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Abstract

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Full Text

Preamble

Systematic Study on Fusion Evaporation Reactions Induced by 48Ca–55Mn Projectiles

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A systematic study on fusion evaporation reactions induced by projectiles from 48Ca to 55Mn for the synthesis of superheavy elements with Z = 112–120 has been performed within the framework of the dinuclear system model. Considering the significant quadrupole deformation of 54Cr, the surface diffusion parameter was adjusted to enable a reliable extrapolation of the model to the 54Cr-induced reactions. The calculated results show that the evaporation residue cross sections for Z = 112 are consistently larger than those for Z = 113, and beyond this point the cross sections exhibit a bell-shaped trend, rising to Z = 115 (Z = 114 for 54Cr-induced reactions) and then decreasing rapidly with increasing atomic number. This behavior is primarily governed by the survival probabilities.

The neutron-deficient nature of 45Sc causes the corresponding reaction systems to deviate from the overall systematic trend. Predictions for the synthesis of elements Z = 119 and Z = 120 indicate that the reactions 45Sc + 249Cf and 50Ti + 249Cf are the most promising candidates, with maximum cross sections of 49.22 fb and 6.56 fb, respectively.

Keywords: Fusion evaporation reactions, Dinuclear system model, Superheavy elements, Evaporation residue cross sections

Introduction

With the completion of the High-Intensity Heavy Ion Accelerator Facility (HIAF) in China this year, a broad program of nuclear physics experiments is being planned [1, 2]. Among the various scientific objectives, the synthesis of new superheavy elements (SHEs) represents a central goal of both experimental and theoretical research. Beyond the extension of the periodic table, such efforts are essential for locating the next shell closures at Z = 114, 120, 124, 126 and N = 172, 184, and for approaching the island of stability [3–6], thereby deepening our understanding of nuclear structure at extreme proton and neutron numbers. Over the past decades, substantial progress has been achieved: elements Z = 107–113 were synthesized via cold fusion reactions based on 208Pb and 209Bi targets [7–13], while elements Z = 112–118 were synthesized via hot fusion reactions induced by the double magic projectile 48Ca and actinide targets [14–22]. This marks the completion of the seventh period of the periodic table.

For the synthesis of elements Z = 119 and Z = 120, conventional hot fusion reactions have become impractical due to the limitations of available target materials, necessitating the use of heavier projectiles such as 50Ti, 51V, 54Cr, 58Fe, and 64Ni. Although several laboratories have carried out experimental attempts with these projectiles, no conclusive evidence for the production of new elements has yet been reported. At GSI, the reactions 64Ni + 238U, 54Cr + 248Cm, and 50Ti + 249Bk were explored for Z = 120 [23–26], and 50Ti + 249Cf for Z = 119 [26], but only three random α-decay chains were observed in the reaction 54Cr + 248Cm, which were insufficient to confirm a new element [27]. JINR investigated the reaction 58Fe + 244Pu for Z = 120 without observing correlated α-decay chains [28]. In 2022, RIKEN estimated the optimal reaction energy for the synthesis of element Z = 119 through the reaction 51V + 248Cm [29]. The experiment aiming to synthesize element Z = 119 via the reaction 54Cr + 243Am will soon be carried out at HIFRL-CAFE2 [30]. More recently, the synthesis of element Z = 116 via 50Ti + 244Pu, 50Ti + 242Pu, and 54Cr + 238U has been reported [31, 32], demonstrating the feasibility of employing projectiles heavier than 48Ca and providing guidance for theoretical studies.

Based on existing experimental data, a variety of theoretical models have been developed to describe fusion evaporation (FE) reactions. Among them, microscopic approaches include the improved quantum molecular dynamics (ImQMD) model [33–36] and the time-dependent Hartree-Fock (TDHF) model [37–40], while several phenomenological models have also been proposed, such as the nucleon collectivization model [41–44], the two-step model [45–47], the fusion-by-diffusion (FBD) model [48–50], and the dinuclear system (DNS) model [51–65]. Although the DNS model has certain limitations in describing the microscopic dynamics of the fusion process, it has been widely adopted owing to its demonstrated accuracy in reproducing evaporation residue (ER) cross sections.

Within the framework of the DNS model, the calculated ER cross sections for reactions induced by 48Ca beams show good agreement with available experimental data. However, whether the model can reliably describe FE reactions induced by other projectiles such as 50Ti and 54Cr, which are now being considered for the synthesis of elements Z = 119 and Z = 120, remains an important question. In this work, the excitation functions of the ER cross sections for the synthesis of elements Z = 112–120 are calculated for a series of reactions induced by the stable projectiles 48Ca, 45Sc, 50Ti, 51V, 54Cr, and 55Mn.

The paper is organized as follows: In Sec. II, a brief introduction of the three stages of the DNS model is presented. In Sec. III, the reliability of the DNS model is examined, and the applicability of the model parameters is discussed. The systematic behavior of the FE reactions induced by different projectiles as well as several anomalous behaviors are analyzed, and the possible combinations for synthesizing the new SHEs Z = 119 and Z = 120 are predicted. Finally, a summary is given in Sec. IV.

II. Theoretical Framework

The DNS model provides a clear physical picture of the reaction mechanism, which can be divided into three stages: capture, fusion, and survival. Therefore, the ER cross section can be expressed as the product of the capture cross section σcap, the fusion probability PCN, and the survival probability Wsur [66]:

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

A. Capture cross section and transmission probability

In the DNS model, the empirical coupled channels approach is usually employed to describe the capture cross section of the system, which can be calculated as the sum of the cross sections for each partial wave J at a given center-of-mass energy Ec.m. [62]:

$$\sigma_{\mathrm{cap}}(E_{\mathrm{c.m.}}) = \frac{\pi}{2\mu E_{\mathrm{c.m.}}} \sum_{J=0}^{J_{\max}} (2J+1) T(E_{\mathrm{c.m.}}, J),$$

where is the reduced mass of the system, defined as = $M_1M_2/(M_1 + M_2)$, where M_1 and M_2 are the masses of the projectile and target, respectively. T(Ec.m., J) denotes the transmission probability. Due to the existence of the quantum tunneling effect, a barrier distribution function is introduced into the calculation [41]:

$$T(E_{\mathrm{c.m.}}, J) = \int f(B) T_{\mathrm{HW}}(E_{\mathrm{c.m.}}, J, B) dB,$$

where THW represents the Hill-Wheeler formula [67]:

$$T_{\mathrm{HW}}(E_{\mathrm{c.m.}}, J, B) = \frac{1}{1 + \exp\left[\frac{2\pi}{\hbar\omega(J)}\left(B + \frac{\hbar^2}{2B_s(J)} J(J+1) - E_{\mathrm{c.m.}}\right)\right]}.$$

The barrier distribution function f(B) is taken as an asymmetric Gaussian form to represent the distribution of the Coulomb barriers:

$$f(B) = \begin{cases} \frac{2}{N\sqrt{\pi}} \exp\left[-\left(\frac{B-B_m}{\Delta_1}\right)^2\right], & B < B_m, \\ \frac{2}{N\sqrt{\pi}} \exp\left[-\left(\frac{B-B_m}{\Delta_2}\right)^2\right], & B > B_m, \end{cases}$$

where f(B) satisfies the condition f(B)dB = 1, and N is the normalization constant given by $N = \sqrt{\pi}(\Delta_1 + \Delta_2)/2$. Here, Δ_1 = 2 MeV, Δ_2 = (B_0 - B)/2, and B = (B_0 + B)/2 represent the left width, right width, and center barrier height, respectively [41]. B_0 is the height of the barrier at zero deformation and B is the height of the saddle point which can be obtained by calculating the nucleus-nucleus interaction potential including the effect of dynamical quadrupole deformation, and it is expressed as [68]:

$$V(R, \beta_1, \beta_2, \theta_1, \theta_2) = \frac{1}{2} C_1 (\beta_1 - \beta_1^0)^2 + \frac{1}{2} C_2 (\beta_2 - \beta_2^0)^2 + V_N(R, \beta_1, \beta_2, \theta_1, \theta_2) + V_C(R, \beta_1, \beta_2, \theta_1, \theta_2).$$

Here, β_1 and β_2 are the dynamical quadrupole deformation parameters of the projectile and target, respectively, and ${\beta_1}^0$ and ${\beta_2}^0$ denote their static deformation parameters. $C_{1,2}$ are the stiffness coefficients of the nuclei [69]:

$$C_i = (\lambda - 1)(2\lambda + 1)R_{0,i}^2\sigma - \frac{3}{2\pi}R_{0,i}(2\lambda + 1)\sigma,$$

where λ denotes the level of the deformation, and for quadrupole deformation $\lambda = 2$. R$_0$, represents the radii of the spherical nuclei, which is calculated by R$_0$, $= 1.16$A^1/^{3}. σ is the surface-tension coefficient, which satisfies the relation 4πR$_0$, $^2\sigma =$ a A^2/^{3}, where a $= 18.32$ MeV.

The Coulomb potential is calculated by the Wong formula [70]:

$$V_C(R,\beta_1,\beta_2,\theta_1,\theta_2) = \frac{Z_{1Z_{2e}}^2}{R} + \frac{Z_{1Z_{2e}}^2}{2R^3}\sum_{i=1,2}\beta_i R_i^2 P_2(\cos\theta_i) + \frac{Z_{1Z_{2e}}^2}{2R^5}\sum_{i=1,2}\beta_i^2 R_i^4 P_2(\cos\theta_i),$$

and the nuclear potential is given by the double folding potential in the sudden approximation [51, 71]:

$$V_N(R) = C_0\left[F_{\text{in}}\int \rho_1(\mathbf{r})\rho_2(\mathbf{r}-\mathbf{R})d\mathbf{r} + F_{\text{ex}}\int \rho_1(\mathbf{r})\rho_2^{2/3}(\mathbf{r}-\mathbf{R})d\mathbf{r}\right],$$

where

$$F_{\text{in,ex}} = f_{\text{in,ex}} + f'_{\text{in,ex}}\frac{N_1 - Z_1}{A_1}\frac{N_2 - Z_2}{A_2}.$$

Here, $_1$ and $_2$ are the nuclear density distribution functions taken as Woods-Saxon types as follows:

$$\rho_1(\mathbf{r}) = \frac{\rho_0}{1 + \exp\left[\frac{r - R_1(\theta_1)}{a}\right]}, \quad \rho_2(\mathbf{r}) = \frac{\rho_0}{1 + \exp\left[\frac{|\mathbf{r}-\mathbf{R}| - R_2(\theta_2)}{a}\right]}.$$

Here, C$_0$ = 300 MeV·fm^3, f = 0.09, f = -2.59, f' = 0.42, f' = 0.54, $_0$ = 0.17 fm^{-3}, and the surface diffusion parameter is usually taken as 0.55 fm. However, considering the noticeable deformations of 54Cr and 55Mn, a value of 0.60 fm is adopted for these two nuclei in this work. R$_1$($_1$) and R$_2$($_2$) are the radii of the deformed nuclei, expressed as:

$$R_i(\theta_i) = R_i\left(1 + \beta_i\sqrt{\frac{5}{4\pi}}P_2(\cos\theta_i)\right).$$

B. Fusion probability and master equation

The DNS model assumes that the dinuclear system is driven by the potential energy surface (PES) to evolve along the mass asymmetry degree of freedom

= (A_2 - A_1)/(A_1 + A_2) through nucleon transfer until a compound nucleus is formed, and the PES is expressed as [62]:

$$U(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2, J) = B(Z_1, N_1) + B(Z_2, N_2) - [B(\mathrm{CN}) - V_{\mathrm{CN}}^{\mathrm{rot}}(J)] + V_{\mathrm{CN}}(Z_1, N_1, Z_2, N_2, R, \beta_1,$$

Here, B(Z_1, N_1), B(Z_2, N_2), and B(CN) represent the binding energies of the projectile, target, and compound nucleus, respectively. V_{CN}^{rot}(J) denotes the rotational energy of the compound nucleus. V_{CN} represents the interaction potential between the projectile and the target, which includes the nuclear potential, the Coulomb potential, and the centrifugal potential [68]:

$$V_{\mathrm{CN}}(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2, J) = V_N(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2) + V_C(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta$$

The nucleon transfer occurs at the bottom of the pocket of the PES, and because the DNS model does not take the relative distance degree of freedom between the projectile and target into account, it depends only on the mass asymmetry , which defines the driving potential. The driving potential governs the mass distribution during the nucleon transfer process. The maximum of the driving potential corresponds to the Businaro-Gallone (B.G.) point. The gap between the B.G. point and the incident point is defined as the inner fusion barrier B_{fus} = U(_B.G.) - U(_i) [72]. The compound nucleus can be formed only when the dinuclear system possesses sufficient inner excitation energy to overcome this barrier; otherwise, the quasifission process will take place.

By summing the probability of the fragment mass distribution beyond the B.G. point and taking the barrier distribution into account, the fusion probability can be obtained as [73]:

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

$$P_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J, B) = \sum_{Z_1, N_1}^{Z_{\mathrm{B.G.}}, N_{\mathrm{B.G.}}} P[Z_1, N_1, E_1, \tau_{\mathrm{int}}(E_{\mathrm{c.m.}}, J, B)],$$

where τ_{int}(Ec.m., J, B) represents the interaction time between the two fragments, which is obtained by the deflection function method [74]. At time t, the probability distribution P(Z_1, N_1, E_1, t) for fragment 1 with proton number Z_1, neutron number N_1, and excitation energy E_1 can be obtained by solving the following master equation:

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

In this equation, W_{Z$_1$,N$_1$; Z$_1$‘,N$_1$’} denotes the transition probability from the state (Z$_1$, N$_1$, E$_1$) to (Z$_1$‘, N$_1$’, E$_1$’), and d_{Z$_1$,N$_1$} represents the number of microscopic dimensions corresponding to the macroscopic state (Z$_1$, N$_1$, E$_1$) [75]. Λ_{qf}(Θ(t)) and Λ_{fis}(Θ(t)) denote the quasifission probability and the fission probability, respectively [76]. Further details can be found in Ref. [77].

C. Survival probability of a compound nucleus

The excited compound nucleus deexcites toward the ground state through neutron evaporation, emission of light charged particles, γ emission, and fission. In the synthesis mechanism of superheavy nuclei, the γ emission and light charged-particle emission processes are usually neglected, and the survival probability is mainly determined by the competition between neutron evaporation and fission. The survival probability of a superheavy nucleus that evaporates x neutrons can be expressed as [78]:

$$W_{\mathrm{sur}}(E^*_{\mathrm{CN}},x,J) = P(E^*_{\mathrm{CN}},x,J)\prod_{i=1}^{x}\frac{\Gamma_n(E_i^*,J)}{\Gamma_n(E_i^*,J)+\Gamma_f(E_i^*,J)}.$$

Here, E_i^* is the excitation energy of the compound nucleus before the emission of the ith neutron, which satisfies the relation E_{i+1}^* = E_i^* - B_n^i - 2T_i, with the initial value E_1^* = E_{CN}^*. B_n^i denotes the neutron separation energy for the emission of the ith neutron, and T_i = $\sqrt{E_i^*/a}$ represents the nuclear temperature before the emission of the ith neutron. For the evaporation of one neutron, the realization probability is given by a parametrized expression [79]:

$$P(E^*_{\mathrm{CN}},1,J) = \exp\left[-\frac{(E^*_{\mathrm{CN}}-B_n-E_{\mathrm{rot}}-2T)^2}{2\sigma^2}\right],$$

where σ is usually taken as 2.5 MeV in the calculations.

For the evaporation of multiple neutrons (x > 1), the realization probability is given by the Jackson formula [80]:

$$P(E^*_{\mathrm{CN}},x,J) = I(\Delta_x,2x-3) - I(\Delta_{x+1},2x-1),$$

where

$$I(z,m)=\int_0^z u^m e^{-u}du,\quad \Delta_x=\frac{E^*_{\rm CN}-\sum_{i=1}^x B_n^i-E_{\rm rot}}{T}.$$

The width of the neutron evaporation channel is given by the Weisskopf theory [81]:

$$\Gamma_n(E^*,J)=\frac{(2s_n+1)m_n}{\pi^2\hbar^2\rho(E^*,J)}\int_0^{E^*-B_n-\delta-1}\varepsilon\rho[(E^*-B_n-\varepsilon),J]\sigma_{\rm inv}(\varepsilon)d\varepsilon,$$

where δ = -12/A, 0, and 12/A correspond to odd-odd, odd-even (or even-odd), and even-even nuclei, respectively [62]. σ_{inv}( ) denotes the inverse cross section of the neutron at energy   [82].

The fission width can be calculated by using the Bohr–Wheeler formula [83]:

$$\Gamma_f(E^*,J)=\frac{1}{2\pi\rho_f(E^*,J)}\int_0^{E^*-B_f-\delta-1}\rho_f[(E^*-B_f-\delta_f-\varepsilon),J]\frac{d\varepsilon}{1+\exp\left[-2\pi(E^*-B_f-\varepsilon)/\hbar\omega_f\right]},$$

where B_f denotes the fission barrier of the compound nucleus with both temperature and angular momentum dependence [84], which can be written as:

$$B_f(E^*,J)=B_{\rm LD}(1-x_{\rm LD}T^2)+B^f_{\rm M}\exp\left(-\frac{E^*}{E_D}\right)\exp\left[\frac{\hbar^2J(J+1)}{2J^2_{\rm s.d.}}-\frac{\hbar^2J(J+1)}{2J^2_{\rm g.s.}}\right].$$

Here, B_{LD} represents the macroscopic part of the fission barrier calculated from the liquid-drop model [85], while B_M^f corresponds to the microscopic part taken from the shell correction energy [86]. x_{LD} = 0.04 is the temperature dependent parameter [84], and E_D is the shell damping energy, for which E_D = 25.65 MeV is adopted in the calculations [87]. J_g.s. and J_s.d. denote the moments of inertia of the compound nucleus at the ground state and at the saddle point, respectively [88].

The level density is calculated by using the Fermi-gas model [62]:

$$\rho(E^*,J)=\frac{2J+1}{2\sqrt{2\pi}\sigma^3}a^{1/4}(E^*-\delta)^{5/4}\exp\left[2\sqrt{a(E^*-\delta)}-\frac{(J+1/2)^2}{2\sigma^2}\right],$$

where σ^2 = 6m^{2}a(E^* - δ)/π^2, and m^2 0.24A^2/^{3}.

The level density parameter with shell correction energy taken into account can be written as [63]:

$$a(E^*, Z, N) = \tilde{a}(A)\left[1 + \frac{E_{\rm sh}(Z, N)}{E^* - \Delta} f(E^* - \Delta)\right],$$

here, $\tilde{a}$(A) = αA + βA^2/^{3}b_s is the asymptotic Fermi-gas value of the level density parameter at high excitation energy. The shell damping factor is given by f(E$^\wedge$*) = 1 - exp(-$\gamma E^\wedge$*), with γ = $\tilde{a}$/(A^4/^{3}). For the neutron evaporation channel, the level density parameter a_n is determined with the parameters α = 0.114, β = 0.098, b_s = 1, and = 0.4 [63]. For the fission channel, the level density parameter a_f satisfies the ratio a_f/a_n = 1.081 [87].

III. Results and Discussion

A. Comparison of experimental data and calculated results

To verify the reliability of the DNS model in calculating the ER cross sections, a series of hot fusion reactions induced by 48Ca for the synthesis of elements with Z = 112–118 were calculated, including 48Ca + 238U, 48Ca + 237Np, 48Ca + 242Pu, 48Ca + 244Pu, 48Ca + 243Am, 48Ca + 245Cm, 48Ca + 248Cm, 48Ca + 249Bk, and 48Ca + 249Cf. The calculated results of the DNS model exhibit reasonable agreement with the corresponding experimental data [14–22, 89–93], as shown in Fig. 1 [Figure 1: see original paper]. Although a few specific evaporation channels, such as the 3n channel of 48Ca + 244Pu, the 2n channel of 48Ca + 243Am, and the 2n channel of 48Ca + 245Cm show slight deviations, the discrepancies remain within about one order of magnitude.

To further examine whether the DNS model can provide an equally reasonable description for FE reactions induced by projectiles other than 48Ca, the FE reactions 50Ti + 242Pu and 50Ti + 244Pu were calculated using the same set of parameters, and the results, shown in Fig. 2 Figure 2: see original paper and Fig. 2(b), exhibit good agreement with the corresponding experimental data [31, 32]. However, applying the same parameters to the reaction 54Cr + 238U leads to a significant overestimation of the ER cross sections, as shown by the thin curve in Fig. 2(c), indicating that the original parameter set is not suitable for the 54Cr-induced reactions.

Table 1 lists the quadrupole deformation parameters of the projectiles obtained from Ref. [94]. 48Ca is a doubly magic nucleus with β_2 = 0.0, and 50Ti has a small deformation with β_2 = -0.064, consistent with the agreement obtained using the original parameters. In contrast, 54Cr exhibits a noticeable quadrupole deformation with β_2 = 0.119, for which the original surface diffusion parameters a$_1$,$_2$ = 0.55 fm in the double folding nuclear potential become inappropriate and lead to an overestimation of the ER cross sections. By adopting a$_1$,$_2$ = 0.6 fm for the 54Cr-induced reactions, the calculated ER cross sections, as shown by the thick curve in Fig. 2(c), match the experimental data within the uncertainties. Therefore, the surface diffusion parameter is taken as a$_1$,$_2$ = 0.6 fm for both the 54Cr- and 55Mn-induced reactions in the following calculations. Substantially, the DNS model can reliably reproduce the FE reactions induced by 48Ca, and with appropriate adjustments of the parameters for deformed projectiles, it retains a reasonable extrapolation capability, providing strong support for the subsequent systematic analysis.

B. Systematic analysis of FE reactions induced by projectiles from 48Ca to 55Mn

The 48Ca-induced hot fusion reactions have achieved great success experimentally, revealing that the maximum ER cross sections exhibit a bell-shaped trend with increasing atomic number Z of the synthesized elements, first rising to a maximum around Z = 115 and then decreasing for larger atomic numbers. For the synthesis of the same element, the ER cross section decreases as the projectile atomic number increases; this trend is clearly seen in the reactions leading to Z = 116 in Fig. 3 [Figure 3: see original paper]. The calculated results follow these systematic trends well and allow for a reasonable extrapolation to the production cross sections of elements Z = 119 and Z = 120. To further explore the systematic variation of FE reactions, we have calculated the excitation functions for the synthesis of elements Z = 112–120 in reactions induced by projectiles from 48Ca to 55Mn. The selected reaction systems, the dominant evaporation channels, the corresponding fission barriers B__f, neutron separation energies B__n, and B__f - B__n values are listed in Table 2 .

Fig. 4 [Figure 4: see original paper] shows the variation of the maximum ER cross sections for the synthesis of elements Z = 112–120 with different projectiles. It can be seen that the cross sections for the 45Sc-induced reactions are relatively small, which does not follow the expected systematic trend. Since the 45Sc systems have the largest mass asymmetry, their inner fusion barriers are correspondingly lower, as shown in Fig. 5 [Figure 5: see original paper], which would normally enhance the ER cross sections.

To further clarify this issue, Fig. 6 [Figure 6: see original paper] presents the fusion cross sections corresponding to the dominant evaporation channels that give the maximum ER cross sections, defined as σ{*fus*} = σ{cap} × P__{CN}, together with the survival probabilities W__{sur}. As shown in Fig. 6(a), the fusion cross section for the 45Sc system is indeed the highest among all the projectiles considered. However, the extremely low survival probabilities shown in Fig. 6(b) are the primary reason why its ER cross sections deviate from the expected systematic trend. For FE reactions that produce highly excited compound nuclei, typically 3–5 neutrons are evaporated before de-exciting to the ground state, and a larger number of available neutrons generally favors the survival of the compound nucleus. Since 45Sc has the lowest N/Z among the projectiles (N/Z = 1.14), the corresponding compound nuclei are relatively neutron-deficient, which suppresses their survival probabilities and ultimately causes the ER cross sections to deviate from the systematic behavior.

For the other reaction systems, as the projectile atomic number increases, the Coulomb repulsion between the projectile and target becomes stronger, leading to a gradual decrease in the ER cross sections. From Fig. 6(a), the fusion cross section for the 48Ca system is the lowest among all projectiles, even though its mass asymmetry is second only to that of 45Sc. Within the DNS framework, after the projectile and target overcome the Coulomb barrier and form the dinuclear system, they must further traverse the Coulomb repulsion to reach the bottom of the potential pocket where nucleon transfer occurs. Compared with the obviously quadrupole-deformed nuclei 54Cr and 55Mn, 48Ca is a doubly magic nucleus with a spherical shape in its ground state, leading to less favorable contact with the targets, which is likely the main reason for its relatively small fusion cross sections.

Indeed, Fig. 7 [Figure 7: see original paper] shows that, for the synthesis of element Z = 112, the distance Δr between the Coulomb barrier and the pocket minimum decreases with increasing projectile atomic number, making it easier for projectiles with larger atomic numbers to reach the pocket bottom. In contrast, 48Ca has the highest N/Z among all projectiles (N/Z = 1.40), which is highly favorable for survival probabilities. Overall, the N/Z of the projectile plays a crucial role in determining the survival probability, and neutron-rich projectiles can significantly enhance the ER cross sections.

Another noticeable anomaly appears in Fig. 4: the calculated cross sections for the synthesis of element Z = 112 are higher than those for Z = 113, which seems inconsistent with the bell-shaped trend. In fact, this phenomenon is also observed in the experimental data, as shown in Fig. 3. The measured cross section is 2.45^{+1.47}*{-0.97} pb for the synthesis of Z = 112 via the reaction 48Ca + 238U, and the corresponding value is 0.9^{+1.6}*{-0.6} pb for the synthesis of Z = 113 via the reaction 48Ca + 237Np.

As shown in Fig. 5, for even-even projectiles 48Ca, 50Ti, and 54Cr, the inner fusion barriers for the synthesis of Z = 112 and Z = 113 do not differ significantly. For the 45Sc-induced reactions, the 231Pa target used for synthesizing Z = 112 contains six fewer neutrons than the 238U target used for synthesizing Z = 113, which leads to a lower inner fusion barrier. This situation occurs for all odd-even projectiles, such that the inner fusion barriers for Z = 112 are typically 1–3 MeV lower than those for Z = 113. Nevertheless, Fig. 6(a) shows that such differences have only minor effects on the fusion cross sections and cannot account for the systematic anomaly observed. In contrast, Fig. 6(b) clearly indicates that the survival probabilities for Z = 112 are roughly five times larger than those for Z = 113 for all projectile-target combinations. These enhanced survival probabilities are the dominant factor responsible for the anomalously large ER cross sections of element Z = 112.

Excluding the case of Z = 112, all systems exhibit a bell-shaped distribution from Z = 113, first increasing and then decreasing, with the maximum ER cross section occurring at Z = 115 for all projectiles except 54Cr. As shown in Fig. 6, although the fusion cross section of the 54Cr-induced reactions for the synthesis of Z = 114 is locally the smallest among its neighboring elements, its survival probability is about 90 times larger than that for Z = 113 and about 4 times larger than that for Z = 115. As shown in Table 2, the reaction 54Cr

+ 232Th for the synthesis of Z = 114 exhibits an abrupt increase in B_f - B_n compared with its adjacent reactions, leading to a significantly enhanced survival probability, which has a strong impact on the ER cross section. This demonstrates that the ER cross section is governed primarily by the survival probability in hot fusion reactions.

With increasing target atomic number, although the mass asymmetry becomes larger, the Coulomb repulsion between the projectile and target increases significantly, leading to a gradual reduction in fusion cross sections. Consequently, the ER cross sections decrease rapidly beyond the maximum. It is worth noting that in Fig. 6, the reactions leading to the synthesis of Z = 119 and Z = 120 induced by 48Ca and 54Cr exhibit trends different from the other systems. This behavior arises because the dominant evaporation channel for the synthesis of Z = 119 lies in the 3n channel, whereas that for Z = 120 lies in the 4n channel. The higher excitation energy in the 4n channel results in a larger fusion cross section but a smaller survival probability for Z = 120 compared with Z = 119. The change in the dominant evaporation channel is mainly caused by the relatively large N/Z of the target nuclei 257Fm and 248Cm. Therefore, the N/Z of the target nuclei is of critical importance in determining the evaporation channel associated with the maximum ER cross section, which provides significant insight for predicting the optimal reaction pathways for the synthesis of new SHEs.

C. Predictions for the synthesis of elements Z = 119 and Z = 120

Fig. 8 [Figure 8: see original paper] shows the excitation functions of the possible reaction systems for the synthesis of element Z = 119. Although the reaction 48Ca + 252Es exhibits a relatively high cross section, it cannot be experimentally realized due to the limited availability of the target material. The 3n channel of the 45Sc + 249Cf reaction gives the largest ER cross section, with a maximum of 49.22 fb at E*_{CN} = 37 MeV among the reactions. This agrees well with the predictions in Ref. [30], which suggested the same optimal combination for the synthesis of element Z = 119.

For the reactions 50Ti + 249Bk, 51V + 248Cm, 54Cr + 243Am, and 55Mn + 244Pu, the most probable evaporation residues are 295119 and 294119. Among them, the 4n channel of 50Ti + 249Bk shows the highest cross section of 43.28 fb, which is very close to the value predicted in Ref. [95]. For the reaction 51V + 248Cm, the 4n channel yields a cross section of 28.65 fb at E*_{CN} = 40 MeV, which falls within the uncertainty range predicted in Ref. [30]. The maximum cross section of the 3n channel reaches 22.41 fb at E*_{CN} = 33 MeV for 54Cr + 243Am, which is in good agreement with the prediction in Ref. [96], giving the maximum cross section about 25 fb at E*_{CN} = 32–35 MeV. For the 55Mn + 244Pu reaction, the maximum ER cross section of 13.95 fb appears at E*_{CN} = 40 MeV, indicating that this reaction also has the potential to successfully synthesize element Z = 119.

Fig. 9 [Figure 9: see original paper] shows the excitation functions of the possible reaction systems for the synthesis of element Z = 120, where the reactions 48Ca + 257Fm and 45Sc + 252Es face the same limitation due to the unavailability of target materials. The maximum cross sections of the reactions 51V + 249Bk and 54Cr + 248Cm are both around 5 fb, while that of 55Mn + 243Am is approximately 1 fb. The 50Ti + 249Cf reaction yields the highest cross section of 6.56 fb in the 3n channel, which is in excellent agreement with the FBD model prediction of about 6 fb for the 3n and 4n channels [50], and is therefore considered the most promising candidate for the synthesis of element Z = 120.

IV. Summary

In this work, within the framework of the DNS model, we calculated the FE reactions leading to the synthesis of superheavy elements with Z = 112–120 induced by projectiles from 48Ca to 55Mn. The calculated ER cross sections show reasonable agreement with the experimental data for 48Ca- and 50Ti-induced reactions, whereas the 54Cr-induced reactions are overestimated by using the same parameter set. The quadrupole deformation of 54Cr is taken into account by adjusting the surface diffusion parameter to 0.60 fm; the recalculated results fall within the experimental uncertainties. This parameter is also adopted for the 55Mn-induced reactions.

The systematic behavior of the calculated ER cross sections is analyzed. The N/Z of the projectile influences the survival probability, causing the 45Sc-induced reactions to deviate from the systematic trend, while the 48Ca-induced reactions exhibit the largest cross sections. The N/Z of the target also affects the dominant evaporation channel, which leads to distinct behavior in the fusion cross sections and survival probabilities for 48Ca- and 54Cr-induced reactions when producing elements Z = 119 and Z = 120. For hot fusion reactions, the survival probability primarily determines the ER cross section, which explains the systematically larger values for Z = 112 than those for Z = 113, and the shift of the maximum for the 54Cr-induced reactions from Z = 115 to Z = 114.

Predictions for elements Z = 119 and Z = 120 suggest that the reactions 45Sc + 249Cf and 50Ti + 249Cf are the most favorable combinations, yielding maximum ER cross sections of 49.22 fb at the incident energy of 211.09 MeV and 6.56 fb at the incident energy of 228.03 MeV. The reactions 54Cr + 243Am and 55Mn + 243Am reach their maximal ER cross sections of 22.41 fb and 1.65 fb at the incident energies of 238.24 MeV and 246.20 MeV, respectively.

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Note: Figure translations are in progress. See original paper for figures.