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Full Text

Preamble

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Theoretical study on fusion dynamics and evaporation residue cross sections for superheavy elements

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Abstract

The nuclear dynamical deformation, fusion probability, and evaporation residue (ER) cross sections for the synthesis of superheavy nuclei are studied with the di-nuclear system model and the related dynamical potential energy surface. The intrinsic energy and maximum dynamical deformations for ^{48}Ca+^{248}Cm are calculated. The effect of dynamical deformation on the potential energy surface and fusion is investigated. It is found that dynamical deformation influences the potential energy surface and fusion probability significantly. The dependence of the fusion probability on angular momentum is investigated. The ER cross sections for some superheavy nuclei in ^{48}Ca-induced reactions are calculated, and it is found that the theoretical results are in good agreement with the experimental results.

Key words: Superheavy nuclei, Production cross section, Fusion mechanism

Introduction

The synthesis of superheavy nuclei (SHN) is an important and interesting field in nuclear physics. Great achievements have been obtained in both experimental and theoretical aspects. Experimentally, studies using cold fusion reactions and hot fusion reactions [1-5] have successfully synthesized SHN with charge numbers up to 118. Theoretically, several models have been proposed to understand the fusion process and predict evaporation residue cross sections, such as the macroscopic dynamical model [6], the fusion-by-diffusion (FBD) models [7-12], the nuclear collectivization model [13,14], the di-nuclear system (DNS) model [15-25], and other models [26].

The evaporation residue (ER) cross sections for SHN decrease with increasing charge number of the SHN; for example, the ER cross section for SHN 118 is less than 1 pb. Researchers are attempting to produce SHN with charge numbers larger than 118, although no expected decay chains were observed in former attempts [27,28]. Thus, it is very important to investigate fusion dynamics and mechanisms. It is also of great necessity to provide theoretical predictions for the optimal projectile-target combination, optimal bombarding energy, and expected ER cross sections for producing SHN, because only under optimal conditions can SHN be successfully synthesized given their extremely low ER cross sections. If theoretical predictions can systematically agree well with available experimental data, the model may provide reliable predictions for SHN not yet synthesized, such as elements 119 and 120.

Heavy-ion reactions are very complicated, where mass transfer is coupled with the dynamical process. Some problems in the fusion process remain unresolved despite much progress. Dynamical deformations [29-31] develop during the fusion process and should be taken into consideration when investigating heavy-ion reactions. Understanding nuclear dynamical deformation is also important for calculating ER cross sections for SHN. In this paper, the dynamical deformation in the reaction is studied, and its effects on the potential energy surface and fusion probability are investigated using the di-nuclear system model with

dynamical potential energy surface (DNS-DynPES model) [32]. The ER cross sections for some ^{48}Ca-induced reactions leading to SHN with charge numbers 112-118 are calculated, and theoretical results are compared with experimental data.

The paper is organized as follows. In Section 2, the theoretical model is introduced. In Section 3, results concerning dynamical deformation, fusion probability, and evaporation residue cross sections are presented. Finally, a summary is given.

2 DNS-DynPES Model

In Ref. [32], we developed a DNS-DynPES model. In this section, we briefly describe the formalism of the theoretical model. Generally, the production of SHN can be separated into three stages: (1) the capture process, where the system overcomes the Coulomb barrier; (2) the fusion process, where the compound nucleus (CN) is formed; and (3) the de-excitation process, where neutrons are emitted to remove excitation energy. The evaporation residue cross section in a heavy-ion fusion reaction can be written as the summation over all partial waves J as

$$\sigma_{ER}(E_{c.m.}) = \sum_{J=0}^{J_{max}} \sigma_{cap}(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J)$$

where $E_{c.m.}$ is the incident energy in the center-of-mass (c.m.) frame. Here $T(E_{c.m.}, J)$ is the transmission probability, and the survival probability $W_{sur}(E_{c.m.}, J)$ is calculated using a statistical model.

The DNS concept was proposed by Volkov [33] and later used to study the competition between complete fusion and quasi-fission and to calculate fusion probabilities in fusion reactions [34-36]. The basic idea of the DNS model is that after the capture process, a DNS in the entrance channel is formed. The DNS then evolves via nucleon transfer along the mass asymmetry coordinate η instead of the direction of the relative distance R between the projectile and target. If nucleon transfer occurs from the light nucleus to the heavy one, the mass asymmetry η increases. Conversely, if nucleon transfer occurs from the heavy nucleus to the light one, the mass asymmetry η decreases and the quasi-fission rate increases, which hinders fusion. Therefore, when η is close to 1, a compound nucleus is formed with high probability, while as η decreases away from 1, compound nucleus formation is hindered and may occur with much lower probability.

We calculate the formation probability P_{CN} of a CN based on the DNS concept. During the nucleon transfer process, any configuration of DNS (A_1, A_2) with $A_1 = 0, 1, \ldots, A_P + A_T$ and $A_2 = A_P + A_T - A_1$ can be formed. The evolution of the distribution function of each DNS with time can be described by a master equation:

$$\frac{dP(A_1,t)}{dt} = \sum_{A_1'} W_{A_1',A_1}(t)P(A_1',t) - \sum_{A_1'} W_{A_1,A_1'}(t)P(A_1,t) - \Lambda_{qf}(A_1,t)P(A_1,t)$$

where W_{A_1',A_1} is defined in Eq. (3). A_1 is explicitly included in the above equation. Since $A_1 + A_2 = A_P + A_T$, only one dimension is needed for a DNS with a local excitation energy shared by the two nuclei in this DNS.

For each nucleus, a valence space is opened due to excitation, and those nucleons in states within the valence space are active for transfer between the two nuclei. The microscopic dimension is

$$\rho(A_1,A_2) = \prod_{k=1}^{2} \frac{N_k!}{m_k!(N_k-m_k)!}$$

where N_k is the number of valence states and m_k is the number of valence nucleons. $\Lambda_{qf}(A_1,A_2)$ is the quasi-fission rate of the DNS (A_1,A_2), and $W_{A_1,A_1'}$ is the mean transition probability between the DNSs (A_1,A_2) and (A_1',A_2').

In Eq. (2), the microscopic dimension, quasi-fission rate, and mean transition probability are all related to the local excitation energy of the DNS, which reads

$$E^*(A_1,t) = E_{c.m.} + Q_{gg} - V(A_1,t) - E_{rot}(J)$$

where Q_{gg} is the Q-value of the reaction, $V(A_1,t)$ is the interaction potential, and $E_{rot}(J)$ is the rotational energy.

The interaction potential between the two nuclei is

$$V(A_1,t) = V_N(A_1,t) + V_C(A_1,t) + V_{def}(A_1,t)$$

Here $V_N(A_1,t)$ is the nuclear potential calculated with a double-folding method [37], and $V_C(A_1,t)$ is the Coulomb interaction potential from Wong' s formula [38]. In this work, a tip-tip orientation of the two deformed nuclei is assumed. The potential energy in the mass asymmetry degree of freedom (the driving potential) at $t = 0$ is defined as

$$V_{driv}(A_1) = V(A_1,t=0) - V(A_P,t=0)$$

The interaction potential between the two nuclei is related to the distance between their centers, and in this paper the interaction potential takes the minimum value in the pocket.

Because of the attractive nuclear force and repulsive Coulomb force, both nuclei in a DNS are distorted, and dynamical deformations develop during the process

of nuclear transfers [29-31]. This results in the time-dependence of the potential energy surface (PES). The dynamical deformations of the two nuclei satisfy

$$C_i\beta_i(t) = -\frac{\partial V(A_1,t)}{\partial \beta_i}$$

with the stiffness parameter C_i (i = 1 and 2) calculated from a liquid drop model [39]. The total dynamical deformation is the average of the dynamical deformations of the two nuclei:

$$\beta(t) = \frac{C_1\beta_1(t) + C_2\beta_2(t)}{C_1 + C_2}$$

Following Refs. [29, 31], we assume that the dynamical deformation evolves in an over-damped motion:

$$\frac{d\beta(t)}{dt} = \frac{1}{\tau_{def}}[\beta_{max} - \beta(t)]$$

In Eq. (9), the relaxation time $\tau_{def} = 40 \times 10^{-22}$ s, and the maximal dynamical deformation is found when the total "intrinsic" energy reaches its minimum.

$$E_{int}(\beta) = V_{driv}(A_1,\beta) + \sum_{i=1}^{2}\frac{1}{2}C_i\beta_i^2$$

The intrinsic energy of the di-nuclear system as a function of nuclear dynamical deformation is shown in Fig. 1(a). For the system above, the maximum dynamical deformation is about 0.32, where the minimum value for the intrinsic energy can be found, and the maximum dynamical deformation is indicated as a dashed line in the figure. The increase in the intrinsic energy of the di-nuclear system when $\beta > 0.32$ can be attributed to the rise in nuclear energies due to their distortions. In our calculations, it is also found that the dynamical deformations increase during the first 120×10^{-22} s and then gradually become saturated. The heavier fragment may acquire more significant dynamical deformation. The interaction potential for the di-nuclear system ^{48}Ca+^{248}Cm as a function of dynamical deformation is shown in Fig. 1(b), and it is found that the interaction potential decreases with increasing dynamical deformation.

[Figure 1: see original paper] Intrinsic energy (a) and potential energy (b) as a function of the dynamical deformation $\delta\beta(t)$ for the reaction. The maximal dynamical deformation $\delta\beta_{max}$ is indicated with the vertical dashed line.

The potential energy surface (the driving potential) for the reaction ^{48}Ca+^{248}Cm is shown in Fig. 2. The mass and charge distributions evolve from the incident channel along the mass asymmetry degree of freedom.

To form the compound nucleus, the di-nuclear configuration must overcome the highest point on the driving potential, and the barrier between the highest point and the incident channel is defined as the inner fusion barrier. The solid squares in Fig. 2 are for the case without dynamical deformation, and the open circles are for the case when dynamical deformation is fully developed. It is found that the potential energy surface changes significantly due to the introduction of dynamical deformation. For example, the highest points on the driving potentials are 15.4 MeV (for solid squares) and 9.11 MeV (for open circles), respectively. The inner fusion barrier, which hinders fusion, may also be influenced by dynamical deformation. The inner fusion barrier for the reaction ^{48}Ca+^{248}Cm at the initial state is 18.93 MeV, while the inner fusion barrier is 29.36 MeV when the dynamical deformation is fully developed, which implies that the fusion probability may be hindered.

[Figure 2: see original paper] Potential energy surface (driving potential) for the reaction ^{48}Ca+^{248}Cm.

The fusion probability for the reaction ^{48}Ca+^{248}Cm at zero angular momentum as a function of incident energy is depicted in Fig. 3. The solid and dashed lines are for cases with and without dynamical deformations, respectively. It is found that the fusion probabilities increase with incident energy for both cases. When the incident energy is below 210 MeV, the fusion probabilities increase rapidly, while after that they increase slowly. It is also found that the fusion probability decreases significantly due to dynamical deformation. For the case of ^{48}Ca+^{248}Cm, the fusion probability with dynamical deformation is about one order of magnitude smaller than that for the case without dynamical deformation. In Ref. [41], the fusion probability for ^{48}Ca+^{248}Cm at $E_{c.m.} = 210$ MeV is found to be about 2.5×10^{-3}, which is much larger than the result in this work. Part of this difference may come from the inclusion of dynamical deformation in this work, implying that more investigations about the fusion process should be carried out.

[Figure 3: see original paper] Fusion probabilities for the reaction ^{48}Ca + ^{248}Cm at $J = 0$ as a function of the incident energy in the c.m. frame. The solid and dashed lines are for with and without dynamical deformations, respectively.

The fusion probabilities for the reaction ^{48}Ca+^{248}Cm as a function of angular momentum (in units of $\hbar$) at three incident energies are depicted in Fig. 4. The solid, dash-dotted, and dashed lines are for incident energies of 210 MeV, 200 MeV, and 190 MeV, respectively. The Q-value for the reaction is about -167 MeV. It is found that the fusion probability decreases with increasing angular momentum. In the region with small angular momentum, the fusion probability decreases slowly, while it drops rapidly when the angular momentum is larger than about $40\hbar$.

[Figure 4: see original paper] Fusion probabilities for the reaction ^{48}Ca+^{248}Cm as a function of the angular momentum at some incident energies.

The ER cross sections for some ^{48}Ca-induced reactions leading to SHN with

charge numbers 112-118 are calculated using Eq. (1). The experimental optimal ER cross sections, bombarding energies, and the number of emitted neutrons [42-45] are listed in Table 1 , together with the theoretical optimal ER cross sections for the corresponding neutron emission channels. It is found that the theoretical results are in good agreement with the experimental results. After SHN 115, the ER cross sections appear to decrease continuously with increasing charge number of the SHN.

4 Conclusion

The nuclear dynamical deformation, fusion probability, and evaporation residue (ER) cross sections for the synthesis of superheavy nuclei are investigated using the di-nuclear system model with dynamical potential energy surface. The intrinsic energy and maximum dynamical deformations for ^{48}Ca+^{248}Cm are calculated. The effect of dynamical deformation on the potential energy surface is found to be significant. The fusion probability as a function of incident energy is calculated, and the dependence of fusion probability on angular momentum is estimated. The fusion probability is significantly hindered by nuclear dynamical deformations. The ER cross sections for some superheavy nuclei in ^{48}Ca-induced reactions are calculated, and it is found that the theoretical results are in good agreement with the experimental results.

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