Production of heavy isotopes in transfer reactions by collisions of $^{238}U + ^{238}U$

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The dynamics of transfer reactions in collisions of two very heavy nuclei $^{238}U + ^{238}U$ is studied within the dinuclear system (DNS) model. Collisions of two actinide nuclei form a superheavy composite system during a very short time, in which a large number of charge and mass transfers may take place. Such reactions have been investigated experimentally as an alternative way for the production of heavy and superheavy nuclei. The role of collision orientation in the production cross sections of heavy nuclides is analyzed systematically. Calculations show that the cross sections decrease drastically as the charged numbers of the heavy fragments increase. The transfer mechanism is favorable to synthesizing heavy neutron-rich isotopes, such as nuclei around the subclosure at $N = 162$ from No ($Z = 102$) to Db ($Z = 105$).

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The synthesis of superheavy nuclei (SHN) is motivated with respect to searching the "island of stability," which is predicted theoretically, and has resulted in a number of experimental studies. There are mainly two sorts of reaction mechanism to produce heavy and superheavy nuclei, namely, multinucleon transfer reactions in collisions of two actinide nuclei [1,2] and fusion-evaporation reactions with a neutron-rich nuclide bombarding a heavy nucleus near shell closure, such as the cold fusion reactions at GSI (Darmstadt, Germany) [3] and the ^{48}Ca bombarding of the actinide nuclei at the Flerov Laboratory of Nuclear Reactions (FLNR) in Dubna (Russia) [4]. However, the decay chains of the nuclei formed by the hot fusion reactions are all neutron-rich nuclides and do not populate presently the known nuclei. Meanwhile, the superheavy isotopes synthesized by the cold fusion and ^{48}Ca-induced reactions are all far away from the doubly magic shell closure beyond ^{208}Pb at the position of protons $Z = 114$–126 and neutrons $N = 184$. Multinucleon transfer reactions in collisions of two actinides might be used to fill the region and examine the influence of the shell effect in the production of heavy isotopes. The production of neutron-rich heavy or superheavy nuclei in low-energy collisions of actinide nuclei was proposed initially by Zagrebaev *et al.* based on the assumption that the shell effects continue to play a significant role in multinucleon transfer reactions [5].

The cross sections of the heavy fragments in strongly damped collisions between very heavy nuclei were found to decrease very rapidly with increasing atomic number [1,2]. Calculations by Zagrebaev and Greiner with a model based on multidimensional Langevin equations [6] showed that the production of the surviving heavy fragments with the charged number $Z > 106$ is rare because of the very small cross sections at the level of 1 pb and even below 1 pb. However, neutron-rich isotopes of Fm and Md were produced at the larger cross section of 0.1 μb. The evolution of the composite system in the damped collisions is mainly influenced by the incident energy and the collision orientation. Recently, the time-dependent Hartree-Fock (TDHF) approach [7] and improved quantum molecular dynamics (ImQMD) model [8] were also used to investigate the dynamics in collisions of $^{238}U + ^{238}U$.

In this work, we use a dinuclear system (DNS) model to investigate the dynamics of the damped collisions of two very heavy nuclei, in which the nucleon transfer is coupled to the relative motion by solving a set of microscopically derived master equations that distinguish between protons and neutrons [9,10]. To treat the diffusion process along proton and neutron degrees of freedom in the damped collisions, the distribution probability is obtained by solving a set of master equations numerically in the potential energy surface of the DNS. The time evolution of the distribution probability $P(Z_1, N_1, E_1, t)$ for fragment 1 with proton number Z_1 and neutron number N_1 and with excitation energy E_1 is described by the following master equations:

$$\begin{aligned}\frac{dP(Z_1, N_1, E_1, t)}{dt} &= \sum_{Z_1'} W_{Z_1,N_1;Z_1',N_1}(t)\,[d_{Z_1,N_1} P(Z_1', N_1, E_1', t) \\ &\quad - d_{Z_1',N_1} P(Z_1, N_1, E_1, t)] \\ &\quad + \sum_{N_1'} W_{Z_1,N_1;Z_1,N_1'}(t)\,[d_{Z_1,N_1} P(Z_1, N_1', E_1', t) \\ &\quad - d_{Z_1,N_1'} P(Z_1, N_1, E_1, t)] \\ &\quad - [\Lambda_{\rm qf}(\Theta(t)) + \Lambda_{\rm fis}(\Theta(t))]\, P(Z_1, N_1, E_1, t). \qquad (1)\end{aligned}$$

Here the $W_{Z_1,N_1;Z_1',N_1}$ ($W_{Z_1,N_1;Z_1,N_1'}$) is the mean transition probability from the channel (Z_1, N_1, E_1) to (Z_1', N_1, E_1') [or (Z_1, N_1, E_1) to (Z_1, N_1', E_1')], and d_{Z_1,N_1} denotes the microscopic dimension corresponding to the macroscopic state (Z_1, N_1, E_1). The sum is taken over all possible proton and neutron numbers that fragment Z_1', N_1' may take, but only one nucleon transfer is considered in the model with the relation $Z_1' = Z_1 \pm 1$ and $N_1' = N_1 \pm 1$. The excitation energy E_1 is determined by the dissipation energy from the relative motion and the potential energy surface of the DNS. The motion of nucleons in the interacting potential is governed by the single-particle Hamiltonian [9,10]. The evolution of the DNS

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along the variable R leads to the quasifission of the DNS. The quasifission rate Λ_{qf} and the fission rate Λ_{fis} of the heavy fragment are estimated with the one-dimensional Kramers formula. The local temperature is given by the Fermi-gas expression $\Theta = \sqrt{\varepsilon^\star/a}$ corresponding to the local excitation energy $\varepsilon^\star$ and the level density parameter $a = A/12$ MeV^{-1} [10].

In the relaxation process of the relative motion, the DNS will be excited by the dissipation of the relative kinetic energy. The local excitation energy is determined by the excitation energy of the composite system and the potential energy surface (PES) of the DNS. The PES of the DNS is given by

$$U(\{\alpha\}) = B(Z_1, N_1) + B(Z_2, N_2) - \left[B(Z, N) + V_{\rm rot}^{\rm CN}(J)\right] + V(\{\alpha\}), \qquad (2)$$

with $Z_1 + Z_2 = Z$ and $N_1 + N_2 = N$ [11]. Here the symbol $\{\alpha\}$ denotes the sign of the quantities $Z_1, N_1, Z_2, N_2; J, R; \beta_1, \beta_2, \theta_1, \theta_2$. The $B(Z_i, N_i)$ $(i = 1, 2)$ and $B(Z, N)$ are the negative binding energies of the fragment (Z_i, N_i) and the compound nucleus (Z, N), respectively, which are calculated from the liquid drop model, in which the shell and the pairing corrections are included reasonably. The $V_{\rm rot}^{\rm CN}$ is the rotation energy of the compound nucleus. The β_i represent the quadrupole deformations of the two fragments. The θ_i denote the angles between the collision orientations and the symmetry axes of deformed nuclei. The interaction potential between fragments (Z_1, N_1) and (Z_2, N_2) includes the nuclear, Coulomb, and centrifugal parts; the detailed calculations are given in Ref. [10]. In the calculation, the distance R between the centers of the two fragments is chosen to be the value at the touching configuration, in which the DNS is assumed to be formed. So the PES depends on the proton and neutron numbers of the fragments. Figure 1 shows the calculated PES as a function of the mass numbers of fragments for the two cases of the nose-nose and side-side orientations (called "tip-tip" and "waist-waist" in the figure). Dissipation to heavier fragments by nucleon transfer is hindered in the nose-nose collisions, and a pocket appears around the nucleus $^{316}120$. The side-side orientation easily reaches the subclosure ^{268}No, but it is also hindered by further dissipation in the high-mass region.

The cross sections of the primary fragments (Z_1, N_1) after the DNS reaches the relaxation balance are calculated as follows:

$$\sigma_{\rm pr}(Z_1, N_1) = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} \sum_{J=0}^{J_{\max}} (2J+1) P(Z_1, N_1, \tau_{\rm int}). \qquad (3)$$

The interaction time $\tau_{\rm int}$ in the dissipation process of two colliding partners is dependent on the incident energy $E_{\rm c.m.}$ in the center-of-mass (c.m.) frame and the angular momentum J, which is calculated by using the deflection function method [12] and has the value of a few 10^{-20} s. The surviving fragments are the decay products of the primary fragments after emitting the particles and γ rays in competition with fission. The cross sections of the surviving fragments are given by

$$\sigma_{\rm sur}(Z_1, N_1) = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} \sum_{J=0}^{J_{\max}} (2J+1) P(Z_1, N_1, E_1, \tau_{\rm int}) \times W_{\rm sur}(E_1, xn, J), \qquad (4)$$

where E_1 is the excitation energy of the fragment (Z_1, N_1). The maximal angular momentum is taken as $J_{\max} = 200$, which includes all partial waves in which the transfer reactions may take place. The survival probability $W_{\rm sur}$ of each fragment can be estimated by using the statistical approach [10].

The dynamics of the damped collisions was investigated by Zagrebaev and Greiner in detail with a model based on multidimensional Langevin equations [6,13]. Larger cross sections in the production of neutron-rich heavy isotopes in collisions of two actinides were pointed out. Within the framework of the DNS model, we calculated the production of the surviving fragments in collisions of ^{238}U + ^{238}U for the nose-nose and side-side orientations at 900 MeV center-of-mass energy as shown in Fig. 2. The collisions of the side-side case need to overcome the higher barrier of the interaction potential in the formation of the DNS. But it is favorable to transfer the nucleon by the master equations in the driving potential and form the target-like fragments. The situation is opposite for the nose-nose collisions. So both cases give a similar result in the production of the

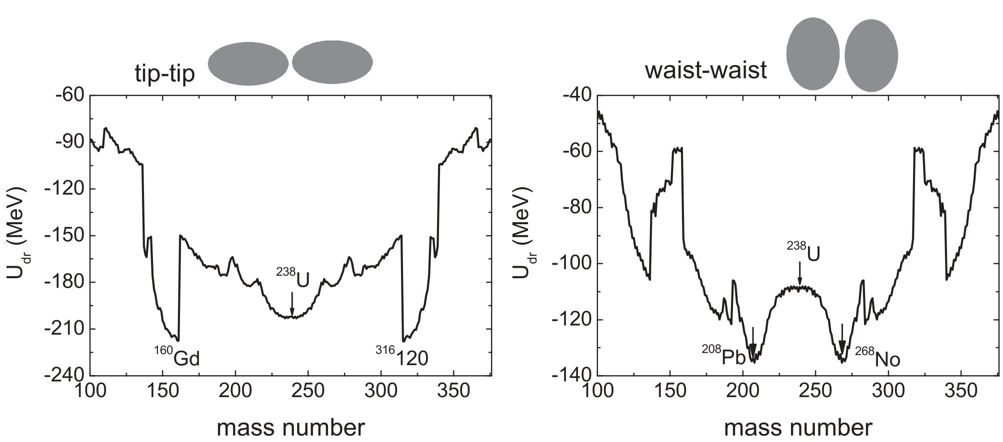

FIG. 1. Driving potentials of the tip-tip and waist-waist collisions in the reaction ^{238}U + ^{238}U.

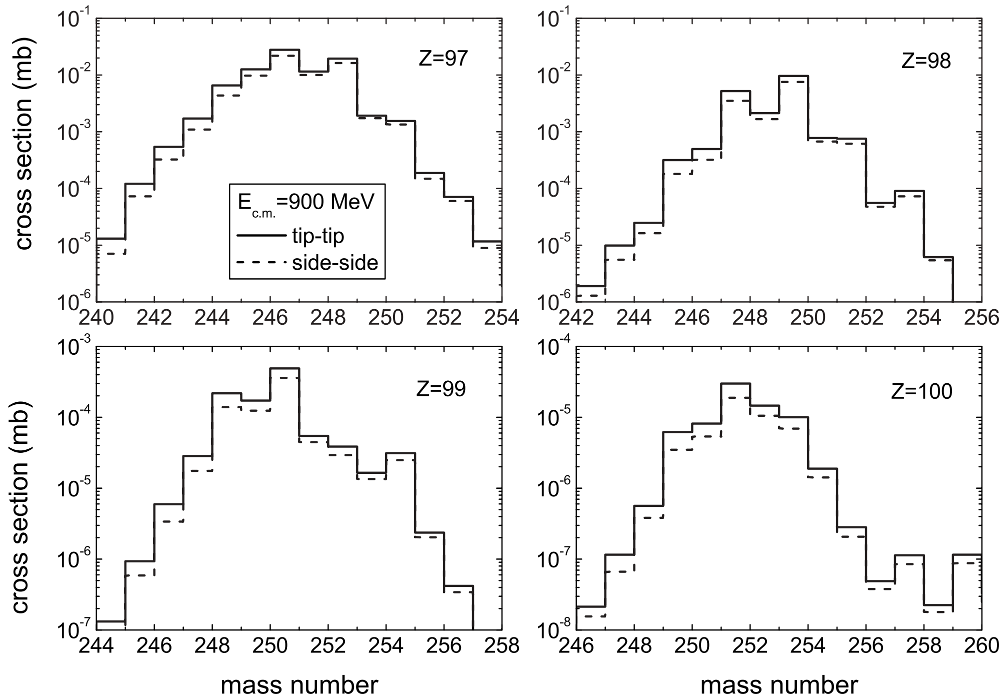

FIG. 2. Comparison of the production cross sections of the Bk, Cf, Es, and Fm isotopes in collisions of ^{238}U with ^{238}U for the tip-tip and side-side orientations.

Bk, Cf, Es, and Fm isotopes. Comparison of the calculated mass distributions and the experimental data of the surviving fragments at $E_{\mathrm{c.m.}} = 800$ MeV is shown in Fig. 3. The cross sections decrease drastically with the atomic numbers of the fragments. The calculated results are the case of the nose-nose collisions, which have the height of the interaction potential at the touching configuration with the value 713 MeV. In the collisions of such heavy systems, there is no Coulomb barrier in the approaching process of two colliding partners. A number of nucleon transfers take place in the reactions of two actinides owing to the dynamical deformations and the fluctuations of all collective degrees of freedoms in the model of Zagrebaev and Greiner [6]. We assume the DNS is formed at the touching configuration in the collisions of two very heavy nuclei. The nucleon transfer is governed by the driving potential in competition with the quasifission of the DNS because of the collision dynamics. The larger quasifission rate of such systems results in the DNS quickly decaying into two fragments because there is no potential pockets. The inner excitation energy of the DNS is dissipated from the kinetic energy of the relative motion overcoming the height of the interaction potential of two colliding nuclei at the touching configuration. The value of the side-side orientation is 813.5 MeV. Inclusion of all orientations in the low-energy damped collisions is important to correctly estimating the cross sections of the primary and surviving fragments.

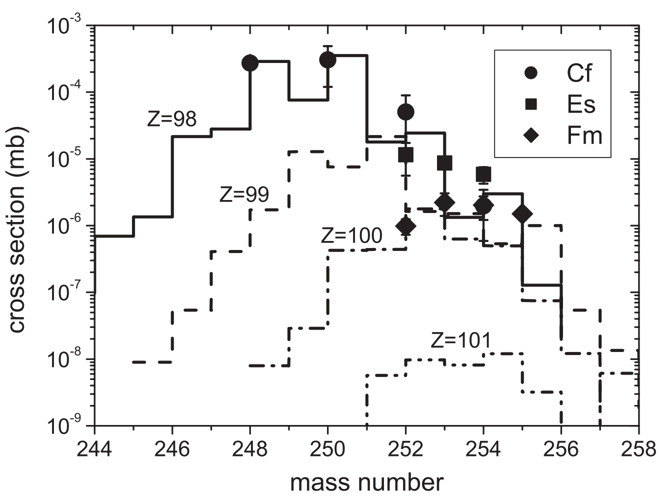

FIG. 3. Calculated mass distributions of the Cf, Es, Fm, and Md isotopes at $E_{\mathrm{c.m.}} = 800$ MeV and compared with the available experimental data [2].

Shown in Fig. 4 are the cross sections of the primary and surviving fragments calculated by using Eqs. (3) and (4) as functions of the charged numbers and mass numbers at the incident energy $E_{\mathrm{c.m.}} = 800$ MeV, respectively. In the damped collisions, the primary fragments result from a number of nucleon transfers in the relaxation process of the colliding partners. The giant composite system retains a very short time of several tens 10^{-22} s due to the strong Coulomb repulsion. Calculations from the TDHF method showed that the collision time depended on the orientation of the colliding system [7]. The cross sections in the production of heavy target-like fragments ($Z > 92$) decrease drastically with the atomic numbers of the fragments. Therefore, the mechanism of the low-energy transfer reactions in collisions of two very heavy nuclei is not suitable for synthesizing superheavy nuclei ($Z > 106$) because of the smaller cross sections at the level of 1 pb and even below 1 pb. Similar results were also

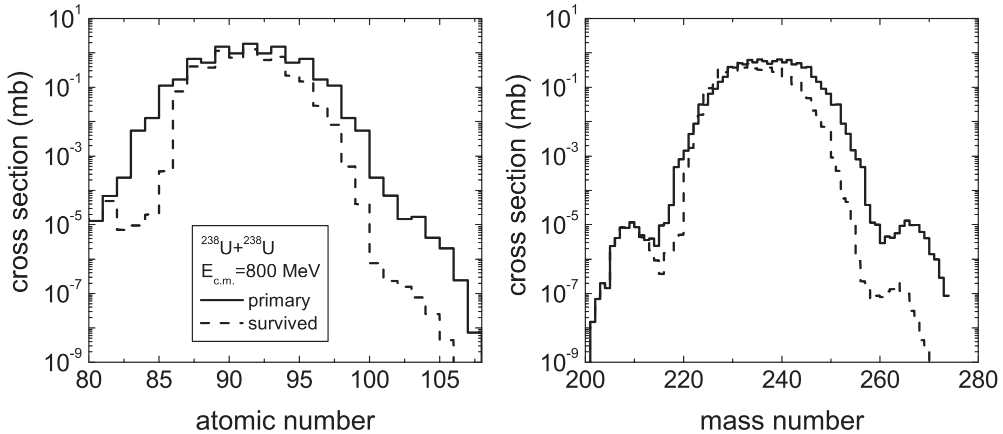

FIG. 4. Cross sections as functions of the charged and mass numbers of the primary and surviving fragments at $E_{\mathrm{c.m.}} = 800$ MeV, respectively.

obtained in Ref. [6]. However, the production of the surviving fragments around the subclosure $N = 162$ has a larger cross section. Calculated cross sections as functions of the mass numbers appear as a bump near the isotopes of the subclosure. Experimental work for studying the influence of the shell closure in the production of the neutron-rich isotopes should be performed in the near future. It is also a good technique for filling in the gap in the new isotopes between the cold fusion and ^{48}Ca-induced reactions.

In summary, the dynamics in collisions of the very heavy system $^{238}\mathrm{U} + {}^{238}\mathrm{U}$ is investigated within the framework of the DNS model. The influence of the collision orientations on the production cross sections of heavy isotopes is discussed systematically. The low-energy transfer reactions in the damped collisions of the actinide nuclei are a good mechanism for producing neutron-rich heavy isotopes, in which shell closure plays an important role in the estimation of the cross sections.

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