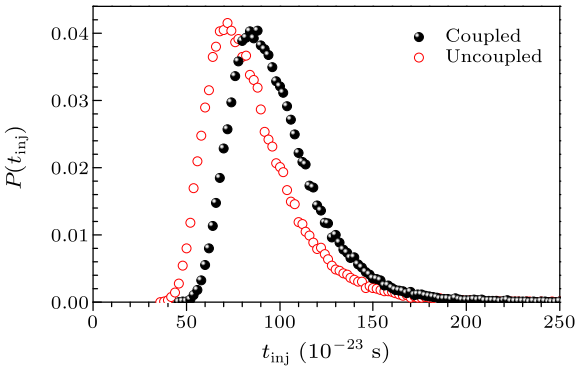

Fig. 2. The distributions of the transition time for the ^{48}Ca+^{238}U system with two approaches of the Langevin equations. The open and closed circles represent the uncoupled and coupled calculations, respectively.

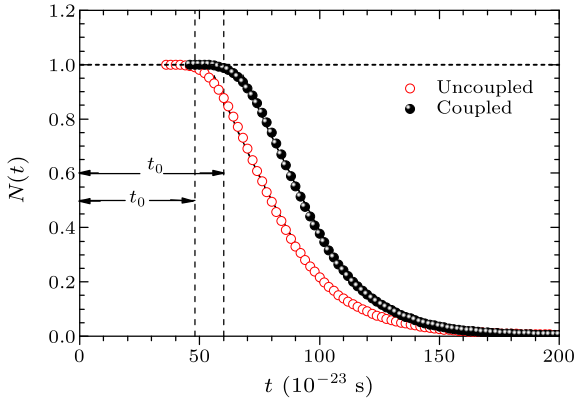

Fig. 3. The number of the dinuclear ^{48}Ca+^{238}U system as a function of time calculated with coupled (solid circles) and uncoupled (open circles) Langevin equations. Here, t_0 is the duration in which there is no transition taking place between the dinuclear and mononuclear regimes. The solid lines are the exponential fit of $N(t)$ during the decay period.

It is seen that the coupling between the neck and radial motions brings about a much narrower distribution and pushes its peak to a slightly larger radial position, which is very sensitive to the ER cross sections. This causes a difference between the results of the present work and that of Ref. [10] for the ^{50}Ti+^{249}Cf system. Actually, there are several coupling terms in the two-dimensional Langevin equation. Sometimes, their effects are in subtle equilibrium. This needs to be further investigated if the ^{50}Ti+^{249}Cf system is the

case.

We would like to point out that at $E_{\rm c.m.} = 200$ MeV, the composite nucleus in the neck evolution process has an excitation energy of about 45 MeV, and therefore its shell structure has most probably already been washed out.

Figure 2 shows the distributions of the transition time for the ^{48}Ca+^{248}U system with two approaches of the Langevin equations. It is found that the coupling between the radial and neck degrees of freedom delays the transition from dinucleus to mononucleus.

In order to evaluate the lifetime of the dinuclear system, the number of the dinucleus $N(t)$ is plotted as a function of time in Fig. 3. Here, we set $N_0 = 1.0$. Since in the case of the asymmetric systems under consideration, the probability of quasifission taking place during neck growth is negligible, $N(t)$ as well as the lifetime of the dinucleus only depend on the neck evolution process. It may be seen that during the interval t_0, no transition occurs, and after t_0 the dinuclear system decays exponentially. We find $t_0 = 4.8$ and 6.0×10^{-22} s, respectively, for the uncoupled and coupled approaches. The lifetime of the dinuclear system for the ^{48}Ca+^{238}U system is about 11.6 and 13.0×10^{-22} s, obtained with the uncoupled and coupled calculations.

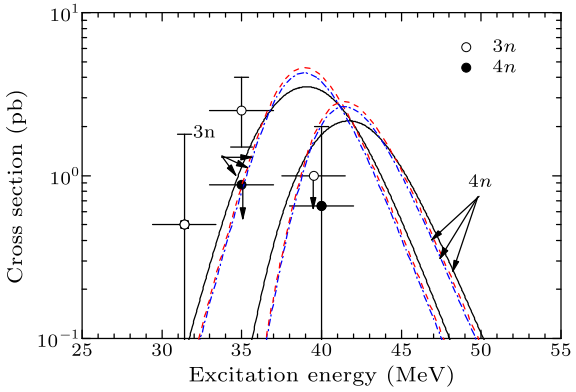

Fig. 4. The predicted evaporation residue cross sections for the $3n$ and $4n$ evaporation channels in the ^{48}Ca+^{238}U reaction leading to the formation of ^{283}112 and ^{282}112 isotopes. The solid and dash-dotted lines represent the results with the s_{inj} distributions calculated in terms of the coupled and uncoupled Langevin equations, respectively. The dashed lines display the cross sections calculated under the frozen approximation. The experimental data are taken from Ref. [29].

The cross section of a superheavy nucleus produced in a heavy ion fusion-evaporation reaction is calculated as follows:

$$\sigma_{\rm ER}(E_{\rm c.m.}) = \pi\lambda^2 \sum_{l=0}^{\infty}(2l+1)P_{\rm capt}(E_{\rm c.m.},l) \cdot P_{\rm fus}(E_{\rm c.m.},l)P_{xn}(E_{\rm c.m.},l). \quad (2)$$

where $P_{\rm capt}$ is the capture probability of the colliding nuclei after overcoming the Coulomb barrier and moving up to the contact point. We calculate $P_{\rm capt}$ by means of the semi-phenomenological barrier distribution function method proposed by Zagrebaev *et al.*[19,20] $P_{\rm fus}$ defines the probability that the system will go from the configuration of two nuclei in contact into the configuration of the compound nucleus (CN). We use a modified "fusion by diffusion" (FBD) model[1,7,10,21] to evaluate the CN formation probability $P_{\rm fus}$,

$$P_{\rm fus}(E_{\rm c.m.},l) = \frac{1}{2}\int {\rm erfc}(\sqrt{B(s_{\rm inj},l)/T})f(s_{\rm inj})ds_{\rm inj}.$$

Here, $B(s_{\rm inj},l)$ is the barrier height measured from the injection point, which consists of the macroscopic deformation energy $\Delta E(s_{\rm inj}, l=0)$ and rotational energy $\Delta E^{\rm rot}(s_{\rm inj},l)$ in the l-dependent FBD model.[1] The macroscopic deformation energy along the asymmetric fission valley is calculated using refined algebraic expressions.[1] The corresponding values of the rotational energy at the injection point and at the symmetric saddle point are calculated with the moments of inertia specified in Ref. [1].

Finally, P_{xn} represents the survival probability of the excited compound nucleus after evaporation of x neutrons in the cooling process. We calculate the last factor P_{xn} in a more or less convenient method; for details see Refs. [22–24]. We only emphasize the following points here: (i) the data of the microscopic shell correction $\Delta^{\rm gs}_{\rm sh}$ in the ground state and the neutron separation energy are taken from Ref. [25], and the macroscopic deformation energies B_{LD} are set to be zero;[23,26] (ii) the shape-dependence of the level density parameters of the daughter nucleus and the fissioning nucleus at the ground and saddle configurations, a_n and a_f, are taken into account;[7,23,27] (iii) the damping parameter of the shell effects $E_D = 18.5$ MeV[28,23] is used; and (iv) the values of the shell correction energy at saddle-point $\Delta^{\rm sd}_{\rm sh}$ are set to be zero,[23] hence the damping of the shell effects directly influences the decay width of neutron emission, Γ_n, rather than the fission width, Γ_f.

Because the neck grows rapidly, much faster than the characteristic speeds of the other collective degrees of freedom, its evolution will be considered as proceeding with the other collective degrees of freedom of the system approximately frozen.[7] Figure 4 displays the predicted evaporation residue (ER) cross sections for the $3n$ and $4n$ evaporation channels in the ^{48}Ca+^{238}U reaction leading to the formation of ^{283}112 and ^{282}112 isotopes and a comparison with the experimental data.[29] We calculate the cross sections in three different approaches, *i.e.* coupled (solid lines), uncoupled (dash-dotted lines) and frozen approximation (dashed lines), where the injection distance is fixed to be zero. It is seen from the figure that the results of the uncoupled and frozen approx-

imation are similar, while the coupling between the radial and neck degrees of freedom reduces the ER cross section by about 30% as compared to the case of frozen approximation.[7] It is noted that very recently Wang *et al.*[30] applied the dinuclear system model to evaluate the hot fusion reactions for the superheavy nuclei with $Z = 112$–120, and found that the calculated ER cross sections are in good agreement with the available experimental data.

In summary, the coupled and uncoupled Langevin equations in two-dimensional collective space are used to study the neck dynamics for the mass asymmetric system ^{48}Ca+^{238}U at the above barrier energy. By solving these Langevin equations, the $s_{\rm inj}$ probability distributions are obtained, which are related to the shape of the composite system at the transition moment. Meanwhile, the distributions of transition time calculated with the coupled and uncoupled Langevin equations are presented. The results show that the coupling between the neck and radial degrees of freedom delays the transition from dinucleus to mononucleus. In addition, we find that the lifetime of the dinuclear system for the asymmetric system ^{48}Ca+^{238}U is about 11.6 and 13.0×10^{-22} s in the uncoupled and coupled cases. This means that a dinucleus formed in a collision of two heavy nuclei quickly changes to a mononucleus with superdeformed shape. We have calculated the ER cross sections for the $3n$ and $4n$ evaporation channels in the ^{48}Ca+^{238}U reaction, leading to the formation of ^{283}112 and ^{282}112 isotopes in three different approaches, *i.e.*, coupled, uncoupled and frozen approximation, and compared them with the experimental data. It is found that the results of the uncoupled and frozen approximation are similar, while the coupling between the radial and neck degrees of freedom reduces the ER cross section by about 30% as compared to the case of frozen approximation because of the $s_{\rm inj}$ distribution being moved to a larger radial position due to the dynamic coupling.

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