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Theoretical study of the synthesis of superheavy nuclei with Z = 119 and 120 in heavy-ion reactions with trans-uranium targets (postprint)

Authors: Nan Wang, En-Guang Zhao, Werner Scheid, Shan-Gui Zhou

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Abstract

By using a newly developed di-nuclear system model with a dynamical potential energy surface—the DNS-DyPES model, hot fusion reactions for synthesizing superheavy nuclei (SHN) with the charge number Z = 112–120 are studied. The calculated evaporation residue cross sections are in good agreement with available data. In the reaction 50Ti+249Bk → 299−x119 + xn, the maximal evaporation residue (ER) cross section is found to be about 0.11 pb for the 4n-emission channel. For projectile-target combinations producing SHN with Z = 120, the ER cross section increases with the mass asymmetry in the incident channel increasing. The maximal ER cross sections for 58Fe+244Pu and 54Cr+248Cm are relatively small (less than 0.01 pb) and those for 50Ti+249Cf and 50Ti+251Cf are about 0.05 and 0.25 pb, respectively.

Full Text

Preamble

Theoretical Study of the Synthesis of Superheavy Nuclei with Z = 119 and 120 in Heavy-Ion Reactions with Trans-Uranium Targets

Nan Wang,[1] En-Guang Zhao,[2,3], Werner Scheid, and Shan-Gui Zhou[2,3,*]

[1]College of Physics, Shenzhen University, Shenzhen 518060, China
[2]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
[3]Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China
School of Physics, Peking University, Beijing 100871, China
Institut für Theoretische Physik der Justus-Liebig-Universität, D-35392 Giessen, Germany

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Using a newly developed dinuclear system model with a dynamical potential energy surface—the DNS-DyPES model—we investigate hot fusion reactions for synthesizing superheavy nuclei (SHN) with charge numbers Z = 112–120. The calculated evaporation residue cross sections are in good agreement with available experimental data. For the reaction Ti + ² Bk → ² ¹¹ + xn, the maximal evaporation residue (ER) cross section is found to be approximately 0.11 pb for the 4n-emission channel. For projectile-target combinations producing SHN with Z = 120, the ER cross section increases with increasing mass asymmetry in the entrance channel. The maximal ER cross sections for Fe + ² Pu and Cr + ² Cm are relatively small (less than 0.01 pb), while those for Ti + ² Cf and Ti + ² ¹Cf are about 0.05 pb and 0.25 pb, respectively.

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Introduction

Over the past decades, significant experimental progress has been achieved in the synthesis of superheavy elements (SHE). To date, SHEs with charge numbers Z 118 have been produced via cold fusion reactions using Pb or Bi targets [1, 2] and hot fusion reactions with Ca projectiles [3, 4]. Several attempts have also been made to synthesize superheavy nuclei (SHN) with Z > 118. For instance, experiments employing the projectile-target combinations Fe + ² Pu [5] and Ti + ² Cf [6] have been conducted to produce element 120, though no -decay chains consistent with fusion-evaporation reaction products were observed.

The evaporation residue (ER) cross section _ER of fusion reactions depends strongly on the projectile-target combination and the incident energy. Investigating these dependencies is particularly interesting and useful when attempting to synthesize new SHEs with Z > 118, as _ER for reactions producing these nuclei becomes extremely small, making experiments considerably more challenging. In recent years, considerable effort has been devoted to investigating the synthesis mechanism of SHN with Z > 118. Using a dinuclear system (DNS) model, Feng et al. calculated the cross sections for cold fusion reactions producing isotopes of elements 119 and 120 as evaporation residues, predicting maximal _ER values of approximately 0.03 pb and 0.09 pb for elements 119 and 120, respectively [7]. Hot fusion reactions with Ti projectiles have been studied extensively using DNS models [8–11], fusion-by-diffusion models [12–15], and other approaches [16, 17]. The optimal incident energy and maximal _ER vary significantly across different models or parameter sets. For example, _ER for the reaction Ti + ² Cf → ² ¹² + 3n ranges from 1.5 to 760 fb [11].

In this work, we investigate hot fusion reactions producing SHN with Z 112, with particular emphasis on elements 119 and 120, using a newly developed DNS model with a dynamical potential energy surface (DyPES) [18, 19] (termed the DNS-DyPES model). The importance of dynamical deformations of fragments in dissipative heavy-ion collisions has long been recognized [20, 21]. Dynami-

cal deformations of the projectile and target in the entrance channel have been incorporated into DNS models [22–24] and are crucial for calculating the local excitation energy of a DNS during nucleon transfer processes. Recently, Huang et al. [25] developed a new DNS model that accounts for the dynamical deformations of each DNS, solving a three-dimensional master equation with three variables: the deformations _i (i = 1 and 2 for each nucleus in a DNS) and the mass asymmetry .

To (i) incorporate the influence of dynamical deformations of nuclei in each DNS and (ii) simplify the calculations, we treat dynamical deformations in a more transparent and economical manner in the DNS-DyPES model. The details of this model will be published elsewhere [19]; here we briefly discuss how dynamical deformation is included.

As usual, the evaporation residue cross section in a heavy-ion fusion reaction is calculated as a summation over all partial waves J:

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

where E_{c.m.} is the incident energy in the center-of-mass frame. In this work, the capture cross section _cap is calculated using an empirical coupled-channel approach [26, 27], and the survival probability W_sur is calculated using a statistical model [28, 29]. During the fusion process, an excited compound nucleus (CN) may be formed. We calculate the formation probability of a CN, P_CN, based on the DNS concept. The DNS concept was proposed by Volkov to describe deep inelastic transfer processes [30] and was later applied to study the competition between complete fusion and quasi-fission and to calculate fusion probabilities in fusion reactions [31–33]. Based on the DNS concept, several models have been developed to investigate the synthesis mechanism of SHN (see [34–37] and references therein).

The fundamental idea of the DNS concept is that after the capture process, a DNS (A_P, A_T) is formed in the entrance channel. The DNS then evolves via nucleon transfer along the mass asymmetry coordinate rather than in the direction of the relative distance R between the projectile and target. During nucleon transfer, any DNS (A_1, A_2) with A_1 = 0, 1, ···, A_P + A_T and A_2 = A_P + A_T - A_1 may be formed. The time evolution of the distribution function for each DNS can be described by a master equation [22–24]:

$$\frac{dP(A_1,t)}{dt} = \int dA_1' \, W_{A_1 A_1'}(t) P(A_1',t) - \int dA_1' \, W_{A_1' A_1}(t) P(A_1,t) - \Lambda_{qf}^{A_1}(t) P(A_1,t).$$

Since A_1 + A_2 = A_P + A_T, only A_1 is explicitly included in the above equation. d_{A_1}(t) is the microscopic dimension for a DNS (A_1, A_2)

with a local excitation energy E* defined in Eq. (3). E*_DNS is shared by the two nuclei in this DNS. For each nucleus, a valence space opens due to excitation, and nucleons in states within this valence space are active for transfer between the two nuclei:

$$d_{A_1}(t) = \prod_{k=1,2} \binom{C_{N_k}^{m_k}}{N_k},$$

where N_k is the number of valence states and m_k is the number of valence nucleons [22]. Λ_{qf}^{A_1}(t) is the quasi-fission probability of the DNS (A_1, A_2), and W_{A_1A'_1}(t) is the mean transition probability between the DNSs (A_1, A_2) and (A'_1, A'_2). For details on solving the master equation, please refer to Refs. [22–24]. Here we focus on the local excitation energy and dynamical deformations.

In Eq. (2), d_{A_1}(t), Λ_{qf}^{A_1}(t), and W_{A_1A'_1}(t) all depend on the local excitation energy of the DNS:

$$E^*_{DNS}(A_1,t) = E_{total} - E^0_{DNS}(A_1,t) - E^{DNS}_{rot}(t),$$

where

$$E_{total} = E_{c.m.} + (M_T + M_P)c^2,$$

$$E^0_{DNS}(A_1,t) = V_{DNS}(A_1,t) + (M_1 + M_2)c^2,$$

$$E^{DNS}_{rot}(t) = \frac{J(J+1)\hbar^2}{2\mathcal{J}_{DNS}(A_1,t)},$$

and V_{DNS}(A_1, t) = V_N(A_1, t) + V_C(A_1, t), with V_N(A_1, t) and V_C(A_1, t) being the nuclear and Coulomb interactions between the two nuclei. The potential energy in the mass asymmetry degree of freedom, often called the driving potential at t = 0, is defined as:

$$V_{PES}(A_1,t) \equiv V_{DNS}(A_1,t) + (M_1 + M_2 - M_T - M_P)c^2.$$

The interaction potential V_{DNS}(A_1, R, t) between the two nuclei in a DNS depends on the distance between their centers R, and V_{DNS}(A_1, t) in Eqs. (5) and (7) takes the minimum value of the pocket with respect to R in V_{DNS}(A_1, R, t), i.e., V_{DNS}(A_1, t) V_{DNS}(A_1, R, t)|{R=R{pocket}}.

Due to the attractive nuclear force and repulsive Coulomb force, both nuclei in a DNS become distorted, and dynamical deformations develop during the process of nucleon transfer [20, 21]. This leads to time dependence of the potential energy surface (PES). The nuclear interaction is calculated using a double-folding method [38], and the Coulomb interaction is obtained from the Wong formula [39]. In this work, we assume a tip-to-tip orientation of the two deformed nuclei and that the dynamical deformations of the two nuclei satisfy _1/ _1 = _2/ _2 = C_1/A_1 = C_2/A_2 [26], with the stiffness parameter C_i (i = 1 and 2) calculated from a liquid-drop model [40]. We then define (_1 + _2)/2 and, following Refs. [20, 21], assume that the dynamical deformation evolves in an overdamped motion:

$$\delta\beta(t) = \delta\beta_{max}\left[1 - e^{-t/\tau_{def}}\right],$$

where the relaxation time _{def} = 40 × 10 ^{22} s [21] and the maximal dynamical deformation _{max} is determined by minimizing the total "intrinsic" energy:

$$E_{int}(A_1, \delta\beta) = V_N(A_1; \beta_1, \beta_2) + V_C(A_1; \beta_1, \beta_2) + \sum_{i=1,2} \frac{C_i \delta\beta_i^2}{2},$$

where the quadrupole deformation _i = _i^0 + _i (i = 1 and 2), with the static deformation parameters _i^0 taken from Ref. [41]. This is illustrated for Ti + ^{2} Cf in Fig. 1 (the black solid curve), where one finds that E_{int} decreases with increasing and reaches its minimum at 0.36.

Figure 2 shows the maximal dynamical deformation _{max} and the DyPES defined in Eq. (7) at t = 0 and t = ∞ as functions of the mass asymmetry coordinate (A_1 - A_2)/(A_1 + A_2) for Ti + ^{2} Cf. Nuclear mass values are taken from Refs. [41, 42]. In general, _{max} becomes smaller as mass asymmetry increases, and approaches zero when → ±1, corresponding to CN formation. The local excitation energy increases as dynamical deformation develops. For DNSs with larger _{max} values, the gain in local excitation energy, V_{PES}^{max}(A_1) V_{PES}(A_1, t = 0) - V_{PES}(A_1, t = ∞), is also larger. Note that since _{max} = 0 for = ±1, the local excitation energy of the CN, E_{CN}^*, is always fixed and equals Q + E_{c.m.}, where Q is the reaction energy. In Fig. 1, we plot the potential energy V_{PES} (the red dotted curve) as a function of for Ti + ^{2} Cf. The potential energy decreases almost linearly with increasing dynamical deformation. Therefore, to reduce computational time, we assume:

$$V_{PES}(A_1, t) = V_{PES}(A_1, t = 0) - \frac{\delta\beta(t)}{\delta\beta_{max}} \delta V_{PES}^{max}(A_1).$$

Note that a dynamical PES has been calculated microscopically to describe the continuous transition from the initial diabatic potential to the asymptotic adia-

batic one due to residual two-body collisions [43, 44]. Exploring the connection between the DyPES in this work and that proposed in Refs. [43, 44] would be an interesting topic.

Results and Discussion

Using the DNS-DyPES model, we systematically studied hot fusion reactions producing superheavy nuclei with charge numbers Z = 112–120. Figure 3 compares the maximal experimentally available evaporation residue cross sections for Ca-induced reactions leading to SHN with Z = 112–118 [4, 45–47] with theoretical values calculated at the indicated center-of-mass incident energies E_{c.m.} (in MeV). The calculated maximal evaporation residue cross sections for Ti-induced reactions leading to SHN with Z = 119 and 120 are also shown. For reactions producing SHN with Z = 112–118, the projectile is Ca and the targets are ^{23} U, ^{23} Np, $^{2\ 2}$Pu, $^{2\ 3}$Am, ^{2} Cm, ^{2} Bk, and ^{2} Cf, respectively. For SHN with Z = 113, 115, and 118, the maximal _ER occurs in the 3n evaporation residue channel, while for Z = 114, 116, and 117, the 4n channel is more favorable. For element 112, our calculations indicate that the ER cross section in the 4n channel leading to $^{2\ 2}$Cn is slightly larger than that in the 3n channel. However, experimentally the maximal _ER is found in the 3n channel, so Fig. 3 presents the calculated and experimental results for $^{2\ 3}$Cn. The calculations are in good agreement with experimental data. We note that including the DyPES in this work reduces the fusion probability and ER cross section by approximately an order of magnitude.

From Z = 112 to 116, the experimental cross sections show a staggering pattern with values between 1 and 10 pb. For Z > 116, the ER cross section decreases almost exponentially with increasing charge number. A similar trend is observed in our calculated results for SHN with Z = 112–118. Whether this trend continues is an intriguing question. Figure 3 also shows the maximal ER cross sections for $^{2\ 11}$ produced in Ti + ^{2} Bk, and for $^{2\ 12}$ (lower circle) and $^{2\ 12}$ (upper circle) produced in Ti + ^{2} Cf and Ti + $^{2\ 1}$Cf, respectively. For element 119, the decreasing trend in ER cross section continues beyond Z = 118, yielding _ER 0.11 pb. This trend also continues for element 120 when using ^{2} Cf as the target, giving _ER 0.05 pb. However, for the 3n-emission channel of Ti + $^{2\ 1}$Cf, which produces $^{2\ 12}$, the maximal ER cross section is about 0.25 pb.

The synthesis of element 119 isotopes using Ti projectiles has been investigated extensively from a theoretical perspective. As mentioned earlier, maximal _ER values from different models or parameter sets vary considerably. Taking the projectile-target combination Ti + ^{2} Bk as an example, maximal _ER ranges from 35 fb [17] and 50 fb [16] up to 570 fb [15]. In this work, we study production cross sections for element 119 using the DNS-DyPES model. Figure 4 shows the excitation functions for Ti + ^{2} Bk leading to $^{2\ \ 2\ 11}$ (solid, dash-dot, and dotted curves). The maximal cross sections for the 3n and 4n channels are approximately 0.06 pb and 0.11 pb, respectively.

Experiments attempting to synthesize SHN with Z = 120 using the projectile-target combination Fe + ² Pu observed no decay chains consistent with fusion-evaporation products [5]. Based on the experimental sensitivity, this null result sets an upper limit of 0.4 pb for _ER. Several predictions have been made for this reaction' s ER cross section. For example, the maximal _ER is predicted to be about 0.1 pb in the 3n channel in Ref. [8] and about 0.003 pb in the 4n channel in Ref. [17]. In this work, the ER cross section in the 4n channel is larger, but the maximal value is only about 4 fb, far below the current experimental limit.

Examining the excitation function for a more asymmetric projectile-target combination, Cr + ² Cm, we find that the maximal cross section is also very small —only about 6 fb in the 4n channel, similar to the results of Ref. [17].

We next investigate Ti-induced reactions for synthesizing SHE isotopes with Z = 120. Figure 5 shows the excitation functions for Ti + ² Cf and Ti + ² ¹Cf. In both cases, the 3n-emission channel yields larger ER cross sections than the 4n channel due to odd-even effects in the survival probability. The maximal cross section for Ti + ² Cf is about 0.05 pb. However, for Ti + ² ¹Cf, the ER cross section can reach 0.25 pb, which is close to the current experimental limit. The large ER cross sections in these two reactions arise because the fusion probability increases considerably with mass asymmetry; the fusion probabilities for Ti + ² ,² ¹Cf are approximately one order of magnitude larger than that for Fe + ² Pu [19].

Summary

We have developed a dinuclear system (DNS) model with a dynamical potential energy surface (DyPES)—the DNS-DyPES model. In this model, the development of dynamical deformations of the two nuclei in a DNS is approximately accounted for, which is crucial for determining the local excitation energy of DNSs involved in the fusion process. Using the DNS-DyPES model, we have investigated heavy-ion fusion reactions with trans-uranium targets. The calculated evaporation residue (ER) cross sections are in good agreement with available experimental values for reactions producing superheavy nuclei with Z = 112–118. We studied the projectile-target combination Ti + ² Bk for synthesizing element 119 and found the maximal ER cross section to be about 0.11 pb for the 4n-emission channel. For projectile-target combinations leading to SHN with Z = 120, the ER cross section increases with increasing mass asymmetry of the entrance channel. The ER cross sections for Fe + ² Pu and Cr + ² Cm are relatively small (less than 10 fb), while those for Ti + ² Cf and Ti + ² ¹Cf are about 0.05 pb and 0.25 pb, respectively.

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