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Letter

Survival probabilities of compound superheavy nuclei towards element 119

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ABSTRACT

To synthesize superheavy element 119 is becoming a highly concerned issue as several experimental projects in major laboratories are being pursued. This work studied the survival probabilities of compound superheavy nuclei after multiple neutron emissions based on microscopic energy dependent fission barriers, demonstrating a significant role of triaxial deformation in decreasing the first fission barriers in the heaviest region. Together with the fusion cross sections by the dinuclear system model, the optimal energy and the residual cross section of ^{243}Am(^{48}Ca, 3n)^{288}Mc are reproduced. Finally the cross sections and optimal beam energies of ^{54}Cr+^{243}Am and ^{50}Ti+^{249}Bk reactions are estimated, providing clues for the synthesis of new elements.

Introduction.— To add new elements in the periodic table is a significant scientific question. To date, elements up to Z = 118 have been synthesized [1], mainly due to the adoption of the ^{48}Ca projectile in fusion-evaporation reactions. However, new elements in the 8th row of the periodic table can not be synthesized using the combination of ^{48}Ca and available targets, and it would be much more challenging. Experimental attempts to synthesize Z = 119 and 120 elements were performed in laboratories using reactions such as ^{58}Fe + ^{244}Pu at JINR [2], ^{51}V + ^{248}Cm at RIKEN [3], and ^{64}Ni + ^{238}U, ^{50}Ti + ^{249}Bk, ^{50}Ti + ^{249}Cf, ^{54}Cr + ^{248}Cm at GSI [4–6], but no evidence of new elements was observed yet. New facilities such as the SHE factory [7] in Dubna and CAFE2 [8] in Lanzhou having very high beam intensities, also joined the search for element 119. Due to limited choices of reaction systems, the reliable estimations of optimal beam energies and cross sections are very desirable for such extremely difficult experiments.

The fission and survival probabilities of highly excited compound superheavy nuclei are crucial in designing the collision energies. Indeed, the energy dependencies of fission barriers are very different for different compound nuclei [9]. For cold fusion compound nuclei, the fission barriers decrease rapidly with increasing excitation energies, and the fission lifetimes would be smaller than that of hot fusion nuclei by 2 orders at high excitations [10]. However, the energy dependence of fission barriers is conventionally taken into account by an empirical damping parameter in modelings of survival probabilities [11]. It should be very cautious when such empirical parameters are used to calculate cross sections of new reaction systems. Furthermore, the survival probability has an "arch" structure and is crucial in determining the optimal projectile energy together with the monotonically increasing fusion probability.

The first chance survival probabilities of compound superheavy nuclei have been studied previously based on microscopic energy dependent fission barriers [12], including energy dependent barrier heights and curvatures. This has not been applied in practical calculations of survival probabilities and cross sections after the evaporation of multiple neutrons. The microscopic fission barriers [12] are much higher than that from macroscopic-microscopic (MM) models [13] in the heaviest region. To resolve this problem, the triaxial deformation should be considered, which plays a significant role in reducing the first barriers [14,15]. Note that the energy dependence of fission barriers can not be self-consistently described by MM models. Besides, the reliable masses of superheavy nuclei are also very relevant for calculations of reaction Q values and survival probabilities [16], which are obtained recently by optimizing Skyrme energy density functionals with α-decay energies up to Z = 118 [17].

In this Letter, we aim to study the optimal beam energies to produce element 119 based on microscopic survival probabilities, which are long-expected since the microscopic studies of fission barriers of compound superheavy nuclei more than a decade ago [9]. The multiple neutron emissions are considered so that energy dependent fission barri-

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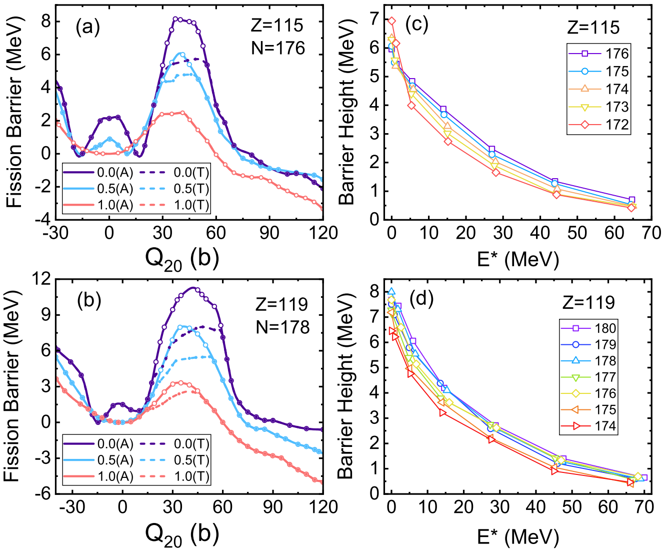

Fig. 1. Calculated fission barriers of Z = 115 (Mc) and Z = 119 compound nuclei. In subfigures (a) and (b), the fission barriers of ^{291}Mc and ^{297}119 at different temperatures with triaxial deformation (T) and axial-symmetric deformation (A) are shown, which are displayed as a function of quardpole deformation Q_{20}. In subfigures (c) and (d), the barrier heights of Z = 115 and Z = 119 isotopes are shown as a function of excitation energies E*.

ers of a cascade of superheavy isotopes are calculated, in which triaxial deformation and octuple deformation are included. Together with the fusion probabilities by the dinuclear system (DNS) model [18], the cross sections and optimal beam energies are predicted. For benchmark, the ^{243}Am(^{48}Ca, 3n)^{288}Mc reaction [7] is reasonably reproduced, for which the latest experimental cross sections are available.

The Method.— The synthesis process of superheavy nuclei can be described as a capture-fusion-evaporation reaction. In this procedure the final residue cross section $\sigma_{ER,xn}$ is written as [18]

$$\begin{aligned}\sigma_{\mathrm{ER},xn}(E_{\mathrm{cm}}) = & \textstyle\sum_J \sigma_{\mathrm{cap}}(E_{\mathrm{cm}}, J) P_{\mathrm{CN}}(E_{\mathrm{cm}}, J) \\ & \times W_{\mathrm{sur},xn}(E_{\mathrm{cm}}, J)\end{aligned} \tag{1}$$

where E_{cm} is the incident energy in the center-of-mass frame and J is the relative angular momentum. $\sigma_{ER,xn}$ depends on the capture cross section σ_{cap}, the probability P_{CN} to form a compound nucleus, and the survival probability $W_{\mathrm{sur},xn}$ of a compound nucleus after the evaporation of multiple neutrons.

The energy dependent (or temperature dependent) fission barriers are calculated by the microscopic self-consistent finite-temperature Hartree-Fock+BCS (FT-BCS) approach [19], in which the quantum shell effects and pairing correlations gradually disappear as excitation energies increase. The finite-temperature Hartree-Fock-Bogoliubov approach is computationally very costly, thus FT-BCS is adopted [10]. The fission barriers from FT-BCS calculations are given in terms of free energies and the excitation energies E^* are self-consistently determined as the temperature varies [10]. The FT-BCS equation is solved by using the HFODD code [20], including the triaxial deformation and octupole deformation (see calculation details in Ref. [21]). The Skyrme force UNEDF1 [22] is adopted for nuclear interaction, which can reasonably describe fission barrier heights. Besides, the density dependent mixed-type pairing interaction [23] is adopted. In principle, the uncertainties of fission barriers can be obtained by Bayesian analysis [24], but it is too expensive for three-dimensional calculations with energy dependence.

To describe the experimental fission probabilities, the energy dependent fission barriers and level density parameters have to be employed [12]. The level density parameter a_0 at the ground state shape is usually taken as $A/12$, where A is the nuclear mass number. Note that the level density parameter of $A/12$ has been widely adopted in modelings of synthesis of superheavy nuclei [18,25,27,28], and the consequences of more complicated formulism of level density [26,29] involving additional parameters are deserved to be studied in the future. To estimate the uncertainties of level densities in this work, results with $A/11$, $A/12$, and $A/13$ are presented for comparison. The level density parameter a_0 is also used in calculations of neutron evaporation width. Besides, the level density parameter at the saddle point a_f/a_0 is taken as an adjustable parameter to reproduce experiments as a_0 varies. Previously our studies demonstrated that the main difference between the Bohr-Wheeler model and the imaginary free energy method (ImF) is because the different level densities between the ground state and the saddle point [12]. The back-shifted Fermi-gas model is used to calculate the level density [25], including the dependence of angular momentum. The fission probabilities are obtained using the hybrid model [12], which is the combination of the Bohr-Wheeler model and the ImF method. The survival probability $W_{\mathrm{sur},xn}$ after the evaporation of x neutrons is [25,26]

$$W_{\mathrm{sur},xn} = P_{xn}(E^*) \prod_{i=1}^{x} \frac{\Gamma_n(E_i^*)}{\Gamma_n(E_i^*) + \Gamma_f(E_i^*)} \tag{2}$$

where $P_{xn}(E^*)$ is the probability of the realization of an xn channel at a given E^*; Γ_n and Γ_f are the energy dependent neutron evaporation width and fission width.

The capture process is described as a penetration through the Coulomb barrier between the nuclei. The capture cross section σ_{cap} is obtained with the transmission probability. The fusion cross sections P_{CN} are calculated with the DNS model. By considering the evolution of dynamical deformations of two colliding nuclei, the DNS with a dynamical potential energy surface is used to describe the complete fusion probability by competing with quasifission [18]. Note that this process is modeled by a diffusion of the DNS with the mass asymmetry degree of freedom, which is different from the fission process with the nuclear deformation degree of freedom. The DNS model has been widely applied in descriptions of fusion cross sections in synthesis of superheavy nuclei [18,25,28,30–34]. The masses of superheavy nuclei are taken from our latest microscopic calculations to calculate reaction Q values and neutron separation energies [17]. The details of DNS calculations are given in a previous work [18].

The Results.— Firstly, the energy dependent fission barriers are calculated, as shown in Fig. 1. It is known that the cross sections are sensitive to the fission barriers, and the optimal beam energies can vary by a few MeV [35]. The fission barriers of ^{291}Mc and ^{297}119 are shown in Fig. 1(a, b), corresponding to ^{48}Ca+ ^{243}Am and ^{54}Cr+ ^{243}Am reactions. The second barriers disappear in both cases due to the octupole deformation. It can be seen that for ^{291}Mc, the fission barrier height is 5.72 MeV with triaxial deformation, while it is about 8.16 MeV with axial symmetry. The significant role of triaxial deformation in reducing the first barrier has been discussed in transuranium nuclei, based on multidimensionally-constrained mean-field models [15,21]. The MM model calculations also indicate that the triaxiality effect is more significant towards neutron-rich superheavy nuclei at N⩾176 [14]. Indeed, we see that triaxiality effect is more significant in ^{297}119 and plays a role even at high temperature (or high excitations). The reduced role of triaxial deformation and octupole deformation at high excitations has also been discussed previously [9,36].

The systematic results of energy dependent fission barrier heights of Z = 115 and Z = 119 nuclei are shown in Fig. 1(c, d). In the FRLDM calculations [13], the fission barrier heights of ^{291}Mc and ^{297}119 are 9.6 MeV and 7.94 MeV, respectively. In another MM calculation, the fission barriers are around 6 MeV in this region [37]. For Z = 115, the heights of fission barriers are reasonable compared to MM calculations in Ref. [37]. It can be seen that barrier heights generally become higher as the neutron number increases towards the N = 184 shell. The fission barrier of ^{287}Mc is higher than that of ^{291}Mc due to the reduced triaxiality effect, but becomes lower than that of ^{291}Mc at high excitations. For Z = 119 isotopes, however, the resulting microscopic fission barrier heights are

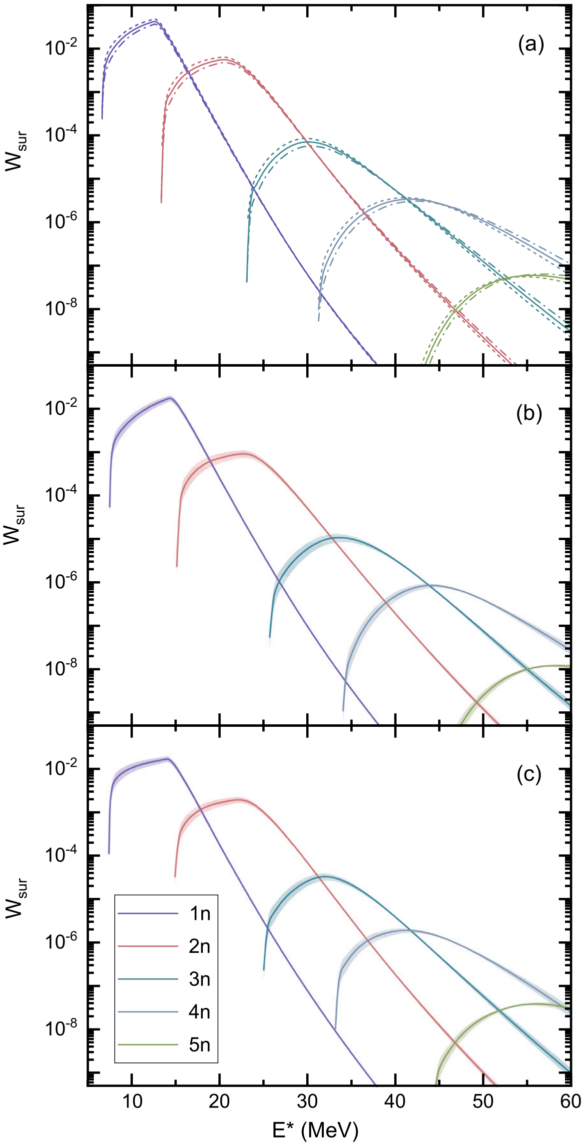

Fig. 2. Calculated survival probabilities of compound nuclei ^{291}Mc (a), ^{297}119 (b) and ^{299}119 (c) based on microscopic energy dependent fission barriers, after the evaporation of multiple neutrons. (a) show the results as the level density parameter a_0 varies while a_f/a_0 is adjusted, in which the dash-dot line, solid line and dashed line denote $a_0=A/11$, $A/12$, and $A/13$, respectively. The shadow in (b, c) shows the uncertainties associated with varying a_0.

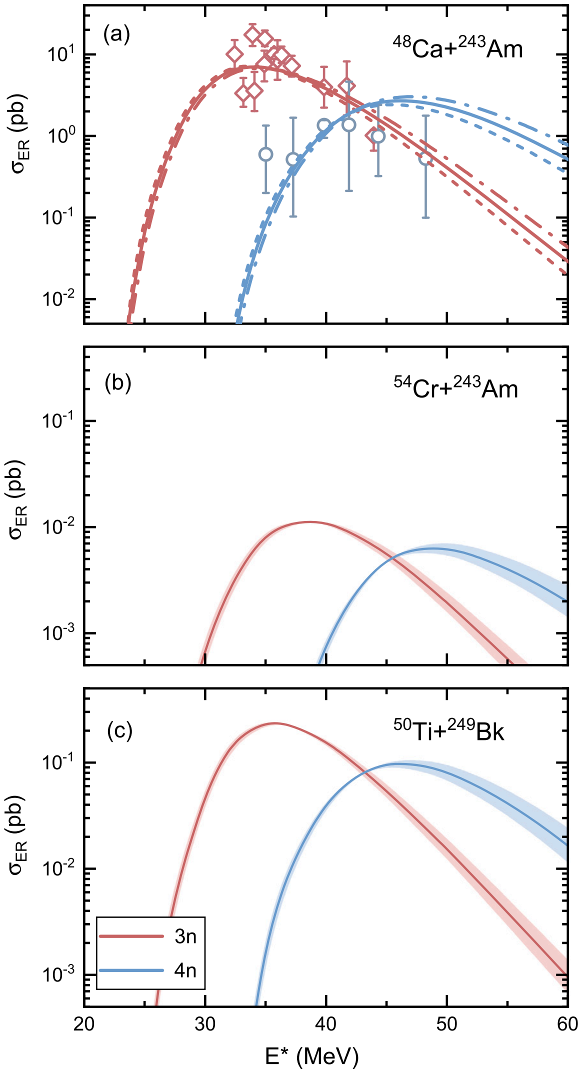

Fig. 3. Calculated residual cross sections of ^{48}Ca+^{243}Am (a), ^{54}Cr+^{243}Am (b) and ^{50}Ti+^{249}Bk (c) reactions after the evaporation of multiple neutrons. The experimental data in the ^{48}Ca+^{243}Am reaction are taken from [7]. Results in (a) are obtained by adjusting the parameter a_f/a_0 as a_0 varies. The shadow in (b, c) shows the uncertainties using the constrained a_f/a_0 as a_0 varies.

higher than MM results [37], but are similar to FRLDM results [13]. The fission barriers of Z = 119 nuclei given by the Weizsäcker-Skyrme (WS4) mass model are lower than 6 MeV [38]. Note that fission barriers obtained by UNEDF1 force are slightly lower than that by SkM* [39] force in this region. Different microscopic calculations predicted that fission barriers around Z = 119 are higher than that of Z = 115 [40], in contrary to MM calculations. On the other hand, the fission barriers of Z = 119 nuclei decrease more rapidly with increasing excitation energies compared to that of Z = 115 nuclei. At $E^*\sim30$ MeV, the barrier heights of Z = 119 nuclei become close to that of Z = 115 nuclei. Thus the higher fission barriers of Z = 119 nuclei at zero temperature are not a problem for calculations of survival probabilities at high excitations.

The survival probabilities $W_{\mathrm{sur},xn}$ of compound superheavy nuclei after multiple neutron emissions as a function of excitation energies are displayed in Fig. 2. The results with different level density parameters $a_0=A/11$, $A/12$ and $A/13$ are shown to estimate the associated uncertainties. Note that a_f/a_0 are adjusted correspondingly to reproduce the residual cross sections of the ^{243}Am+^{48}Ca reaction at the $3n$ evaporation channel. a_f/a_0 are taken as 1.07, 1.085, 1.1 for $a_0=A/11$, $A/12$ and $A/13$, respectively. Then the effect due to different level density parameters is not significant. For ^{291}Mc, its neutron separation energy S_n is 6.77 MeV, which is larger than its barrier height of 5.72 MeV. Consequently its first chance survival probability is very small. In contrast, the survival probabilities at $1n$ and $3n$ channels would be enhanced if the compound nucleus has an odd-number of neutrons due to a smaller S_n. For the $3n$ channel, the largest survival probability is around $E^*\sim30$ MeV, which is slightly smaller than the optimal excitation energy ∼34 MeV in experimental residual cross sections [7], since the monotonically increasing fusion probability would suppress the low-energy contribution and shift the optimal point to slightly higher energies. Therefore the energy of the largest survival probability provides a lower limit, irrespective of the capture and fusion process. The survival probabilities of ^{297}119 are smaller than that of ^{299}119, mainly due to its lower fission barriers and larger S_n. For ^{291}Mc, its survival probabilities are larger than that of ^{299,297}119 at the $3n$ channel due to its smaller S_n, although its fission barriers are lower.

In self-consistent calculations of energy dependent fission barriers, the curvatures ω_0 around the ground state are also energy dependent [10]. At high excitations, the survival probabilities can be enhanced significantly by multiplying the factor ω_0/T (T denotes temperature) [12], which is included in the ImF method but not in the standard Bohr-Wheeler method. In this work, the factor ω_0/T is included in calculations of survival probabilities, where ω_0 is much decreased towards high excitations [12]. To some extent, the factor ω_0/T compensates for the increasing dissipation effect at high excitations [41]. This is supported by the observation of ^{243}Am(^{48}Ca, 5n)^{286}Mc at $E^* \sim 50$ MeV [7].

Finally the residual cross sections $\sigma_{\mathrm{ER},xn}$ of ^{48}Ca+^{243}Am, ^{54}Cr+^{243}Am and ^{50}Ti+^{249}Bk reactions are calculated, as shown in Fig. 3. The updated cross sections of ^{48}Ca+^{243}Am at the 3n channel are reproduced by adopting $a_f/a_0 = 1.085$. Such a factor a_f/a_0 is also used in calculations of Z = 119 nuclei. The shadow region shows the uncertainties due to different level density parameters. The optimal excitation energy is around 33 MeV in the 3n channel, which is very close to the experimental value around 34 MeV [7]. The cross section at the 4n channel is also reasonably reproduced. The estimated cross section of the 2n channel is very large, however, the experimental cross section is small. This is also shown in Ref. [18] with different fission barriers. Actually it is often that calculations below the Bass barrier [42] are too optimistic, as demonstrated by different reactions [43]. Here the Bass barrier is around $E^* = 32$ MeV. Therefore we are focusing on 3n and 4n channels only, which are the most promising reactions.

For the ^{50}Ti+^{249}Bk reaction, the estimated cross section at the 3n channel is about 0.22 pb at $E^* \sim 35$ MeV. In the experiment performed at GSI [5], the cross section limit is below 50 fb at $E^* \sim 43$ MeV. Based on our calculations, the chances to discover element 119 could be much larger with a lower beam energy at the 3n channel. There are also predictions that the optimal reaction is at the 4n channel [28,34]. For the ^{54}Cr+^{243}Am reaction, the estimated cross section is about 11 fb at $E^* \sim 37.5$ MeV in the 3n channel. This is an extremely low cross section for experiments. For example, the discovery of Z = 113 element in RIKEN observed 3 events by taking 553 days of beam time with a cross section of 22 fb [44]. For comparison, another recent theoretical study with different fission barriers estimated that the cross section is 25 fb at $E^* \sim 33$ MeV in the 3n channel [31]. The calculated optimal beam energies E_{cm} are 226.8 MeV and 245.3 MeV for ^{50}Ti+^{249}Bk and ^{54}Cr+^{243}Am reactions, respectively, based on the reaction Q values given in our previous work [17]. There are extensive studies of ^{50}Ti+^{249}Bk and ^{54}Cr+^{243}Am cross sections, as summarized in [28]. The uncertainties in optimal beam energies in the same channel are generally less than 4 MeV. In addition, the fast fission could play a role to reduce the cross sections at high angular momentum [31], and in this respect the microscopic dynamical study of fusion process is needed. Note that the fast fission of a mononucleus is later than the quasifission, as explained in [31]. The machine learning methods [45–47] might also be useful to infer the optimal collision energy for the production of superheavy nuclei, by learning comprehensive existing experimental data (cross sections, nuclear masses, α-decay energies).

Summary.— The survival probabilities of compound superheavy nuclei are studied based on microscopic energy dependent fission barriers, aiming to synthesize the highly concerned new element Z = 119. The triaxial deformation plays a significant role in reducing the fission barriers of Z = 119 isotopes even at high excitation energies. Together with the fusion probability from the DNS model, the residual cross sections after the evaporation of multiple neutrons are obtained. This is a long-expected work since the microscopic studies of energy dependent fission barriers more than a decade ago. The cross sections of ^{243}Am(^{48}Ca, 3n)^{288}Mc can be reasonably described by adjusting a_f/a_0. Our calculations indicate that the ^{50}Ti+^{249}Bk reaction with a lower beam energy is promising to synthesize Z = 119 element.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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