

Synthesis of the superheavy elements beyond Og: extrapolating from ^{48}Ca to ^{54}Cr

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Abstract

Theoretical predictions on the optimal reaction energies are essential for producing superheavy elements (SHEs) beyond Og. Due to the limitation of the targets, synthesizing elements 119 and 120 will require beams of 50Ti and/or 54Cr ions. However, is it reliable to theoretically extrapolate from the well-investigated 48Ca induced reactions to those with heavier projectiles? In this work, we answer this question from two perspectives: radial and mass asymmetry degrees of freedom. The Smoluchowski diffusion equation is employed in the mass asymmetry degree of freedom for the first time, in which by fitting the calculations to experimental evaporation residue cross sections (ERCS) for the reactions of 48Ca as projectiles with the actinide targets, a strong linear correlation between the contact distance (D_{cont}) and center-of-mass energy excess above the Coulomb barrier ($E_{\text{c.m.}} - B_0$) is found and a parametrization formula is introduced. The calculations based on the fitted formula satisfactorily reproduce the available experimental data of the ERCS. Furthermore, thanks to the recent experimental data, we extrapolate the calculation in the reactions $50\text{Ti} + 242\text{Pu}$, $50\text{Ti} + 244\text{Pu}$, and $54\text{Cr} + 238\text{U}$. The calculations reproduce the experimental data rather well within the experimental errors in both perspectives. Our results demonstrate that theoretically extrapolating the projectile from 48Ca to 50Ti and 54Cr for synthesizing SHEs beyond Og is relatively reliable

Full Text

Preamble

Synthesis of the superheavy elements beyond Og: extrapolating from Yueping Fang and Long Zhu 1, 2, 1 Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China Guangxi Key Laboratory of Nuclear Physics and Nuclear Technology, Guangxi Normal University, Guilin 541004, China Theoretical predictions on the optimal reaction energies are essential for producing superheavy elements (SHEs) beyond Og. Due to the limitation of the targets, synthesizing elements 119 and 120 will require beams and/or ions. However, is it reliable to theoretically extrapolate from the well-investigated induced reactions to those with heavier projectiles? In this work, we answer this question from two perspectives: radial and mass asymmetry degrees of freedom. The Smoluchowski diffusion equation is employed in the mass asymmetry degree of freedom for the first time, in which by fitting the calculations to experimental evaporation residue cross sections (ERCS) for the reactions of as projectiles with the actinide targets, a strong linear correlation between the contact distance () and center-of-mass energy excess above the Coulomb barrier) is found and a parametrization formula is introduced. The calculations based on the fitted formula satisfactorily reproduce the available experimental data of the ERCS. Furthermore, thanks to the recent experimental data, we extrapolate the calculation in the reactions , and . The calculations reproduce the exper-

imental data rather well within the experimental errors in both perspectives. Our results demonstrate that theoretically extrapolating the projectile from Ca to Ti and for synthesizing SHEs beyond Og is relatively reliable.

Keywords

Superheavy nuclei, Fusion reaction, Smoluchowski diffusion equation, Evaporation residue cross section

INTRODUCTION

The synthesis of superheavy elements (SHEs) is a frontier of research in nuclear physics [1]. With regard to the hot fusion reactions, a remarkable progress has been made in the synthesis of SHEs by employing double magic projectile

48 Ca and actinide targets [6–10]. In recent years, to open the 6

eighth period, worldwide efforts have been made to produce SHEs beyond Oganesson (Og). Unfortunately, no correlated

decay chains were observed. A key challenge is determining 9

the optimal incident energy (OIE), which mainly depends on theoretical predictions [1]. It is worth noting that because of the plenty of experimental data, most of the theories can describe the Ca induced fusion-evaporation reactions quite well. However, in order to synthesize SHEs beyond Og, projectiles heavier than such as Fe, and Ni are considered among the most promising candidates [2]. Is it reliable to extrapolate theoretically from the well-investigated Ca induced reactions to those with heavier projectiles for predicting the OIEs?

Due to the complexity of the synthesis mechanisms of 20

SHEs, particularly the presence of delicate ambiguities [3] the fusion process is not well understood theoretically [4]. The fusion probability is particularly important for re-

vealing the mechanism of synthesizing the SHEs, which is 24

usually calculated by using diffusion models [5], master equations [6], or empirical formulas [7]. These theories describe the dynamics of the formation of compound nuclei from different degrees of freedom, mainly at the radial degree of freedom: distance between the centers of the nuclei (corresponding to the elongation of a mononucleus) and the

mass asymmetry degree of freedom: $\eta = A_1 - A_2 / A_1 + A_2$ (A_1 and 31

are the mass numbers of the two nuclei that make up the compound nuclei).

A lot of theoretical studies have been performed to investi-

gate the synthesis of SHEs with $Z = 119$ and 120. However, 35

predictions in different theoretical models exhibit significant 36

uncertainty and model dependence []. In this case, it is imperative to address several critical aspects to provide reliable theoretical predictions: (i) How to evaluate the uncertainty of the theoretical model? In Ref. [], the Bayesian uncertainty quantification method is employed to evaluate the uncertainty of the calculated ERCS in the dinuclear system model. (ii) How can we reduce the model dependence of theoretical predictions? One weak model-dependence method (the OIE law) is proposed based on the strong correlation between the OIEs, the Coulomb barrier height of side collision, and the value []. (iii) Is it reliable to extrapolate predictions from ? In this work, utilizing the latest experimental data projectiles introduced reactions [], we quantify the reliability of extrapolation from within a one-dimensional model by employing the Smoluchowski diffusion equation, which is examined from two distinct perspectives: the radial degree of freedom and the mass asymmetry degree of freedom.

The Smoluchowski diffusion equation provides a concise physical image, in which the fusion probability is described by an analytical formula.

It has been effectively applied in the investigation of the SHEs synthesis based on the radial degree of freedom for both cold and hot fusion reactions []. During the fusion stage, the system undergoes diffusion across a one-dimensional parabolic barrier to overcome the fusion barrier and form the compound nucleus. Also, as shown in the following, the only adjustable parameter is obtained from systematic behaviors, which will relatively reduce the uncertainty introduced by the theoretical model, making it well suited to investigate the extrapolation properties. In the present study, we adopt the Smoluchowski

diffusion equation to investigate the theoretical extrapolation ability from to heavier projectiles () for synthesizing the SHEs. In order to strengthen the reliability, in addition to the radial degree of freedom we also employ the Smoluchowski diffusion equation in the mass asymmetry degree of freedom for the first time.

THEORETICAL DESCRIPTIONS Theoretically, the synthesis of SHEs can be divided into three steps and the ERCS is calculated as the summation over all partial waves

$$\sigma_{ER}(E_{c.m.}) =$$

where denotes the incident energy in the center-of-mass

system. The excitation energy $E^* = E_{c.m.} + Q$. The values of 80

Q calculated by using the Myers mass table [is the transmission probability. is the fusion probability and denotes the survival probability.

In the capture process, the projectile nucleus overcomes the Coulomb potential barrier to form a dinuclear system.

The penetration probability is given by the well-known Hill-Wheeler formula [

$$T(E_{c.m.}, J) = 1$$

$1 + \exp$ where denotes the barrier height for head-on collision. correspond to the position and curvature of the barrier under the l th partial wave, respectively. The barrier curvature can be calculated using the formula

$$\omega(l) =$$

is calculated by using the Smoluchowski diffusion equation [

$$\partial_t t = -(\partial_x W)' + TW'' \quad (3) \quad 97$$

The Brownian particle moves along the stretching degree of 98

freedom in a viscous fluid, which is characterized by a re-

pulsive parabolic potential $V(x) = -bx^2/2$. The constant 100

G is a friction coefficient. The initial probability distribution 101

is assumed to be a delta function at the event injection point. And it is assumed that is a Gaussian distribution function that elongates over time. When the interaction

time approaches infinity, the probability of the Gaussian dis- 105

tribution being on the right side of the maximum point of the potential barrier is:

$$P_{fus}(E_{c.m.}, J) = 1$$

results from the angular momentum)-dependent potential energy surface of the colliding sys- is the temperature of the fusing system. is the inner fusion barrier that a binuclear system must overcome to form a compound nucleus during the subsequent fusion process after capture. We study the complex fusion process in terms of the evolution of two degrees of freedom, radial and mass asymmetry degrees of freedom, respectively. Specific details are discussed in detail later.

The excited compound nucleus can evaporate light particles, such as neutrons, protons, and particles. We employ the Monte Carlo method to calculate the decay probabilities in each channel. In the l th deexcitation step the probability of evaporating the neutron (n) channel can be written as $\Gamma_n = \Gamma$

where, $\Gamma_{tot} = \Gamma_n + \Gamma_p + \Gamma_\alpha + \Gamma_\gamma + \Gamma_f$, which is addressed 124

in detail in Ref. [1]. The partial decay widths for the evaporation of neutron can be estimated by the Weisskopf-Ewing theory [2] Compared to the standard Bohr-Wheeler fission width [3] we assume that the quantal penetration and reflection of the barrier can be represented by the Hill-Wheeler approximation [4]. The modified Bohr-Wheeler fission width is:

$$\Gamma_f(E^*, J) = 1/2 \pi \rho_f(E^*, J)$$

$$1 + \exp[$$

Here $\omega = 1$ MeV. The fission barrier height $B_f(E^*)$ in Γ_f is 134

given as [

$$B_f(E^*) = -E_{0sh} - E^*/E_d, \quad (8) \quad 136$$

is the shell correction energy which is taken from Ref. [is the damping factor of the shell effects.

RESULTS AND DISCUSSION Fusion at the radial degree of freedom The fusion barrier is a key physical quantity for calculating the fusion probability. From the view point of radial degree of freedom (mostly related to quadrupole moment), the fusion could be considered as the reverse process of the fission with fixed octupole moment in Eq.) can be calculated as

$$B_{Rfus}(J) = E_{sd} - E_{inj} + E_{rotsd}(J) - E_{rotinj}(J). \quad (9) \quad 147$$

for the hot fusion reactions with projectiles as a function of , deduced from analysis of experimental data [In this work, the deformation energies including the saddle point and the injection point are calculated by us-

ing the finite range liquid drop model (FRLDM) [61 , 62]. 150

The injection point denotes the closest touching con-

figuration (R_{min}) in capture process and an initial condition 152

undergoing the shape evolution toward the compound nu-

cleus by overcoming an inner barrier, expressed as $S_{inj} = 154$

. Details of rotational energy are given in Ref. [As shown in Fig. (a), the fusion process is overcoming the inner fusion barrier with the evolution of the configurations from injection point to the saddle point. The position of injection point plays an important role on the fusion probability. The expression for the can be derived from the experimental data by fitting the calculations to the experimentally measured maximum values of the ERCS. The fitting results of the values as a function of the excess of the center-of-mass energy over the Coulomb barrier is shown in Fig. (b), where represents the nucleus-nucleus interaction potential in the entrance channel, which prevent the system from capture. The strong linear correlation between is shown and the systematics can be fitted

$$S_{inj} = 2.253 \text{ fm} - 0.0165 \times (E_{c.m.} - B_0) \text{ fm} / \text{MeV}. \quad (10) \quad 171$$

The red shaded area in Fig. (b) indicates the error margin , which is estimated to be . The different colors of the points represent the different neutron evaporation channels. The error bars of are derived from the uncertainty of the experimental value.

It is evident from Fig. (b) that the injection distance increases as the value of decreases. This is because for the low incident energy the system has sufficient time for nucleon rearrangement, thereby facilitating neck formation

at the relatively large distance. In contrast, for high incident energy, a more compressed configuration for neck formation is required. The same behavior is also shown in Ref. [1]. The strong correlation observed between the values and the corresponding energies provides support for the fission barriers proposed by Kowal et al [Eq. ()] determines the systematics of the injection point. the Eq. () with the experimental data. The calculated ERCS (solid lines) can reproduce the experimental data within the error bar rather well. Therefore, the systematical behavior for as well as the good description of the experimental data show that the Smoluchowski diffusion equation at the radial degree of freedom is a reasonable approach for investigating the extrapolation behavior to heavier projectiles.

Fusion at the mass asymmetry degree of freedom Fission is a slow process dominated by neck evolution dynamics. Similarly, the fusion process has sufficient time for shape relaxation. Also, the relatively high dissipated excitation energy could weaken the influence of shell effects. To strengthen the reliability of theoretical results, it is worth studying the fusion process from different perspective: the mass asymmetry degree of freedom (mostly related to In low-energy heavy-ion nuclear reactions, nucleon transfer and mass rearrangement between colliding partners play a crucial role.

Therefore, the mass asymmetry is usually selected as a key macroscopic variable to describe fusion process. We also obtain an approximately inverted parabolic potential energy surface and investigate the fusion based on the Smoluchowski diffusion equation. In the nuclear fusion process under the mass-asymmetry degree of freedom, the evolution in radial is frozen and the nucleon transfer takes place at the contact position which can be described by the distance between surfaces of the two colliding nuclei (). The reaction of the system towards fusion generally refers to the transfer of nucleons from the lighter nucleus (either the projectile or the target) to the heavier nucleus, evolving in the direction of increasing the mass asymmetry . The evolution of this process can be described by the diffusion of the mass asymmetry degree of freedom (see Fig. (a)) [After capture, fusion takes place and the compound nucleus is formed when the dinuclear system overcomes the inner fusion barrier . The more asymmetry configurations

ERCS are compared with the available experimental data for the reactions [(a), [(b), [(c), [(d), [(e), [(f), [(h), and [(i). The calculated ERCS in the channels $2n$, $3n$, $4n$, and $5n$ are denoted by the green lines, red lines, blue lines, and black lines, respectively. Here, dash-dotted lines denote the results from previous theoretical work [1]. Vertical arrows denote the excitation energies corresponding to collisions at for each reaction. than those on the B.G. point are considered as the occurrence of fusion [1] is calculated to be equal to the difference between the driving potential at the B.G. point and the driving potential at the injection point (of the projectile-target combination), as shown in Fig. is mainly determined by the details of the potential energy surface (PES) which is the potential energy of the dinuclear system along the direction and can be

written as $\Delta(Z_i, N_i)$ ($i = 1, 2$) here, are the radii of the two nuclei.

$\Delta(Z_i, N_i)$ ($i = 1, 2$) is the mass excess of the i th fragment [235]

is the nucleus-nucleus interaction potential, which comprises the Coulomb potential and the nuclear potential is written by Wong formula, and is written by the double-folding method. Details can be found in Ref. [1]. Here, r refers to the surface distance between two colliding nuclei for nucleon transfer process taking place [1] can be calculated as

$$B_{\eta}^{\text{fus}}(J) = U(\eta_B, G) - U(\eta_i) \quad (12) \quad 243$$

Similarly, the relationship between the contact distance is shown in Fig. (b), within the er-

(b), dependence of the ror bar a linear relationship between is obtained. This interesting behavior represent that the consideration of the Smoluchowski diffusion equation at the mass asymmetry degree of freedom is reasonable. The systematical behavior can be written as

$$D_{\text{cont}} = 2.435 \text{ fm} - 0.0618 \times (E_{\text{c.m.}} - B_0) \text{ fm} / \text{MeV} \quad (13) \quad 251$$

Unexpectedly, we observe that the inner fusion barrier exhibits a systematic similarity in the mass asymmetry and radial degrees of freedom. This suggests that to some extent the descriptions of the fusion process of both degrees of freedom share similarities and are comparable. Both perspectives are important reaction degrees of freedom in the fusion process.

Studying the fusion reactions from multiple perspectives is crucial for verifying the reliability of the theoretical extrapolation from Ca to In order to testify the method, by using Eq. () the calculated ERCS in Ca induced reactions are compared with the experimental data, as shown in Fig. . The calculated results (dashed lines) are in good agreement with both the experimental ERCS and the optimal energies. The above results give us confidence based on the Smoluchowski diffusion equation at mass asymmetry degree of freedom to investigate the ERCS of fusion reactions leading to new elements. In vious work Ref. [1]. It is found that the 3n evaporation channel is dominant, which is consistent with the results in Ref. [1]. We observe that for the reactions , our theoretical predictions agree better with experimental results than those reported in Ref. [1]. This is probably because in Ref. [1], the capture transmission coefficients are calculated using a simple sharp cutoff approximation. This approach is known to underestimate the capture cross-section below the Coulomb barrier.

The extrapolation of projectiles with Ti and In the above calculations, we notice that the Smoluchowski diffusion equation based on the radial and mass asymmetry degrees of freedom describes the experimental data in induced reactions quite well. As we mentioned above, we need to clarify whether it is reasonable to extrapolate the model including the systematical behaviors of induced reactions. Based on the values of determined by Eq. () and Eq. (). The calculated

results in the reactions are shown in Fig. . The calculated results for all reactions are in good agreement with the experimental data for both perspectives of radial and mass asymmetry degrees of freedom. We would like to state that the transition to heavier projectiles, such as reasonable and reliable according to current theories.

Calculations show that the ERCS for the heavier projectiles

50 Ti

and 54 Cr in the synthesis of SHEs with $Z = 116$ are 296

nearly one order of magnitude lower than that for the reaction 297

induced by the projectile. This reduction is primarily due to the lower mass asymmetry in the entrance channel of the reactions involving as projectiles, coupled with a higher fusion barrier. As a result, the system has a lower probability of fusion through diffusion.

D. The ERCS for synthesizing the SHE with $Z=119$ 303

To further investigate ERCS of synthesizing SHE with Z

$= 119$. In Fig. 5 [Figure 5: see original paper] , we conducted a study on the possibility 305

of synthesizing superheavy nuclei $Z = 119$ using 50 Ti, 51 V, 306

Cr as the projectiles. In the radial degree of freedom,

the OIEs for producing the element with $Z = 119$ via the reac- 308

tions , and are estimated to be 224.5 MeV, 231.3 MeV, and 242.3 MeV, respectively. Correspondingly, under the mass asymmetric degree of freedom, the OIEs are predicted to be 224.5 MeV, 231.3 MeV, and 240.3 MeV, respectively. The predicted OIEs are close to the results from the OIE law proposed in Ref [especially for the reactions

SUMMARY

The ERCS for synthesizing SHEs based on the different perspectives (radial and mass asymmetry degrees of freedom) within the concept of Smoluchowski diffusion equation are investigated. By calibrating the injection point distance and contact distance as adjustable parameters using the experimental ERCS data from Ca induced fusion reactions, we observe the strong linear systematic behaviors of . The inner fusion barrier shows a systematic similarity in both the radial and mass asymmetry degrees of freedom, which suggests that to some certain extent radial and mass asymmetry degrees of freedom are similar and comparable in their description of the fusion process. The parameterization of are then used for extrapolation to calculate the ERCS in the reactions

50 Ti +

, and The calculated results show good agreement with the recent experimental data from LBNL [] and Dubna [], which indicate that the theoretical calculations are relatively reliable in extrapolating the projectiles from Ca to Ti and Cr for synthesizing SHEs beyond Og. Finally, we present predictions of ERCS and OIEs

for the synthesis of SHN with $Z = 119$ from both radial and 337

mass asymmetry degrees of freedom. The predicted OIEs in radial and mass asymmetry degrees of freedom are consistent with each other, as well as the results in Ref. [This work also inspires us to utilize microscopic theories (such as density functional theories [] for calculating multidimensional PES and address it within the framework of the Smoluchowski diffusion equation.

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No. 23lgbj003. , and in radial degree of freedom (solid lines) and mass asymmetry degree of freedom (dashed lines) together with corresponding error corridors. Blue full squares represent experimental data for the $4n$ reaction channel of the reactions], and

, and predicted in radial degree of freedom (solid lines) and mass asymmetry degree of freedom (dashed lines) together with corresponding error corridors. The gray solid circles represent the maximum value of the ERCS for the $3n$ channels, corresponding to the optimal excitation energies.

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