Influence of entrance channels on formation of superheavy nuclei in massive fusion reactions

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Abstract

Within the framework of the dinuclear system (DNS) model, the production cross sections of superheavy nuclei Hs (Z=108) and Z=112 combined with different reaction systems are analyzed systematically. It is found that the mass asymmetries and the reaction Q values of the combinations play a very important role on the formation cross sections of the evaporation residues. Both methods by solving the master equations along the mass asymmetry degree of freedom (1D) and along the proton and the neutron degrees of freedom (2D) are compared each other and with the available experimental results.

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The synthesis of heavy or superheavy nuclei (SHN) is a very important subject in nuclear physics motivated with respect to the island of stability which is predicted theoretically, and has obtained much experimental research with fusion-evaporation reactions \cite{1,2}. Combinations with a doubly magic nucleus or nearly magic nucleus are usually chosen owing to the larger reaction Q values. Six new elements with Z=107-112 were synthesized in cold fusion reactions for the first time and investigated at GSI (Darmstadt, Germany) with the heavy-ion accelerator UNILAC and the SHIP separator \cite{1,3}. Recently, experiments on the synthesis of element 113 in the \textsuperscript{70}Zn+\textsuperscript{209}Bi reaction have been performed successfully at RIKEN (Tokyo, Japan) \cite{4}. However, it is difficulty to produce heavier SHN in the cold fusion reactions because of the smaller production cross sections that are lower than 1 pb for Z > 113. The superheavy elements Z=113-116, 118

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were synthesized at FLNR in Dubna (Russia) with the double magic nucleus $^{48}$Ca bombarding actinide nuclei [5, 6, 7]. New heavy isotopes $^{259}$Db and $^{265}$Bh have also been synthesized at HIRFL in Lanzhou (China) [8]. Further experimental works are necessary in order to testify the new synthesized SHN. A better understanding of the formation of SHN in the massive fusion reactions is still a challenge for theory.

In this letter, we focus on the influence of the entrance mass asymmetry and the reaction $Q$ value of projectile-target combinations on the production cross sections of superheavy residues. In the DNS model, the evaporation residue cross section is expressed as a sum over partial waves with angular momentum $J$ at the centre-of-mass energy $E_{c.m.}$ [9, 10, 11],

$$\sigma_{ER}(E_{c.m.}) = \frac{\pi \hbar^2}{2\mu E_{c.m.}} \sum_{J=0}^{J_{max}} (2J + 1)T(E_{c.m.}, J)P_{CN}(E_{c.m.}, J)W_{sur}(E_{c.m.}, J).$$  (1)

Here, $T(E_{c.m.}, J)$ is the transmission probability of the two colliding nuclei overcoming the Coulomb potential barrier in the entrance channel to form the DNS. The $P_{CN}$ is the probability that the system will evolve from a touching configuration into the compound nucleus in competition with quasi-fission of the DNS and fission of the heavy fragment. The last term is the survival probability of the formed compound nucleus, which can be estimated with the statistical evaporation model by considering the competition between neutron evaporation and fission [9]. We take the maximal angular momentum as $J_{max} = 30$ since the fission barrier of the heavy nucleus disappears at high spin [12].

In order to describe the fusion dynamics as a diffusion process along proton and neutron degrees of freedom, the fusion 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 function $P(Z_1, N_1, E_1, t)$ for fragment 1 with proton number $Z_1$ and neutron number $N_1$ with excitation energy $E_1$ is described by the following master equations [13],

$$\frac{dP(Z_1, N_1, E_1, t)}{dt} = \sum_{Z_1'} W_{Z_1,N_1;Z_1',N_1}(t) \left[ d_{Z_1,N_1} P(Z_1', N_1, E_1, t) - d_{Z_1,N_1} P(Z_1, N_1, E_1, t) \right] + \sum_{N_1'} W_{Z_1,N_1;Z_1',N_1}(t) \left[ d_{Z_1,N_1} P(Z_1, N_1', E_1, t) - d_{Z_1,N_1} P(Z_1, N_1, E_1, t) \right] - \left[ \Lambda^{qf}(\Theta(t)) + \Lambda^{fis}(\Theta(t)) \right] P(Z_1, N_1, E_1, t).$$  (2)

Here $W_{Z_1,N_1;Z_1',N_1}$ ($W_{Z_1,N_1;Z_1',N_1}$) 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 $Z'_1 = Z_1 \pm 1$ 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 along the variable $R$ leads to the quasi-fission of the DNS. The quasi-fission rate $\Lambda^{qf}$ and the fission rate $\Lambda^{fis}$ can be estimated with the one-dimensional Kramers formula $[10, 11]$. 

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 of the DNS. The potential energy surface (PES) of the DNS is given by 

$$U(Z_1, N_1, Z_2, N_2; J, R; \beta_1, \beta_2, \theta_1, \theta_2) = B(Z_1, N_1) + B(Z_2, N_2) - \left[ B(Z, N) + V_{ro}^{CN}(J) \right] + V(Z_1, N_1, Z_2, N_2; J, R; \beta_1, \beta_2, \theta_1, \theta_2)$$

with $Z_1 + Z_2 = Z$ and $N_1 + N_2 = N$. Here $B(Z_i, N_i)(i = 1, 2)$ and $B(Z, N)$ are the negative binding energies of the fragment $(Z_i, N_i)$ and the compound nucleus $(Z, N)$, respectively, in which the shell and the pairing corrections are included reasonably. The $V_{ro}^{CN}$ is the rotation energy of the compound nucleus. The $\beta_i$ represent the quadrupole deformations of the two fragments. The $\theta_i$ denote the angles between the collision orientations and the symmetry axes of deformed nuclei. The interaction potential between fragment $(Z_1, N_1)$ and $(Z_2, N_2)$ includes the nuclear, Coulomb and centrifugal parts, the details are given in Ref. $[10]$. In the calculation, the distance $R$ between the centers of the two fragments is chosen to be the value which gives the minimum of the interaction potential, in which the DNS is considered to be formed. So the PES depends on the proton and neutron numbers of the fragment. In Fig.1 we give the potential energy surface in the reaction $^{30}$Si+$^{252}$Cf as functions of the protons and neutrons of the fragments in the left panel. The incident point is shown by the solid circle and the minimum way in the PES is added by the thick line. The driving potential as a function of the mass asymmetry that was calculated in Ref. $[9, 10]$ is also given in the right panel and compared with the minimum way in the left panel. The driving potential at the incident point in 1D PES is located at the maximum value, so there is no the inner fusion barrier for the system, which results in a too large fusion probability. Therefore, we solve the master equations within the 2D PES to get the fusion probability for the systems with larger mass asymmetries.

The formation probability of the compound nucleus at the Coulomb barrier $B$ (here a barrier
distribution $f(B)$ is considered) and for angular momentum $J$ is given by\cite{9,10}

$$P_{CN}(E_{c.m.}, J, B) = \sum_{Z_1=1}^{Z_{BG}} \sum_{N_1=1}^{N_{BG}} P(Z_1, N_1, E_1, \tau_{int}(E_{c.m.}, J, B)).$$  \tag{4}$$

We obtain the fusion probability as

$$P_{CN}(E_{c.m.}, J) = \int f(B) P_{CN}(E_{c.m.}, J, B) dB, \tag{5}$$

where the barrier distribution function is taken in asymmetric Gaussian form.

The survival probability of the excited compound nucleus cooled by the neutron evaporation in competition with fission is expressed as follows:

$$W_{sur}(E^*_{CN}, x, J) = P(E^*_{CN}, x, J) \prod_{i=1}^{x} \left( \frac{\Gamma_n(E^*_i, J)}{\Gamma_n(E^*_i, J) + \Gamma_f(E^*_i, J)} \right),$$  \tag{6}$$

where the $E^*_i, J$ are the excitation energy and the spin of the compound nucleus, respectively. The $E^*_1$ is the excitation energy before evaporating the $i$th neutron, which has the relation

$$E^*_{i+1} = E^*_i - B^n_i - 2T_i,$$  \tag{7}$$

with the initial condition $E^*_1 = E^*_{CN}$. The energy $B^n_i$ is the separation energy of the $i$th neutron. The nuclear temperature $T_i$ is given as $E^*_i = aT_i^2 - T_i$ with the level density parameter $a$. $P(E^*_{CN}, x, J)$ is the realization probability of emitting $x$ neutrons. The widths of neutron evaporation and fission are calculated using the statistical model. The details can be found in Refs. \cite{9,11}.

With this procedure introduced above, we calculated the evaporation residue excitation functions using the 1D and 2D master equations in the reaction $^{48}$Ca+$^{238}$U as shown in Fig.2 represented by dashed and solid lines, respectively, and compared them with the experimental data performed in Dubna \cite{14} and at GSI \cite{15}. The GSI results show that the formation cross sections in the 3n channel at the same excitation energy with 35 MeV have a slight decrease, which are in a good agreement with our 1D calculations. In the whole range, the 2D calculations give smaller cross sections than 1D master equations owing to the decrease of the fusion probability. For the considered system, the value of the PES at the incident point is located at the line of the minimum way. So the 1D master equations can give reasonable results. However, for the systems with larger mass asymmetries and larger quadrupole deformation parameters, e.g. $^{16}$O+$^{238}$U, $^{22}$Ne+$^{244}$Pu, etc, the 1D master equations give too large fusion probabilities.

The synthesis of heavy or superheavy nuclei through fusing two stable nuclei is inhibited by the so-called quasi-fission process. The entrance channel combinations of projectile and target
will influence the fusion dynamics. The suppression of the evaporation residue cross sections for less fissile compound systems such as $^{216}\text{Ra}$ and $^{220}\text{Th}$ when reactions are involved in projectiles heavier than $^{12}\text{C}$ and $^{16}\text{O}$ was observed in Refs. [16]. The wider width of the mass distributions for the fission-like fragments was also reported in Ref. [17]. In Fig.3 we calculated the transmission and fusion probabilities using the 2D master equations for the reactions $^{34}\text{S}+^{238}\text{U}$, $^{64}\text{Fe}+^{208}\text{Pb}$ and $^{136}\text{Xe}+^{136}\text{Xe}$ which lead to the same compound nucleus $^{272}\text{Hs}$ formation. The larger transmission probabilities were found in the reactions $^{64}\text{Fe}+^{208}\text{Pb}$ and $^{136}\text{Xe}+^{136}\text{Xe}$ owing to the larger Q values (absolute values). Smaller mass asymmetries of the two systems result in a decrease of the fusion probabilities. The evaporation residue excitation functions in 1n-5n channels are shown in Fig.4. The competition of the capture and the fusion process of the three systems leads to different trends of the evaporation channels. The 3n and 4n channels in the reaction $^{34}\text{S}+^{238}\text{U}$, 1n and 2n channels in the reaction $^{64}\text{Fe}+^{208}\text{Pb}$ are favorable to produce the isotopes $^{269,268}\text{Hs}$ and $^{271,270}\text{Hs}$. Although the system $^{136}\text{Xe}+^{136}\text{Xe}$ consists of two magic nuclei, the higher inner fusion barrier decreases the fusion probabilities and enhances the quasi-fission rate of the DNS, hence leads to the smaller cross sections of the Hs isotopes. The upper limit cross sections for evaporation residues $\sigma_{(1-3)n} \leq 4$ pb were observed in a recent experiment [18], which are much lower than the ones predicted by the fusion by diffusion model [19]. In the DNS model, the larger mass asymmetry favors the nucleon transfer from the light projectile to heavy target, and therefore enhances the fusion probability of two colliding nuclei.

The superheavy element Z=112 was synthesized at GSI with the new isotope $^{277}\text{Hs}$ in cold fusion reaction $^{70}\text{Zn}+^{208}\text{Pb}$ [20] and also fabricated with more neutron-rich isotopes $^{282,283}\text{Hs}$ in $^{48}\text{Ca}$ induced reaction $^{48}\text{Ca}+^{238}\text{U}$. We analyzed the combinations $^{30}\text{Si}+^{252}\text{Cf}$, $^{36}\text{S}+^{250}\text{Cm}$, $^{40}\text{Ar}+^{244}\text{Pu}$ and $^{48}\text{Ca}+^{238}\text{U}$ which lead to the production of new isotopes of the element Z=112 between the cold fusion reactions and the $^{48}\text{Ca}$ induced reactions as shown in Fig.5. The 2n, 3n and 4n channels in the reaction $^{30}\text{Si}+^{252}\text{Cf}$, and the 4n channel in the reaction $^{36}\text{S}+^{250}\text{Cm}$ have larger cross section to produce new isotopes due to the larger fusion probabilities of the two colliding nuclei.

In summary, we systematically analyzed the entrance channel effects of synthesizing SHN using the DNS model. The systems with larger entrance mass asymmetry and larger reaction Q value can enhance the capture and fusion probabilities of two colliding nuclei. Calculations were carried out for the reactions $^{34}\text{S}+^{238}\text{U}$, $^{64}\text{Fe}+^{208}\text{Pb}$ and $^{136}\text{Xe}+^{136}\text{Xe}$ which lead to the same compound nucleus formation. The 2n, 3n and 4n channels in the reaction $^{30}\text{Si}+^{252}\text{Cf}$, and the 4n channel in the reaction $^{36}\text{S}+^{250}\text{Cm}$ are favorable to synthesize new isotopes of the element Z=112 at the stated excitation energies.
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Figure 1: The potential energy surface of the DNS in the reaction $^{30}$Si+$^{252}$Cf as functions of the protons and neutrons of the fragments (left panel) and the mass asymmetry coordinate (right panel).

Figure 2: Comparison of the calculated evaporation residue excitation functions using the 1D and 2D master equations with the available experimental data in the reaction $^{48}$Ca+$^{238}$U.
Figure 3: Calculated transmission and fusion probabilities as functions of the excitation energies of the compound nucleus for the reactions $^{34}$S$+^{238}$U, $^{64}$Fe$+^{208}$Pb and $^{136}$Xe$+^{136}$Xe.

Figure 4: Comparison of the calculated evaporation residue cross sections in 1n-5n channels using the 2D master equations for the reactions $^{34}$S$+^{238}$U, $^{64}$Fe$+^{208}$Pb and $^{136}$Xe$+^{136}$Xe.
Figure 5: The same as in Fig.4, but for the reactions $^{30}\text{Si}+^{252}\text{Cf}$, $^{36}\text{S}+^{250}\text{Cm}$, $^{40}\text{Ar}+^{244}\text{Pu}$ and $^{48}\text{Ca}+^{238}\text{U}$ leading to the formation of the element $Z=112$. 