Study on the formation of the composite system of ^{238}U+^{238}U*

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Abstract Strongly damped reactions of ^{238}U+^{238}U, at $E_{\rm cm}$ = 680—1880 MeV have been studied based on the improved quantum molecular dynamics model. We find that at a certain energy region the entrance channel potential is weakly repulsive and the dissipation is very strong after touching configuration, these two effects make the time delay of re-separation for colliding system. The single particle potential well of the transiently formed composite system has Coulomb barrier about 15—20 MeV high at the surface, which makes the excited unbound protons being still embedded in the potential well and moving in a common mono-single particle potential for a period of time and thus restrains from quick decay of the composite system.

Key words ImQMD model, strongly damped reaction, dissipation

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Recently renewed interest to the strongly damped reactions between very heavy nuclei, like U+U is conditioned by the necessity to clarify much better than before the dynamics of very heavy nuclear collisions at low excitation energy and by a search for new ways for the production of neutron-rich superheavy nuclei. Based on coupled Langevin-type equations the model for simultaneous description of deep inelastic scattering ,quasi-fission, fusion and regular fission was proposed in Ref. [1]. Within this model the collisions of ^{238}U+^{238}U, ^{232}Th+^{250}Cf and ^{238}U+^{248}Cm were investigated as an alternative way for the production of super-heavy elements and the large charge and mass transfer were found in those reactions due to inverse quasi-fission process[2]. Owing to the very large colliding system and very complicated process, a large number of collective degrees of freedom have to be involved in the macroscopic model to obtain a realistic description of the process. Thus one will meet difficulties by macroscopic dynamics model. In addition, the difficulty in calculation of multi-dimensional adiabatic potential energy surface and the large uncertainty in the strength of nuclear friction and its form-factor are still not yet solved. In this case, a microscopic transport theory model is worthy to be tried[3].

By using the microscopic dynamic model, the motions such as shape deformations, neck formation and rupture, nucleon transfer and so on are involved naturally, automatically and simultaneously. Therefore there is no need to introduce the friction strengths and their form-factors, mass parameters, etc., which are known to have a large uncertainty, but have to be introduced in the macroscopic description. The quantum molecular dynamics (QMD) model being successfully used in intermediate energy heavy-ion collisions was successfully extended to apply to heavy ion collisions at energies near the barrier by making

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a serious improvements[4, 5]. In the model both the mean field and collision term are treated properly. Thus, in principle, the dissipation, diffusion and correlation effects are all included without introducing any freely adjusting parameter. In this work we apply it to study the entrance channel potential, translation kinetic energy loss, single particle potentials and single particle energies to see how the giant composite systems of U+U are formed.

In the ImQMD model, each nucleon is represented by a Gaussian wave packet,

$$\phi_{\rm i}(\boldsymbol{r}) = \frac{1}{(2\pi\sigma_{\rm r}^2)^{3/4}} \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_{\rm i})^2}{4\sigma_{\rm r}^2} + \frac{\rm i}{\hbar}\boldsymbol{r}\cdot\boldsymbol{p}_{\rm i}\right], \quad (1)$$

where $\boldsymbol{r}_{\rm i}, \boldsymbol{p}_{\rm i}$, are the centers of i-th wave packet in the coordinate and momentum space, respectively. $\sigma_{\rm r}$ represents the spatial spread of the wave packet. The total N-body wave function is assumed to be the direct product of these coherent states. Through a Wigner transformation, the one-body phase space distribution function for N-distinguishable particles is given. The effects of the Pauli principle are considered. The approximative treatment of antisymmetrization is adopted by means of the phase space occupation constraint method[6]. The propagation of nucleons under the self-consistently generated mean field is governed by Hamiltonian equations of motion and the Hamiltonian consists of the kinetic energy and effective interaction potential energy. The effective interaction potential energy includes the nuclear local interaction potential energy and Coulomb interaction potential energy. The former is obtained from the integration of the nuclear local interaction potential energy density functional. The latter is the sum of the direct and the exchange contribution. The parameters used are the same as in Ref. [3]. The procedure of making initial nuclei of projectile and target is similar to that in Refs. [3, 5]. The binding energy for ^{238}U is required to be 7.57±0.05 MeV/nucleon and the root mean square radii to be 7.36 ± 0.2 fm. The pre-prepared nuclei are tested according to above requirements, and the bound nuclei evolve stably without spurious emission within 3000 fm/c.

Firstly we study the entrance channel potential energy which is define as

$$V_{\rm b}(R) = E_{12}(R) - E_1 - E_2. \quad (2)$$

Here R is the distance between the centers of mass of projectile and target. $E_{12}(R)$, E_1 and E_2 are the total energy of the whole system, the energies of the projectile(like) and target (like) part, respectively. Fig. 1 shows the $V_{\rm b}(R)$ for ^{238}U+^{238}U. The long-dashed curve represents the potential obtained with frozen density. In the real reactions, the density of the reaction partners evolves with time and is controlled by both the mean field and collision term self-consistently. Consequently, the realistic potential experienced by the reaction partners should be different from that calculated by the frozen density. Here we define the potential obtained from the realistic time dependent density as the dynamical potential which is incident energy dependent. The solid curve in Fig. 1 shows the dynamic potential at incident energy to be just above the Coulomb barrier. For comparison we also show the adiabatic potential calculated by the two center shell model[7] in which the liquid drop energy plus the shell correction are considered. The adiabatic potential is shown by the short-dashed line, which is found to be close to the dynamic potential after the touching configuration of two nuclei. Both the dynamic and adiabatic potential at contacting configuration are not steep with respect to the variation of the distance between the centers of mass of reaction partners. From the weak repulsively dynamic (and adiabatic) potential, one may expect that it is possible for the composite systems to exist for a period of time when the strong dissipation exists in the composite system.

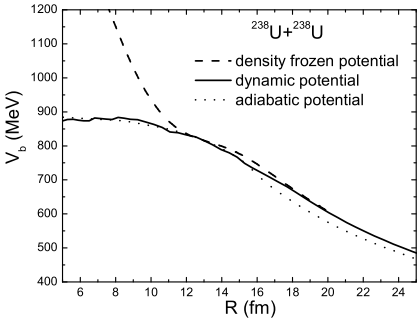

Fig. 1. The entrance channel potential energy of the system of ^{238}U+^{238}U as a function of distance between centers of mass of projectile and target.

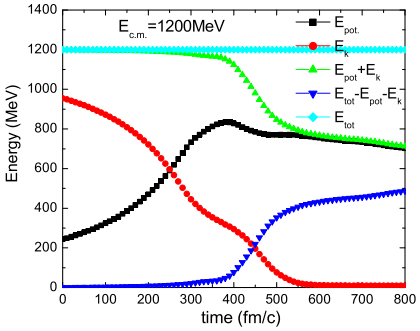

Fig. 2. (color online) The translation kinetic energy of relative motion (solid circles), potential energy (solid squares) and excitation energy (solid downward triangles) as a function of reaction time for the system of ^{238}U+^{238}U.

For estimating the dissipation in Fig. 2 we show the time evolution of the translation kinetic energy in the relative motion (solid circles), potential energy (solid squares) and excitation energy (solid downward triangles) for reaction ^{238}U+^{238}U. One can see that before touching configuration(TC) a part of translation kinetic energy converts into potential energy and after TC the excitation energy of the system begins to increase. At about 600 fm/c almost all translation kinetic energy in relative motion dissipates out and the excitation energy reaches a saturation value. According to the definition of two-body dissipation function in hydrodynamics $\left(-\frac{\mathrm{d}E}{\mathrm{d}t}=\sum\gamma_{\mathrm{i,j}}\dot{q}_{\mathrm{i}}\dot{q}_{\mathrm{j}}\right)$ we can roughly estimate the two body viscosity for relative motion from the translation kinetic energy loss.In Fig. 3 we show the translation kinetic energy loss as a function of square of velocity of relative motion. When only a relative motion is considered, the two-body viscosity can be estimated as about 2-5×10^{-21} MeV·s·fm^{-2}, which is indeed strong dissipation. In order to see how the highly excited composite system can be restrained from a prompt decay, we investigate the single particle potential in which the neutrons and protons are embedded. The single particle potential is defined as

$$V_{\mathrm{sp}}(\boldsymbol{r})=\int\rho(\boldsymbol{r}')V(\boldsymbol{r}-\boldsymbol{r}')\mathrm{d}\boldsymbol{r}', \tag{3}$$

with $\rho(\boldsymbol{r})$ being the density distribution of the system and $V(\boldsymbol{r}-\boldsymbol{r}')$ the effective nucleon-nucleon interaction. In Fig. 4 we show the single-particle potentials for a typical event of the reaction ^{238}U+^{238}U at E_{cm} = 780 MeV from t =100 fm/c to t = 1300 fm/c. The energies of all protons are also shown. From the figure one sees that: Before contact of two reaction partners there exists a higher barrier between two center single particle potentials and nucleons in two nuclei move in their own potential well, only a few protons are excited to unbound state due to Coulomb excitation. Those unbound protons are still embedded in the potential well because of the strong Coulomb barrier at the edge of the potential well. After two reaction partners touching each other (from about t = 500 fm/c to 1200 fm/c), the barrier between two center single particle potentials gradually disappears, and more protons (neutrons) are excited. One finds that almost all excited protons (a part of which even already are unbound) are still embedded in the potential well due to the about 15—20 MeV high strong Coulomb barrier at the edge of the potential well. The individual nucleons have been moving in their common mono-single particle potential well for a period of time, thus forming the giant composite system. Soon after the division of the common single particle potential into two center ones, the composite system will re-separate.

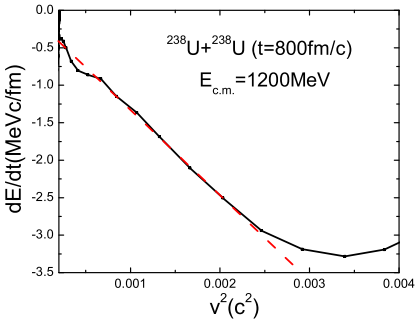

Fig. 3. The translation kinetic energy loss of relative motion due to excitation of the system as a function of square of velocity of relative motion for the system of ^{238}U+^{238}U.

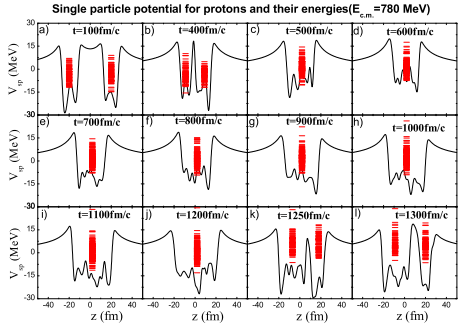

Fig. 4. The single particle potentials and single particle energies of protons for a typical event of the reaction ^{238}U+^{238}U at E_{cm} = 780 MeV.

From these studies, we learn that the weak repulsion of the nucleus-nucleus interaction potential after touching configuration, the strong dissipation and strong Coulomb barrier of single particle potential may lead to existence of the giant composite system for a period of time.

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