

Production of superheavy nuclei in collisions of ^{48}Ca , ^{50}Ti , ^{51}V and ^{54}Cr on actinide nuclei with the Skyrme energy-density functional*

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Abstract: Within the framework of the dinuclear system (DNS) model, the synthesis of superheavy nuclei in ^{48}Ca -, ^{50}Ti -, ^{51}V -, and ^{54}Cr -induced fusion reactions on actinide nuclei has been systematically investigated. The nucleus–nucleus potential and the potential energy surface in the DNS model are calculated using the well-established Skyrme energy-density functional with the parameter sets SKM, SKM*, Ska, Z, and SLy4, respectively. The available experimental data from Dubna, GSI, RIKEN, and Berkeley are well reproduced by the model. It is found that the fusion-evaporation residue excitation functions and production cross sections of superheavy nuclei are correlated with nuclear matter properties. The ^{48}Ca -induced reaction, i.e., $^{48}\text{Ca} + ^{248}\text{Cm}$, has a larger production cross section for synthesizing the superheavy nucleus livermorium than the non-magic systems $^{50}\text{Ti} + ^{244}\text{Pu}$ and $^{54}\text{Cr} + ^{238}\text{U}$. The production cross sections of new superheavy elements with atomic numbers $Z = 119$ and 120 in the reactions $^{51}\text{V} + ^{248}\text{Cm}$ and $^{54}\text{Cr} + ^{243}\text{Am}/^{248}\text{Cm}$ are thoroughly investigated. The fusion-evaporation excitation functions strongly depend on the Skyrme parameters, particularly at excitation energies below 40 MeV.

Keywords: Superheavy nuclei, Skyrme energy density functional, Potential energy surface, DNS model

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I. INTRODUCTION

In the past several decades, the synthesis of superheavy nuclei (SHNs) in terrestrial laboratories via fusion-evaporation reactions has made substantial progress, reaching the element oganesson ($Z = 118$). Up to now, the seventh period of the periodic table has been completely filled. Extending the periodic table is important not only for basic science, but also for applications in chemistry, materials science, biology, interdisciplinary science, etc. The synthesis of new superheavy elements or SHNs is complicated by the quasifission mechanism that occurs before compound-nucleus formation in fusion reactions. Shell effects bind nucleons and enable the existence of SHNs, thereby motivating predictions of the “island of stability”. Low-energy fusion reactions are multidimensional quantum-tunneling processes, in which collective excitation, dynamical deformation, nucleon or cluster transfer, etc., are coupled to compound-nucleus formation through overcoming the Coulomb barrier [1]. Up to now, fusion reactions in low-energy heavy-ion collisions have been extensively investigated, including weakly

bound nucleus-induced reactions [2], nuclear fusion at deep sub-barrier energies for astrophysical interest [3], and the synthesis of superheavy nuclei (SHNs) [4, 5]. Roughly one third of the nuclides on the nuclear chart have been synthesized in laboratories via fusion reactions [6]. With the establishment of radioactive beam facilities worldwide, such as RIBF at RIKEN (Japan) [7], SPIRAL2 at GANIL (France) [8], FRIB at MSU (USA) [9], and HIAF at IMP (China) [10], the synthesis of new SHNs on the “island of stability” via fusion reactions induced by neutron-rich radioactive beams or via multinucleon transfer (MNT) reactions may become possible in future experiments. Accurate estimation of SHN production cross sections is particularly important for experimental synthesis, including the optimal choice of reaction system, beam energy, evaporation channel, and so on.

The nucleus-nucleus (NN) potential influences fusion dynamics. A key quantity is the Coulomb barrier, which determines the capture and fusion of two colliding partners and is mainly composed of the nuclear, centrifugal, and repulsive Coulomb potentials. Usually, the NN po-

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tential is used to calculate the fusion cross section within a quantum-penetration or coupled-channel approach. The fusion probability rapidly decreases as the incident energy is reduced below the Coulomb barrier. Bass proposed an empirical formula for estimating the Coulomb barrier and fusion cross section [11]. In light and medium reaction systems, the compound nucleus is formed after overcoming the Coulomb barrier, and this process has been extensively investigated in studies of stellar fusion and nuclear structure. However, in heavy projectile-target combinations for SHN formation, quasifission proceeds before compound-nucleus formation; in this process, the disintegration of the colliding system after a few nucleon transfers hinders compound-nucleus formation. Neck dynamics, shape evolution, collective excitation, nucleon (cluster) transfer, etc., influence fusion dynamics and compound-nucleus formation. It is well known from transport models, e.g., the time-dependent Hartree-Fock (TDHF) approach [12] and the quantum molecular dynamics (QMD) model [13], that the NN potential in fusion reactions is associated with shape evolution and beam energy. There are mainly two types of NN potentials, namely, the adiabatic potential [14] and phenomenological potentials within the prompt approximation, such as the Woods-Saxon potential [15], proximity potential [16], and double-folding potentials with Yukawa-plus-exponential, density-dependent M3Y force, Migdal force, etc. [17–20]. The NN potential can also be calculated within the energy-density functional approach based on effective nucleon-nucleon interactions, i.e., the Skyrme force [21, 22], the finite-range Gogny interaction [23], etc. An advantage of the energy-density functional approach is that it provides a unified description of nuclear structure, nuclear dynamics, and nuclear matter based on effective nucleon-nucleon interactions.

In this work, the NN potential is calculated within the Skyrme energy-density functional framework. The potential energy surface is obtained with this approach, and SHN production is discussed by implementing it into the dinuclear system (DNS) model. The article is organized as follows. In Section 2, we briefly describe Skyrme energy-density functional theory and the potential energy surface in the DNS model. The fusion-evaporation excitation functions for SHN production in the ^{48}Ca -, ^{50}Ti -, ^{51}V -, and ^{54}Cr -induced reactions on actinide nuclei are systematically investigated in Section 3. A summary and perspective on new SHN production are presented in Section 4.

II. BRIEF DESCRIPTION OF THE MODEL

The DNS model has been extensively applied to quasi-fission dynamics, multinucleon transfer reactions, pre-equilibrium cluster emission, and deep-inelastic collisions, among others, in which the dissipation of the relat-

ive motion energy and rotational energy of the colliding system into internal degrees of freedom such as excitation energy is assumed to occur at the touching configuration. The evolution of the DNS system toward the formation of a compound nucleus mainly proceeds along two degrees of freedom, namely, the radial motion via the decay of the DNS and the nucleon (cluster) transfer via the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ or the charge asymmetry $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$ [24–27]. In accordance with the temporal evolution of the system, projectile-target capture by overcoming the Coulomb barrier, the competition between quasi-fission and complete fusion through nucleon transfer to form the compound nucleus, and the de-excitation of the thermal compound nucleus proceed to form the SHN. The production cross section in the fusion-evaporation reaction is calculated by summing over the partial waves J at an incident center-of-mass energy $E_{c.m.}$ as

$$\sigma_{ER}(E_{c.m.}) = \frac{\pi \hbar^2}{2\mu E_{c.m.}} \sum_{J=0}^{J_{max}} (2J+1) T(E_{c.m.}, J) \times P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J) \quad (1)$$

Here, $T(E_{c.m.}, J)$ is the transmission probability for overcoming the Coulomb barrier, and it is given by the Hill–Wheeler formula with a Gaussian-type barrier distribution, as described in [25].

$$T(E_{c.m.}, J) = \int f(B) \frac{1}{1 + \exp \left\{ -\frac{2\pi}{\hbar\omega(J)} \left[E_{c.m.} - B - \frac{J(J+1)\hbar^2}{2\mu R_B^2(J)} \right] \right\}} dB, \quad (2)$$

with $\hbar\omega(J)$ denoting the width of the parabolic barrier at the barrier radius $R_B(J)$, where $R_B = r_{0b} * (A_P^{1/3} + A_T^{1/3})$ and $r_{0b} = 1.4 \sim 1.5$ fm. The distribution function is assumed to have the Gaussian form $f(B) = \frac{1}{N} \exp[-((B - B_m)/\Delta)^2]$, where the normalization constant satisfies the condition $\int f(B) dB = 1$. The quantities B_m and Δ are evaluated as $B_m = (B_C + B_S)/2$ and $\Delta = (B_C - B_S)/2$, respectively. Here, B_C and B_S denote the Coulomb barrier for the waist-to-waist orientation in nuclear collisions and the barrier height at the saddle point with varying quadrupole deformation, respectively.

In the DNS model, accurate estimation of the NN potential is important for calculating the transmission and formation probabilities, which affect the production cross section of SHN and the structural distribution of the fusion-evaporation excitation function. The NN potential consists of nuclear, Coulomb, and centrifugal contributions, as follows [25, 28]

$$V(R, \alpha_P, \alpha_T, J) = V_{nuc}(R, \alpha_P, \alpha_T) + V_{Coul}(R, \alpha_P, \alpha_T) + \frac{\hbar^2}{2\xi_{rel}} J(J+1). \quad (3)$$

Here, the Coulomb potential including quadrupole deformation is calculated using the well-known Wong formula [29]. The α_i denote the nuclear radius R_i , quadrupole deformation β_i , the polar angle θ_i between the collision direction and the symmetry axis of the deformed nucleus, with $i = P, T$ denoting the projectile and target nuclei, and the relative moment of inertia ξ_{rel} . The center-of-mass distance R between the projectile and target nuclei is correlated with the quadrupole deformation parameter. The deformation effect is included in both the nuclear and Coulomb potentials, resulting in the orientation dependence of the Coulomb barrier and influencing the quasifission dynamics in fusion-evaporation reactions.

In the DNS model, the nuclear potential was initially calculated using the Morse potential [30], the Woods-Saxon potential [25], and the double-folding approach with Migdal force [31]. In this work, the nuclear potential is calculated using the Skyrme energy-density functional (EDF) in spherical coordinates (r , θ , and ϕ), as in [32, 33]

$$V_{nuc}(R, \{\alpha\}_P, \{\alpha\}_T) = E_{sys}(R, \{\alpha\}_P, \{\alpha\}_T) - E_P(\{\alpha\}_P) - E_T(\{\alpha\}_T). \quad (4)$$

The E_{sys} , E_P , and E_T are the total binding energies arising from the nucleon-nucleon interaction for the colliding system, projectile, and target nuclei, respectively, calculated by multiple integration as $E = \int \int \int \varepsilon[\rho_p(\mathbf{r}), \rho_n(\mathbf{r})] r^2 \sin(\theta) dr d\theta d\phi$. The total energies of the colliding system, projectile, and target nuclei are calculated using the EDF method as

$$E_{sys}(\mathbf{R}, \{\alpha\}_P, \{\alpha\}_T) = \int \varepsilon[\rho_{1p}(\mathbf{r}) + \rho_{2p}(\mathbf{R} - \mathbf{r}), \rho_{1n}(\mathbf{r}) + \rho_{2n}(\mathbf{R} - \mathbf{r})] d\mathbf{r}, \quad (5)$$

$$E_P(\{\alpha\}_P) = \int \varepsilon[\rho_{1p}(\mathbf{r}), \rho_{1n}(\mathbf{r})] d\mathbf{r} \quad (6)$$

and

$$E_T(\{\alpha\}_T) = \int \varepsilon[\rho_{2p}(\mathbf{R} - \mathbf{r}), \rho_{2n}(\mathbf{R} - \mathbf{r})] d\mathbf{r}, \quad (7)$$

respectively. The density profiles of the proton and neutron distributions for the projectile and target nuclides are assumed under the sudden approximation. For example,

the Woods-Saxon form for the projectile nuclide is given as

$$\rho_{1i}(\mathbf{r}) = \frac{\rho_{1i_0}}{1 + \exp[\mathbf{r} - R_1/a_i]}, i = \{n, p\} \quad (8)$$

with the diffuseness coefficient a_i in the range 0.55–0.65 fm. The parameters ρ_{1i_0} and a_i are obtained by fitting the results of the Skyrme-Hartree-Fock method. The projectile radius with quadrupole deformation is given by

$$R_1 = R_{01} \left(1 + \sqrt{\frac{5}{4\pi}} \beta_2 \frac{3\cos^2\theta - 1}{2} \right) \quad (9)$$

with $R_{01} = 1.28A_p^{1/3} - 0.76 + 0.8A_p^{-1/3}$ fm, where A_p is the mass number of the projectile nucleus. A similar method is used to calculate the system energy and the target energy. Details can be found in Ref. [34].

Based on the well-known extended Thomas-Fermi (ETF) approximation, the kinetic-energy term, with protons and neutrons distinguished, is calculated up to the second-order correction. The energy-density functional is expressed as follows [22]

$$\varepsilon_{kin}[\rho_p(\mathbf{r}), \rho_n(\mathbf{r})] = \frac{\hbar^2}{2m} [\varepsilon_{kin}^p(\mathbf{r}) + \varepsilon_{kin}^n(\mathbf{r})] + \varepsilon_{pot}(\mathbf{r}). \quad (10)$$

The kinetic-energy density functional is given by

$$\begin{aligned} \varepsilon_{kin}^i(\mathbf{r}) = & \frac{3}{5} (3\pi^2)^{2/3} \rho_i^{5/3} + \frac{1}{36} \frac{(\nabla \rho_i)^2}{\rho_i} + \frac{1}{3} \Delta \rho_i \\ & + \frac{1}{6} \frac{\nabla \rho_i \nabla f_i + \rho_i \Delta f_i}{f_i} - \frac{1}{12} \rho_i \left(\frac{\nabla f_i}{f_i} \right)^2 \\ & + \frac{1}{2} \rho_i \left(\frac{2m}{\hbar^2} \frac{W_0}{2} \frac{\nabla(\rho + \rho_i)}{f_i} \right)^2 \end{aligned} \quad (11)$$

with the factor

$$f_i = 1 + \frac{2m}{\hbar^2} \left(\frac{3t_1 + 5t_2}{16} + \frac{t_2 x_2}{4} \right) \rho_i(\mathbf{r}). \quad (12)$$

Here, the local densities of protons and neutrons are denoted by ρ_i with $i = n, p$, the total density is $\rho = \rho_n + \rho_p$, and the kinetic energy density is $\varepsilon_{kin} = \varepsilon_{kin}^n + \varepsilon_{kin}^p$. These quantities are specified separately for the colliding system, the projectile, and the target nuclei. The potential-energy density functional is evaluated by

$$\begin{aligned} \varepsilon_{pot}(\mathbf{r}) = & \frac{t_0}{2} \left[\left(1 + \frac{1}{2} x_0 \right) \rho^2 - \left(x_0 + \frac{1}{2} \right) (\rho_p^2 + \rho_n^2) \right] \\ & + \frac{1}{12} t_3 \rho^\alpha \left[\left(1 + \frac{1}{2} x_3 \right) \rho^2 - \left(x_3 + \frac{1}{2} \right) (\rho_p^2 + \rho_n^2) \right] \end{aligned}$$

$$\begin{aligned}
& + \frac{1}{4} [t_1(1 + \frac{1}{2}x_1) + t_2(1 + \frac{1}{2}x_2)] \tau \rho \\
& + \frac{1}{4} [t_2(x_2 + \frac{1}{2}) - t_1(x_1 + \frac{1}{2})] (\tau_p \rho_p + \tau_n \rho_n) \\
& + \frac{1}{16} [3t_1(1 + \frac{1}{2}x_1) - t_2(1 + \frac{1}{2}x_2)] (\nabla \rho)^2 \\
& - \frac{1}{16} [3t_1(x_1 + \frac{1}{2}) + t_2(x_2 + \frac{1}{2})] ((\nabla \rho_n)^2 + (\nabla \rho_p)^2) \\
& - \frac{mW_0^2}{2\hbar^2} \left[\frac{\rho_p}{f_p} (2\nabla \rho_p + \nabla \rho_n)^2 + \frac{\rho_n}{f_n} (2\nabla \rho_n + \nabla \rho_p)^2 \right]. \quad (13)
\end{aligned}$$

The parameters $t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3$, the density-dependent stiffness α , the spin-orbit strength W_0 , the symmetry energy coefficient a_s , the nucleon effective mass m_∞^* , and the incompressibility modulus K_∞ are listed in Table 1. Five sets of Skyrme parameters, SkM, SkM* [35], Z [36], SKa [37], and SLy4 [38], are compared in the calculations. The selected forces self-consistently describe the ground-state binding energies, root-mean-square radii of finite nuclei around the magic numbers, and nuclear matter properties (symmetry energy, saturation density, etc.).

The nucleus-nucleus (NN) potential is important for describing nuclear dynamics, i.e., α decay, low-energy heavy-ion collisions, quasi-fission processes, fusion-evaporation reactions, etc. [39, 40]. The quasifission yields, fusion-fission products, fusion cross sections, fusion-evaporation excitation functions, isotopic distributions, and angular and kinetic energy spectra in deep-inelastic collisions or multinucleon transfer reactions are associated with the NN potential. Dynamical deformation, collective excitation, shape evolution, initial orientation, etc. are correlated with the nucleus-nucleus potential and influence fusion dynamics [41–43]. In low-en-

ergy nuclear collisions, the nucleon density profiles of the reaction system vary with time and lead to very complicated NN potentials and potential energy surfaces. Two typical approximations are usually used in reaction models, i.e., the sudden approximation and the adiabatic approach. In the calculations, the sudden approximation with frozen nuclear density is used for the potential energy surface and for estimating SHN production, i.e., in the DNS model. As a typical reaction type, the ^{48}Ca -induced fusion reactions on actinide nuclides were chosen because they were successfully used to synthesize SHNs with charge numbers $Z=112$ – 118 at Dubna. The Skyrme forces SKM, SKM*, SKa, Z, and SLy4, corresponding to different incompressibility moduli of nuclear matter at normal density, are selected in the calculation. Shown in Fig. 1 is a comparison of the NN potentials obtained with different Skyrme forces in the collisions of $^{48}\text{Ca}+^{243}\text{Am}$ and $^{48}\text{Ca}+^{248}\text{Cm}$, respectively. The difference among the NN potentials from the Skyrme forces is pronounced, which is mainly caused by the difference in the incompressibility modulus of nuclear matter. It is well known that the DNS is assumed to be formed at the bottom of the potential pocket. A broader and deeper potential pocket is favorable for compound nucleus formation against quasifission reactions.

The formation of superheavy nuclei in massive fusion reactions is complicated because of fusion hindrance and the involvement of a set of degrees of freedom, i.e., nucleon/cluster transfer, shape evolution, neck formation, relative-motion energy, and angular-momentum dissipation. In the DNS model, the density profiles of the colliding nuclei are assumed to be frozen, and the neck dynamics is not included. The nucleon/cluster transfer is coupled to the relative degrees of freedom through the master equations via the potential energy surface (PES). The PES is expressed as follows

$$U(R, \alpha_p, \alpha_T, J) = Q_{gg}(Z_1, N_1) + V(R, \alpha_p, \alpha_T, J) \quad (14)$$

with $Q_{gg}(Z_1, N_1) = B(Z_1, N_1) + B(Z_2, N_2) - B(Z_{com}, N_{com})$, $Z_1 = Z_{com} - Z_2$, and $N_1 = N_{com} - N_2$. Here, $B(Z_i, N_i)$ ($i = 1, 2$) and $B(Z_{com}, N_{com})$ are the ground-state binding energies of fragment (Z_i, N_i) and compound nucleus (Z_{com}, N_{com}), respectively. It is obvious that nuclear-structure effects, such as shell effects and pairing correlations, are included in the PES. Figure 2 shows the driving potential as a function of mass asymmetry ($\eta = (A_1 - A_2)/A_{CN}$) for the reactions $^{48}\text{Ca} + ^{243}\text{Am}$ and $^{48}\text{Ca} + ^{248}\text{Cm}$, respectively. The Businaro-Gallone (B.G.) point is marked at the maximum of the driving potential. It should be noted that the driving potential is defined as the minimum value for a fixed mass asymmetry. The differences in the driving potentials obtained with the Skyrme forces SKM, SKM*, SKa, Z, and SLy4 arise from the NN potential. The fu-

Table 1. The Skyrme parameters used in the calculations.

Parameter	SkM	SkM*	SLy4	SKa	Z
t_0 (MeV fm ³)	-2645	-2645	-2488.9	-1602.8	-1140.3
t_1 (MeV fm ⁵)	385	410	486.8	570.9	309.6
t_2 (MeV fm ⁵)	-120	-135	-546.4	-67.7	-122.2
t_3 (MeV fm ^{3+3\alpha})	15595	15595	13777	8000	11608
x_0	0.09	0.09	0.834	-0.02	0.798
x_1	0	0	-0.344	0	0
x_2	0	0	-1.0	0	0
x_3	0	0	1.354	-0.286	1.632
W_0 (MeV fm ⁵)	130	130	123	125	120
α	1/6	1/6	1/6	1/3	0.8
a_s (MeV)	30.8	30.1	32.0	33.0	26.9
m_∞^*/m	0.79	0.79	0.70	0.61	0.84
K_∞ (MeV)	217	217	230	261	330

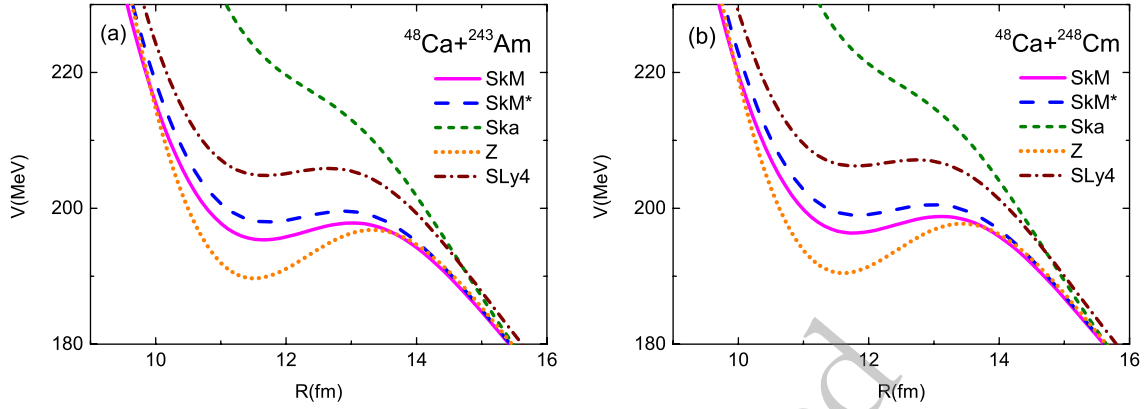


Fig. 1. (color online) Comparison of the NN potentials calculated using the Skyrme forces SKM, SKM*, SKa, Z, and SLy4 for the reactions $^{48}\text{Ca}+^{243}\text{Am}$ (left panel) and $^{48}\text{Ca}+^{248}\text{Cm}$ (right panel), respectively.

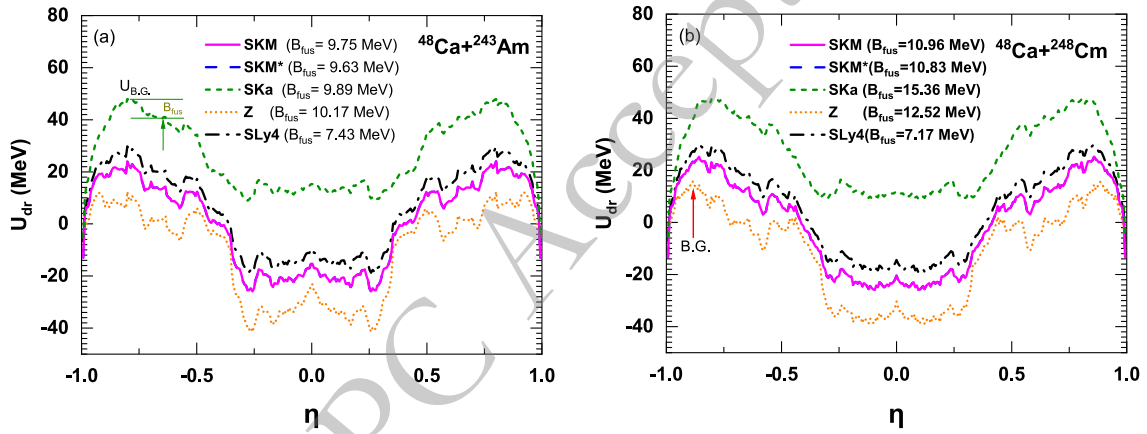


Fig. 2. (color online) The driving potential as a function of mass asymmetry for the reactions (a) $^{48}\text{Ca} + ^{243}\text{Am}$ and (b) $^{48}\text{Ca} + ^{248}\text{Cm}$.

sion probability is related to the inner fusion barrier, which is defined as the difference between the driving potential at the B.G. point and that at the incident projectile-target mass asymmetry, according to the relation $B_{fus} = U_{dr}(\eta_{B.G.}) - U_{dr}(\eta_i)$. A lower inner fusion barrier is favorable for compound-nucleus formation, e.g., 7.43 MeV for the reaction $^{48}\text{Ca} + ^{243}\text{Am}$ and 7.17 MeV for $^{48}\text{Ca} + ^{248}\text{Cm}$. The inner fusion barrier is a crucial quantity for evaluating fusion hindrance in massive fusion reactions.

Shown in Fig. 3 are the transmission probabilities and capture excitation functions for the reactions $^{48}\text{Ca} + ^{243}\text{Am}$, $^{48}\text{Ca} + ^{248}\text{Cm}$, $^{51}\text{V} + ^{243}\text{Am}$, and $^{54}\text{Cr} + ^{243}\text{Am}$ with the parameter SKM, respectively. It is evident that the Dubna data for the reaction $^{48}\text{Ca} + ^{248}\text{Cm}$ are well reproduced by the Skyrme energy-density-functional approach [44]. The magnitudes of the cross sections are comparable for the systems $^{48}\text{Ca} + ^{243}\text{Am}$, $^{48}\text{Ca} + ^{248}\text{Cm}$, and $^{51}\text{V} + ^{243}\text{Am}$. The enhancement of the capture cross section in the sub-barrier region for the reaction $^{54}\text{Cr} + ^{243}\text{Am}$ is caused by the larger negative Q-value, which is favorable for increasing the evaporation-residue cross section in the 2n channel. However, for the reaction $^{48}\text{Ca} + ^{248}\text{Cm}$, the capture cross sections at excitation energies of

20–30 MeV are overestimated by one order of magnitude compared with the Dubna data. This discrepancy is caused by the width of the Gaussian-like barrier distribution in Eq. (2). A smaller barrier width leads to a reduction in the transmission probability at sub-barrier energies. For example, an asymmetric barrier distribution is favorable for reproducing the experimental data [25].

The fusion probability P_{CN} is described within the DNS model by taking into account the competition with quasi-fission and fission of the heavy fragment [27]. In this model, nucleon transfer is described by solving a set of microscopically derived master equations while distinguishing the isospin effect as follows

$$\begin{aligned} \frac{dP(Z_1, N_1, E_1, t)}{dt} = & \sum_{Z'_1} W_{Z_1, N_1; Z'_1, N'_1}(t) [d_{Z_1, N_1} P(Z'_1, N_1, E'_1, t) \\ & - d_{Z'_1, N'_1} P(Z_1, N_1, E_1, t)] \\ & + \sum_{N'_1} W_{Z_1, N_1; Z_1, N'_1}(t) [d_{Z_1, N_1} P(Z_1, N'_1, E'_1, t) \\ & - d_{Z_1, N'_1} P(Z_1, N_1, E_1, t)]. \end{aligned} \quad (15)$$

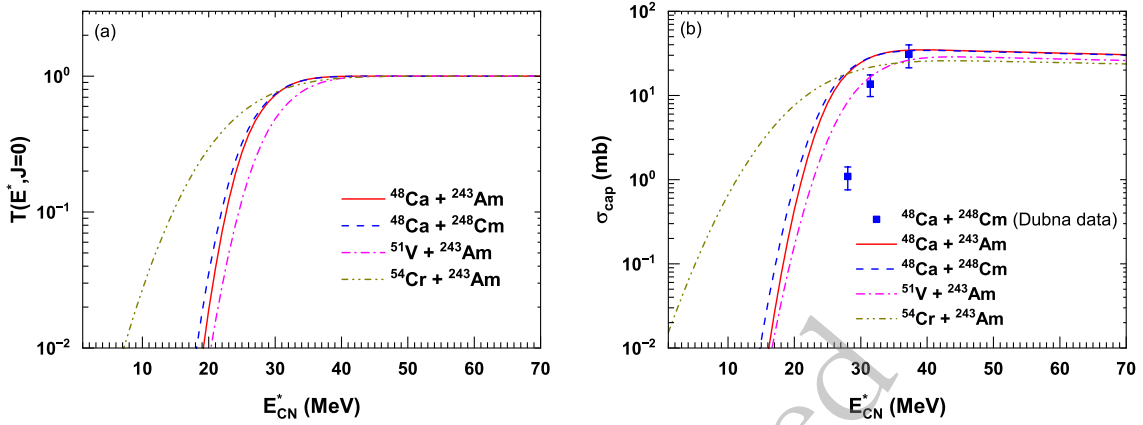


Fig. 3. (color online) (a) The transmission probabilities at angular momentum $J = 0$ and (b) the capture cross sections as functions of the excitation energy of the compound nucleus for the reactions $^{48}\text{Ca} + ^{243}\text{Am}$, $^{48}\text{Ca} + ^{248}\text{Cm}$, $^{51}\text{V} + ^{243}\text{Am}$, and $^{54}\text{Cr} + ^{243}\text{Am}$, respectively. The available data for $^{48}\text{Ca} + ^{248}\text{Cm}$ are taken from Dubna [44].

Here, $W_{Z_1, N_1; Z'_1, N'_1}(W_{Z_1, N_1; Z_1, N'_1})$ denotes the mean transition probability from the channel (Z_1, N_1, E_1) to (Z'_1, N'_1, E'_1) [or from (Z_1, N_1, E_1) to (Z_1, N'_1, E'_1)], and d_{Z_1, N_1} denotes the microscopic dimension corresponding to the macroscopic state (Z_1, N_1, E_1) . The sum is taken over all possible proton and neutron numbers that the fragment Z'_1, N'_1 may assume. However, only one-nucleon transfer is considered in the model, with the relations $Z'_1 = Z_1 \pm 1$ and $N'_1 = N_1 \pm 1$. The excitation energy E_1 is determined by the dissipation energy from the relative motion and the potential energy surface of the DNS.

The compound nucleus is formed by overcoming the inner fusion barrier. The fusion probability is estimated by integrating the distribution probability $P(Z_1, N_1, E_1, t)$ to the B.G. point. The formation probability of the compound nucleus at the barrier B and angular momentum J is given by

$$P_{CN}(E_{c.m.}, J) = \sum_{Z=1}^{Z_{B.G.}} \sum_{N=1}^{N_{B.G.}} P(Z_1, N_1, E_1, \tau_{int}) \quad (16)$$

Here, the interaction time τ_{int} is obtained using the deflection-function method [25]. The fusion cross section is calculated as

$$\sigma_{fus}(E_{c.m.}) = \frac{\pi \hbar^2}{2\mu E_{c.m.}} \sum_{J=0}^{J_{max}} (2J+1) T(E_{c.m.}, J) \times P_{CN}(E_{c.m.}, J). \quad (17)$$

The compound nucleus formed in fusion reactions is excited and cools by evaporating γ -rays and light particles (neutrons, protons, α particles, etc.), in competition with fission. The survival probability of the excited nucleus in the channel involving evaporation of the x -th neutron, the y -th proton, and the z -th alpha particle is expressed as [45]

$$W_{sur}(E_{CN}^*, x, y, z, J) = P(E_{CN}^*, x, y, z, J) \times \prod_{i=1}^x \frac{\Gamma_n(E_i^*, J)}{\Gamma_{tot}(E_i^*, J)} \prod_{j=1}^y \frac{\Gamma_p(E_j^*, J)}{\Gamma_{tot}(E_j^*, J)} \times \prod_{k=1}^z \frac{\Gamma_\alpha(E_k^*, J)}{\Gamma_{tot}(E_k^*, J)}. \quad (18)$$

Here, E_{CN}^* and J are the excitation energy, evaluated from the mass table in Ref. [46], and the spin of the excited nucleus, respectively. The total width Γ_{tot} is the sum of the partial widths for particle evaporation, γ emission, and fission. The excitation energy E_s^* before the evaporation of the s -th particle is evaluated by

$$E_{s+1}^* = E_s^* - B_i^n - B_j^p - B_k^\alpha - 2T_s \quad (19)$$

with the initial condition $E_1^* = E_{CN}^*$ and $s = i + j + k$. Here, B_i^n , B_j^p , and B_k^α denote the separation energies of the i -th neutron, j -th proton, and k -th alpha particle, respectively. The nuclear temperature T_i is given by $E_i^* = aT_i^2 - T_i$, where a is the level density parameter. The excitation energy of the compound nucleus is estimated as $E_{CN}^* = E_{c.m.} + Q_{PT}$, where $E_{c.m.}$ is the incident energy in the center-of-mass system and the reaction Q -value is given by $Q_{PT} = \Delta M_P + \Delta M_T - \Delta M_C$, with the mass excesses M_P , M_T , and M_C corresponding to the projectile, target, and compound nuclei, respectively.

Assuming that electric dipole radiation dominates the γ -emission, the decay width is calculated by

$$\Gamma_\gamma(E_{CN}^*, J) = \frac{3}{\rho(E^*, J)} \int_{\varepsilon=0}^{E^* - \delta - \frac{1}{a}} \rho(E^* - E_{rot} - \varepsilon, J) f_{E_1}(\varepsilon) d\varepsilon, \quad (20)$$

and

$$f_{E_1}(\varepsilon) = \frac{4}{3\pi} \frac{1+\kappa}{mc^2} \frac{e^2}{\hbar c} \frac{NZ}{A} \frac{\Gamma_G \varepsilon^4}{(\Gamma_G \varepsilon)^2 + (\Gamma_G^2 - \varepsilon^2)^2}. \quad (21)$$

Here, $\kappa = 0.75$, and Γ_G and E_G denote the width and position of the electric dipole resonance, respectively. For a heavy nucleus, $\Gamma_G = 5$ MeV [47],

$$E_G = \frac{167.23}{A^{1/3} \sqrt{1.959 + 14.074A^{-1/3}}} \text{MeV}. \quad (22)$$

The particle decay widths are evaluated using Weisskopf evaporation theory [48].

$$\Gamma_\nu(E^*, J) = (2s_\nu + 1) \frac{m_\nu}{\pi^2 \hbar^2 \rho(E^*, J)} \int_0^{E^* - B_\nu - \delta - \varepsilon_n - \frac{1}{a}} \varepsilon \rho(E^* - B_\nu - \delta_n - E_{rot} - \varepsilon, J) \sigma_{inv}(\varepsilon) d\varepsilon. \quad (23)$$

Here, s_ν , m_ν , and B_ν are the spin, mass, and binding energy of the evaporated particle, respectively. The pairing correction energy δ is set to $12/\sqrt{A}$, 0, and $-12/\sqrt{A}$ MeV for even-even, even-odd, and odd-odd nuclei, respectively. The inverse cross section is given by $\sigma_{inv} = \pi R_\nu^2 T(\nu)$. The penetration probability is taken to be unity for neutrons, whereas for charged particles, $T(\nu) = (1 + \exp(\pi(V_c(\nu) - \varepsilon)/\hbar\omega))^{-1}$, with $\hbar\omega = 5$ and 8 MeV for protons and alpha particles, respectively. The fission width is calculated using the Bohr-Wheeler formula in a manner similar to that in Ref. [25]. The energy spectra of neutrons and charged particles in fusion-evaporation reactions are well described by the evaporation approach [49].

The level density is calculated using the Fermi-gas model as [50],

$$\rho(E^*, J) = K_{coll} \cdot \frac{2J+1}{24 \sqrt{2} \sigma^3 a^{1/4} (E^* - \delta)^{5/4}} \times \exp \left[2 \sqrt{a(E^* - \delta)} - \frac{(J+1/2)^2}{2\sigma^2} \right], \quad (24)$$

with $\sigma^2 = 6\bar{m}^2 \sqrt{a(E^* - \delta)}/\pi^2$ and $\bar{m} \approx 0.24A^{2/3}$. Here, K_{coll} is the collective enhancement factor, which includes rotational and vibrational effects [51]. The level density parameter is related to the shell correction energy $E_{sh}(Z, N)$ and the excitation energy E^* of the nucleus as

$$a(E^*, Z, N) = \tilde{a}(A)[1 + E_{sh}(Z, N)f(E^* - \Delta)/(E^* - \Delta)]. \quad (25)$$

Here, $\tilde{a}(A) = \alpha A + \beta A^{2/3} b_s$ denotes the asymptotic Fermi-gas value of the level-density parameter at high ex-

citation energy. The shell-damping factor is given by

$$f(E^*) = 1 - \exp(-\gamma E^*) \quad (26)$$

with $\gamma = \tilde{a}/(\epsilon A^{4/3})$ MeV $^{-1}$. The parameters α , β , b_s , and ϵ are taken to be 0.114, 0.098, 1., and 0.4, respectively [27]. The shell-correction energy is taken from the mass table of the finite-range droplet model (FRDM2012) [52].

For single-particle evaporation, the realization probability is given by

$$P(E_{CN}^*, J) = \exp \left(-\frac{(E_{CN}^* - B_s - 2T)^2}{2\sigma^2} \right). \quad (27)$$

The width σ is chosen to reproduce the experimental width of fusion-evaporation excitation functions. The realization probability $P(E_{CN}^*, x, y, z, J)$ for the evaporation of x neutrons, y protons, and z alpha particles at the excitation energy E_{CN}^* and angular momentum J is calculated using the Jackson formula [53] as

$$P(E_{CN}^*, s, J) = I(\Delta_s, 2s-3) - I(\Delta_{s+1}, 2s-1), \quad (28)$$

where the quantities I and Δ are given as follows:

$$I(z, m) = \frac{1}{m!} \int_0^z u^m e^{-u} du, \quad (29)$$

$$\Delta_s = \frac{E_{CN}^* - \sum_{i=1}^s B_i^\nu}{T_i}. \quad (30)$$

The B_i^ν is the separation energy for the evaporation of the i -th particle, and $s(x, y, z) = x + y + z$. The spectrum of realization probabilities determines the structure of the survival probability in each evaporation channel. The separation energies of neutrons and charged particles are calculated from the FRDM2012 mass table. It has been noted that the Skyrme EDF method has been used to calculate the nuclear masses of SHN with high accuracy in comparison with the AME2020 mass table [54, 55]. The survival probability of excited SHN is influenced by the particle separation energy and the fission barrier. A self-consistent description of fusion and survival probabilities in the formation of SHN based on the Skyrme EDF is expected to be improved in the future, including the mass table and fission barrier. More precise calculations of the nuclear mass table and fission barrier using the Skyrme EDF method may be feasible with artificial intelligence (AI) technology.

III. RESULTS AND DISCUSSION

The nucleus–nucleus potential is significant in low-energy heavy-ion collisions, including fusion cross sections, quasifission dynamics, fusion–fission reactions, and fusion–evaporation processes for synthesizing heavy or superheavy nuclei. A repulsive core with an incompressibility modulus of $K = 228$ MeV was introduced into the Michigan-3-Yukawa-Reid effective potential to describe the fusion cross sections at energies far below the Coulomb barrier in the reaction of $^{64}\text{Ni} + ^{64}\text{Ni}$ [56]. The energy-density functional method provides a bridge between the nucleon–nucleon effective force and the nuclear matter equation of state, i.e., the Skyrme effective interaction, relativistic invariant theory based on the meson-exchange concept, chiral effective theory, etc. The effective Skyrme force is expected to provide a unified description of nuclear ground-state properties, nuclear reactions, and nuclear matter. The potential energy surface influences nuclear dynamics in fusion–evaporation and fusion–fission reactions. Consequently, the fusion cross sections are correlated with the incompressibility modulus and the effective nucleon–nucleon interaction.

Shown in Fig. 4 are the fusion–evaporation residue excitation functions for the reaction of $^{48}\text{Ca} + ^{243}\text{Am}$ producing moscovium, calculated with the Skyrme parameters SKM, SKM*, Ska, Z, and SLy4, together with the available data from Dubna [57–63]. It is obvious from the ex-

perimental measurements that the maximum cross section of 20 pb is observed at an excitation energy of 35 MeV in the 3n evaporation channel. The production cross sections of SHNs with different Skyrme forces are related to the equation of state at densities in the overlap region and to nuclear matter properties. Overall, the fusion–evaporation excitation functions obtained with the parameter SLy4 ($K = 230$ MeV) are consistent with the available data. The uncertainties associated with the Skyrme forces in the SHN production cross sections are collected and compared in Fig. 4 (f). It is demonstrated that the maximum cross sections in the 2n–5n evaporation channels are similar for different Skyrme forces.

The fusion–evaporation residue excitation functions with the Skyrme parameters SKM, SKM*, Ska, Z, and SLy4 for the reaction of $^{48}\text{Ca} + ^{248}\text{Cm}$ are calculated and compared with the available data from Dubna [64–68], GSI [69], and RIKEN [70], as shown in Fig. 5. It is obvious that the maximum cross section in the 4n channel is 5 pb at $E_{CN}^* = 40$ MeV. The uncertainties in the production cross sections are large for different Skyrme forces owing to the different equations of state in the overlap density region, in comparison with the reaction of $^{48}\text{Ca} + ^{243}\text{Am}$. The lower cross section for producing livermorium than for producing moscovium is mainly caused by the reduction of the fission barrier of the compound nucleus, which manifests the dominance of the shell ef-

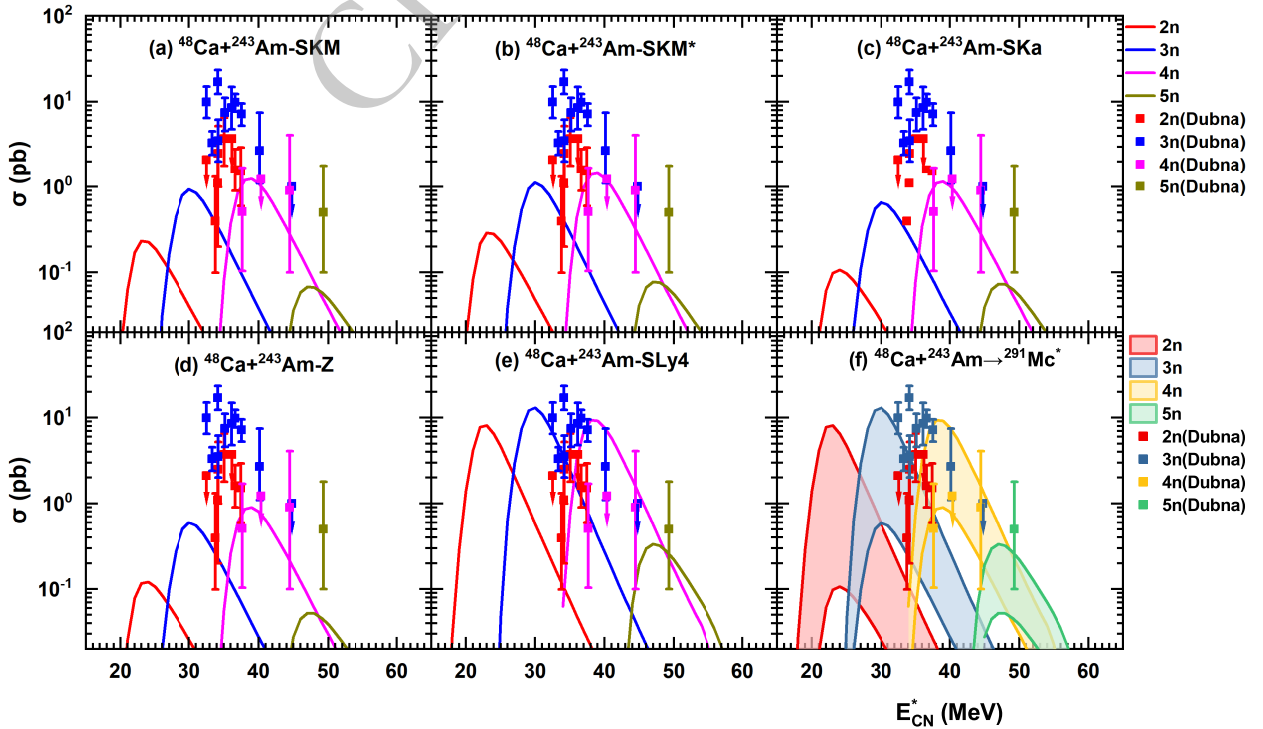


Fig. 4. (color online) Comparison of the fusion–evaporation residue excitation functions for the $^{48}\text{Ca} + ^{243}\text{Am}$ reaction leading to the production of moscovium, calculated using the Skyrme parameter sets SKM, SKM*, Ska, Z, and SLy4, with the available data from Dubna [57–63].

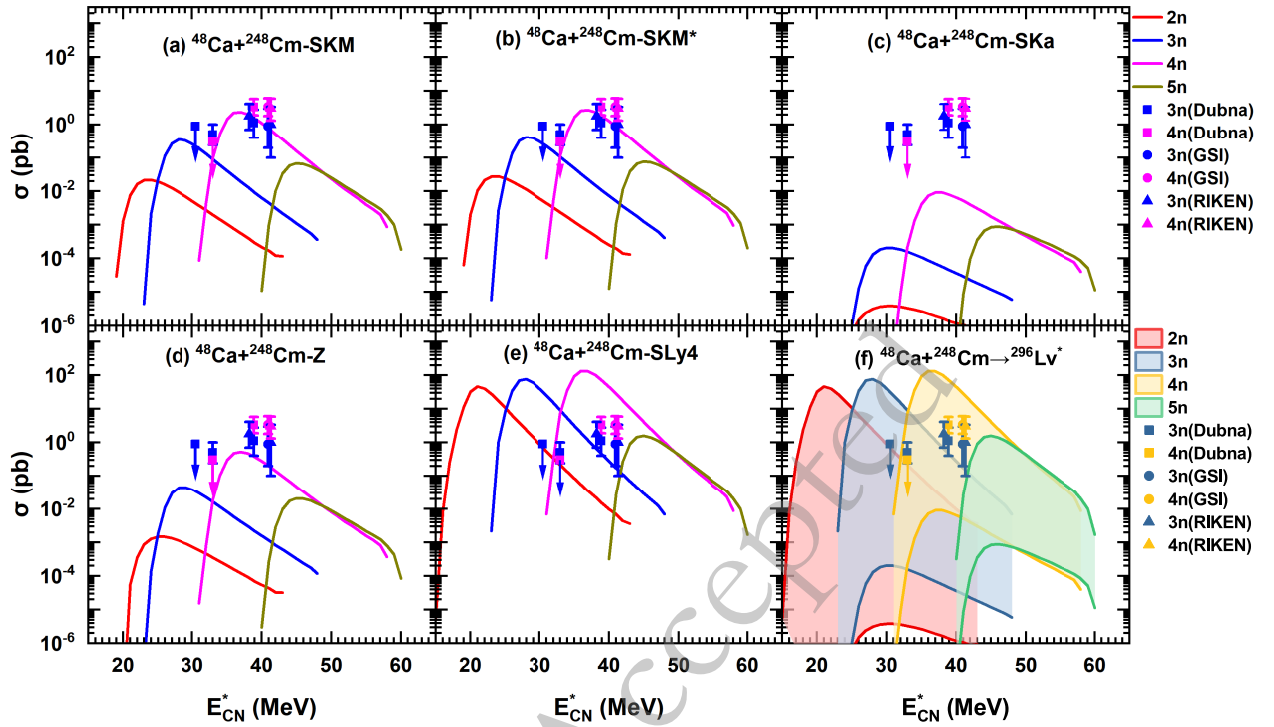


Fig. 5. (color online) The fusion-evaporation residue excitation functions calculated with the Skyrme parameters SKM, SKM*, Ska, Z, and SLy4 for the $^{48}\text{Ca}+^{248}\text{Cm}$ reaction leading to the production of livermorium are compared with the available data from Refs. [64–68], the GSI data from Ref. [69], and the RIKEN data from Ref. [70].

fect in the formation of SHN. The ER cross section in the 2n channel with SLy4 is higher than those with the other Skyrme forces because of the larger fusion probability (lower inner fusion barrier).

Recently, new superheavy elements beyond oganesson have attracted attention in both experimental and theoretical studies. The ^{48}Ca -induced reactions face some obstacles owing to the handling of target materials. Combinations of ^{50}Ti , ^{51}V , and ^{54}Cr projectiles with actinide nuclei possibly pave the way for synthesizing the new elements 119 and 120. Experimental attempts to produce these new elements are being carried out at IMP, Dubna, RIKEN, and Berkeley. In comparison with the ^{48}Ca -induced reactions, the production cross sections of SHN are usually reduced in the ^{50}Ti -, ^{51}V -, and ^{54}Cr -induced reactions because of the higher inner fusion barrier and smaller Q-value.

Shown in Fig. 6 are the fusion-evaporation residue excitation functions for the reaction $^{50}\text{Ti}+^{238}\text{U}$. It is obvious that the 5n channel has a cross section below 0.01 pb, and the distribution structure differs among the Skyrme parameters SKM, SKM*, Ska, Z, and SLy4. Roughly, the 2n-4n channels, with maximal cross sections of 0.1-1 pb, are obtained with the Skyrme forces SKM, SKM*, Ska, and Z. However, the parameter SLy4 predicts larger cross sections for flerovium production. The differences among the Skyrme forces in calculating the fusion-evaporation excitation functions are mainly caused by the

NN potential and the potential pocket (width and height). A narrower potential pocket leads to a lower fusion probability and results in reduced SHN cross sections.

The attempt using a ^{50}Ti beam on ^{244}Pu was performed at Berkeley [71]. A comparison between the calculated results and the experimental data is shown in Fig. 7. Basically, the 4n channel is available for producing livermorium and is consistent with the data for the Skyrme forces SKM, SKM*, and Z. The parameter Ska predicts unexpectedly very low cross sections. The uncertainties in the SHN production cross sections are huge, with a magnitude of 2-5 orders, particularly at decreasing excitation energy. Besides the capture probability and PES, the neutron separation energy, level density, fission barrier, etc. can also be calculated by the energy-density functional method. The most credible predictions are obtained with the Skyrme parameters SKM (SKM*), e.g., 0.44 pb (2n), 0.36 pb (3n), 0.51 pb (4n), and 6.5 fb (5n) at excitation energies of 24 MeV, 31 MeV, 40 MeV, and 49 MeV for the reaction $^{50}\text{Ti}+^{238}\text{U}$, and 0.86 pb (2n), 0.50 pb (3n), 1.37 pb (4n), and 0.047 pb (5n) at excitation energies of 24 MeV, 32 MeV, 42 MeV, and 50 MeV for the reaction $^{50}\text{Ti}+^{244}\text{Pu}$.

The ^{51}V -induced reactions have attracted considerable attention for the synthesis of new SHN beyond ^{48}Ca . A more mass-asymmetric system is available for enhancing the fusion probability. As a test of the new reaction mechanism, the $^{51}\text{V}+^{243}\text{Am}$ system is feasible for produ-

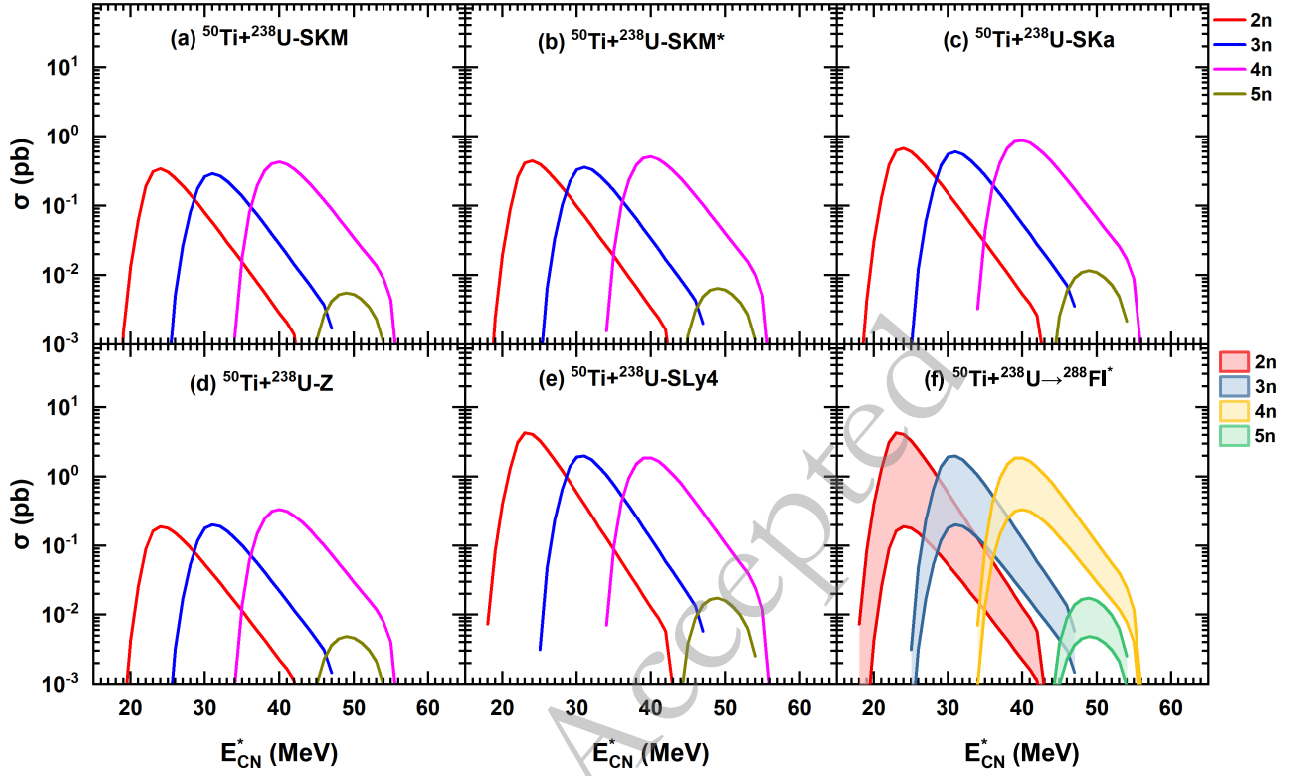


Fig. 6. (color online) The fusion–evaporation residue excitation functions were calculated using the DNS model with the Skyrme parameter sets SKM, SKM*, SKa, Z, and SLy4 for the $^{50}\text{Ti}+^{238}\text{U}$ reaction.

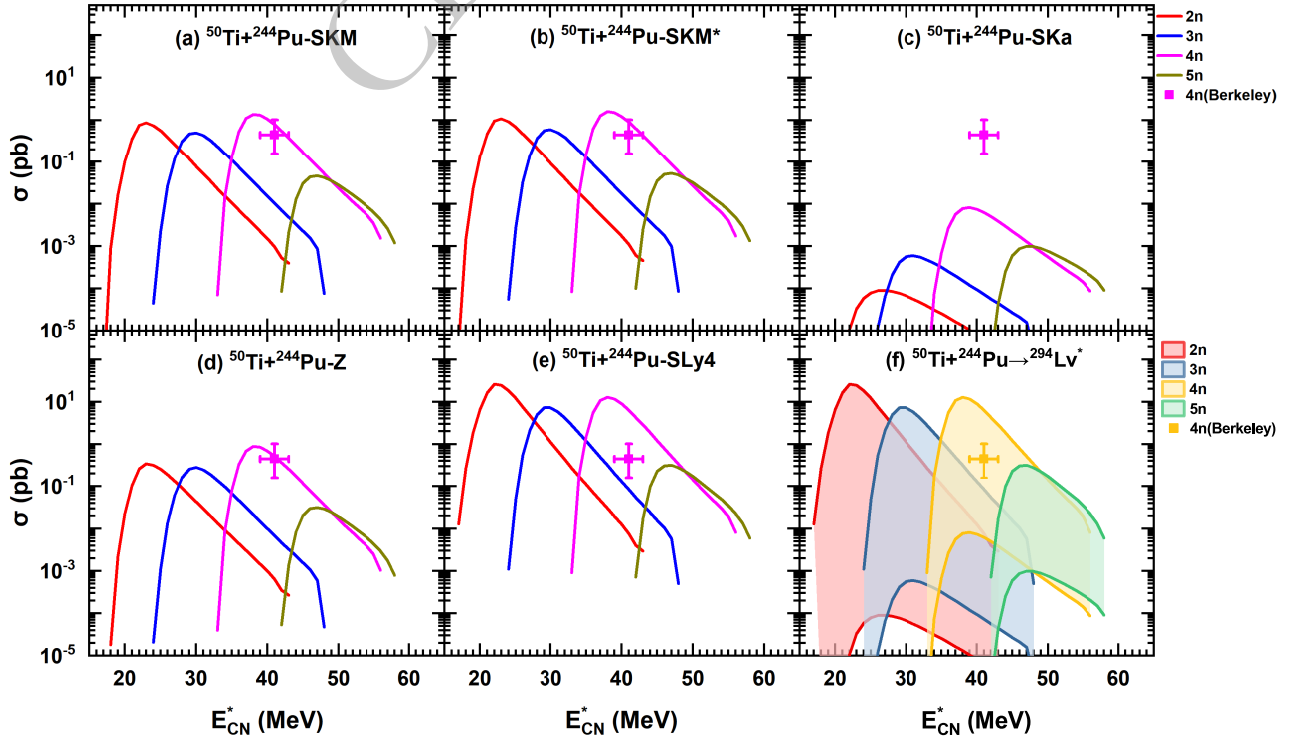


Fig. 7. (color online) Production of the SHN livermorium using the Skyrme energy density functional with SkM, SkM*, Ska, Z, and SLy4 in the $^{50}\text{Ti}+^{244}\text{Pu}$ reaction, compared with recent experimental data from Berkeley [71].

cing oganesson in experiments. The fusion-evaporation excitation functions calculated with the Skyrme parameters SKM, SKM*, SKa, Z, and SLy4 are compared, as shown in Fig. 8. The cross sections in the 2–4n channels may be measurable in experiments.

The ^{51}V -induced reactions are of particular interest in experiments at RIKEN, i.e., $^{51}\text{V} + ^{248}\text{Cm}$ for synthesizing the new element 119. However, for the synthesis of element 119, a production cross section below 1 fb is found with the Skyrme forces SKM, SKM*, SKa, and Z, as shown in Fig. 9. Such a very low cross section still poses difficulties for the synthesis of element 119 in laboratories. It is noticed that unexpectedly larger cross sections in the 2n channel exist in the ^{50}Ti -, ^{51}V -, and ^{54}Cr -induced reactions, although the excitation energies are below the Coulomb barrier. The optimal evaporation channel for synthesizing SHNs is related to the energy dependence of the capture, fusion, and survival probabilities. The rapid increase in the capture and fusion probabilities enhances the 2n channel. The overestimation of the fusion probability in the low-excitation-energy domain increases the 2n cross section. Multi-dimensional diffusion in the formation of SHN is expected to solve this problem, e.g., through neck evolution and cluster transfer.

In recent years, high-intensity ^{54}Cr beams have become available at accelerators worldwide, i.e., the SHE factory in Dubna, the SHE special accelerator (CAFe), and the gas-filled recoil separator spectrometer

(SHANS2). Figure 10 shows the fusion-evaporation excitation functions calculated by the DNS model with the Skyrme energy density functional using SKM, SKM*, SKa, Z, and SLy4 for the reaction $^{54}\text{Cr} + ^{238}\text{U}$, together with the Dubna data [72]. The production cross section of ^{288}Lv in the 4n channel is well reproduced with the Skyrme forces SKM, SKM* and Z. The 4n channel at an excitation energy of 41 MeV is the optimal route for synthesizing SHN, and the excitation energy is higher than that of 38 MeV in the reaction of $^{48}\text{Ca} + ^{248}\text{Cm}$ for producing livermorium. The larger binding energy of the doubly magic nucleus increases the Q-value and favors SHN formation through the survival probability. Accurate estimation of the fusion-evaporation excitation function induced by ^{54}Cr on actinide nuclei is helpful for synthesizing new elements in laboratories.

We calculated the oganesson production in the $^{54}\text{Cr} + ^{244}\text{Pu}$ reaction, as shown in Fig. 11. The 2–4n evaporation channels dominate SHN formation, with cross sections in the range of $1\text{--}10^{-5}$ pb. Measurements of this system are expected to test the prediction and extend the synthesis of new SHN with ^{54}Cr beams. The synthesis of new elements has attracted much experimental attention, e.g., $^{58}\text{Fe} + ^{244}\text{Pu}$ [73], $^{64}\text{Ni} + ^{238}\text{U}$, $^{54}\text{Cr} + ^{248}\text{Cm}$ and $^{50}\text{Ti} + ^{249}\text{Cf}$ [74]. The fusion-evaporation excitation functions for synthesizing the new SHEs with $Z=119$ and $Z=120$ in the reactions of $^{54}\text{Cr} + ^{243}\text{Am}$ and $^{54}\text{Cr} + ^{248}\text{Cm}$ are calculated, as shown in Fig. 12 and Fig. 13, respectively.

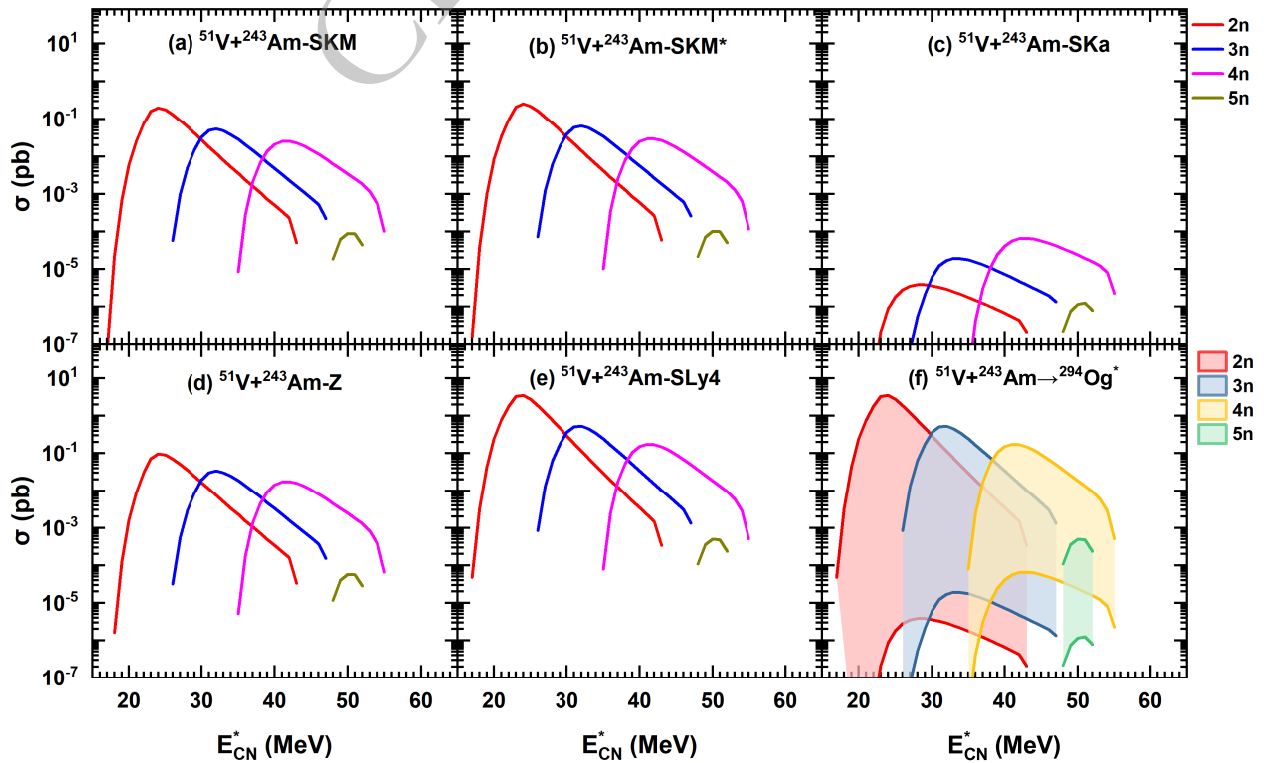


Fig. 8. (color online) Same as shown in Fig. 6, but for the reaction $^{51}\text{V} + ^{243}\text{Am}$.

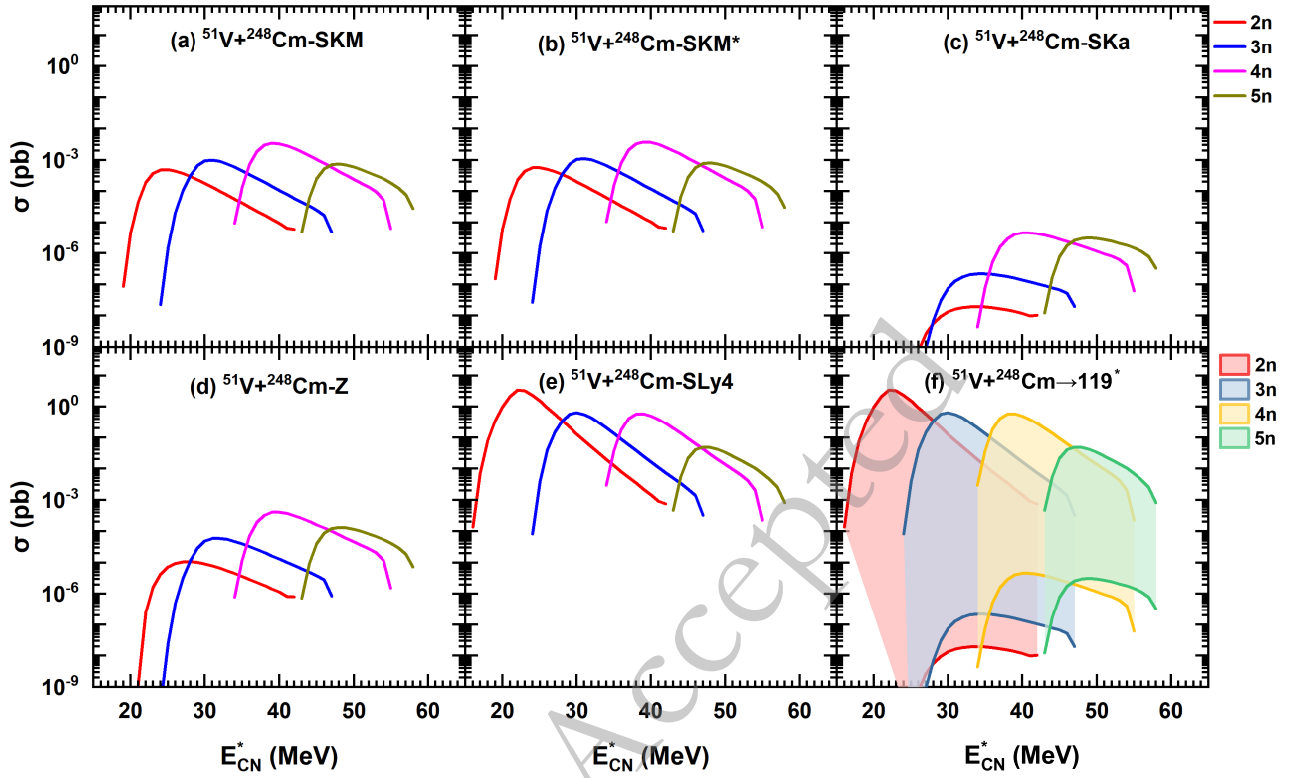


Fig. 9. (color online) The fusion-evaporation excitation functions for the reaction $^{51}\text{V}+^{248}\text{Cm}$, calculated using the Skyrme parameter sets SKM, SKM*, SKa, Z, and SLy4, for the production of the superheavy element with $Z=119$.

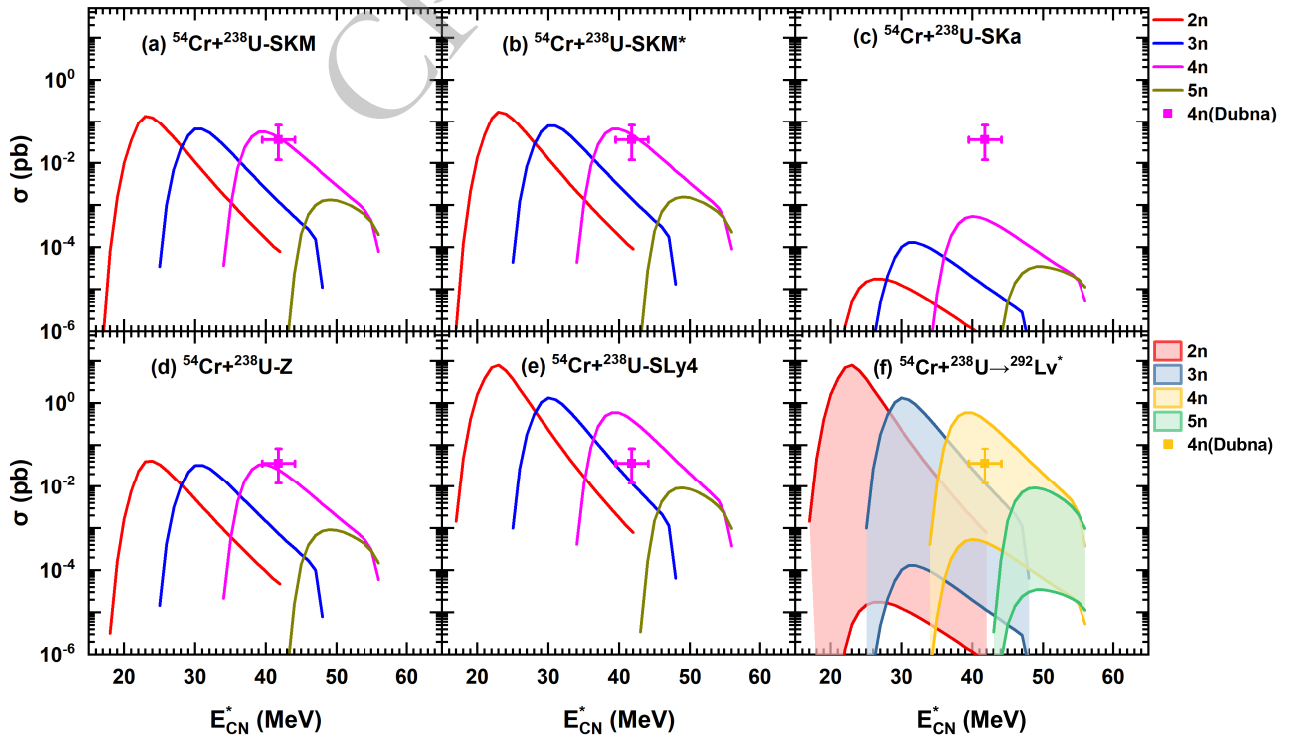


Fig. 10. (color online) Production of the superheavy nucleus livermorium, calculated using the DNS model with the Skyrme energy density functional parameterizations SKM, SKM*, SKa, Z, and SLy4 for the reaction $^{54}\text{Cr}+^{238}\text{U}$, is compared with recent experimental data from Dubna [72].

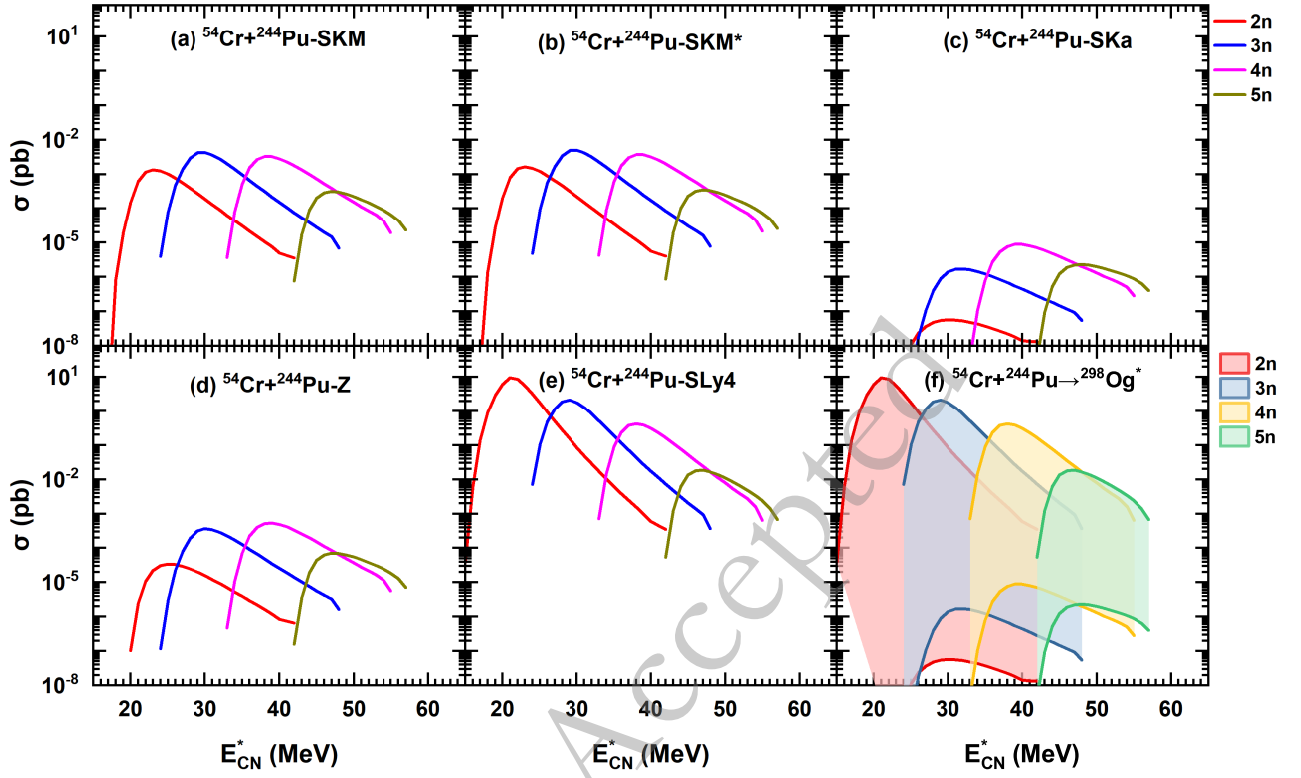


Fig. 11. (color online) Same as shown in Fig. 6, but for the reaction $^{54}\text{Cr}+^{244}\text{Pu}$.

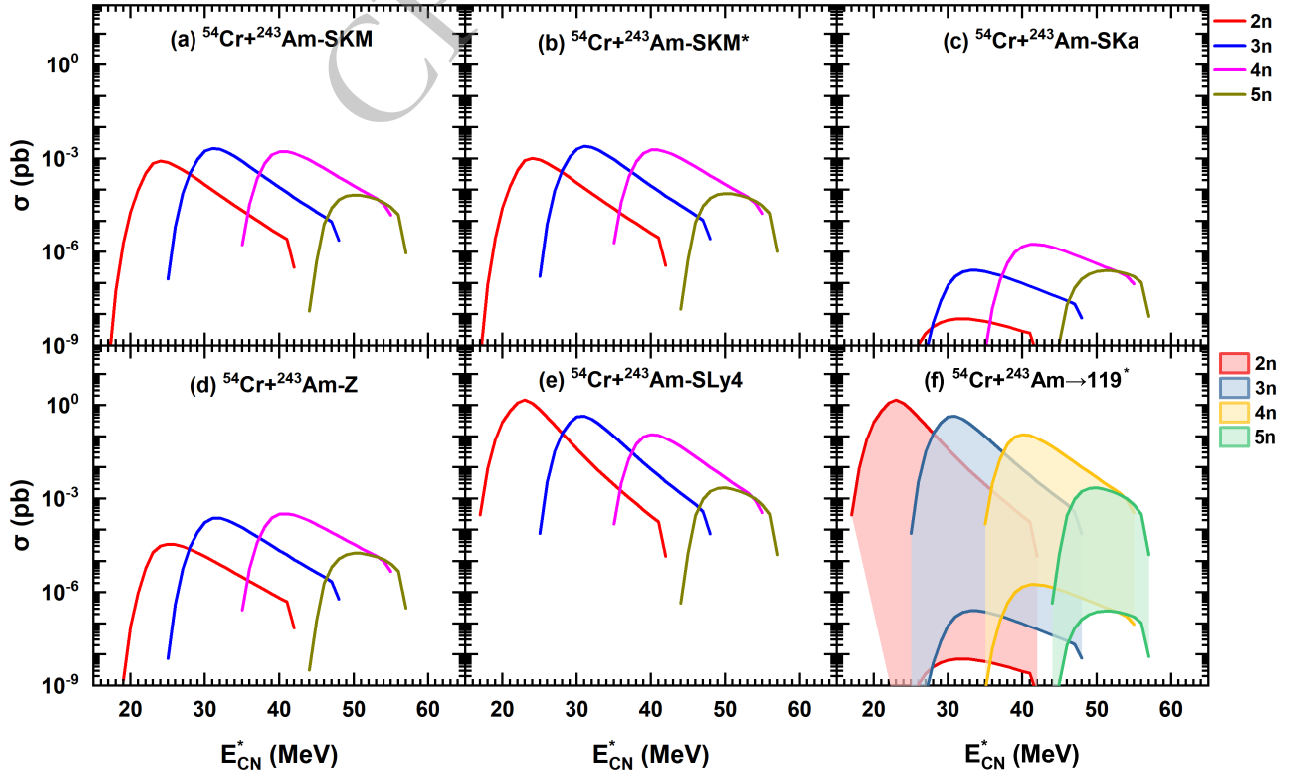


Fig. 12. (color online) The fusion-evaporation excitation functions for synthesizing a new SHE with $Z=119$ in the reaction $^{54}\text{Cr}+^{243}\text{Am}$.

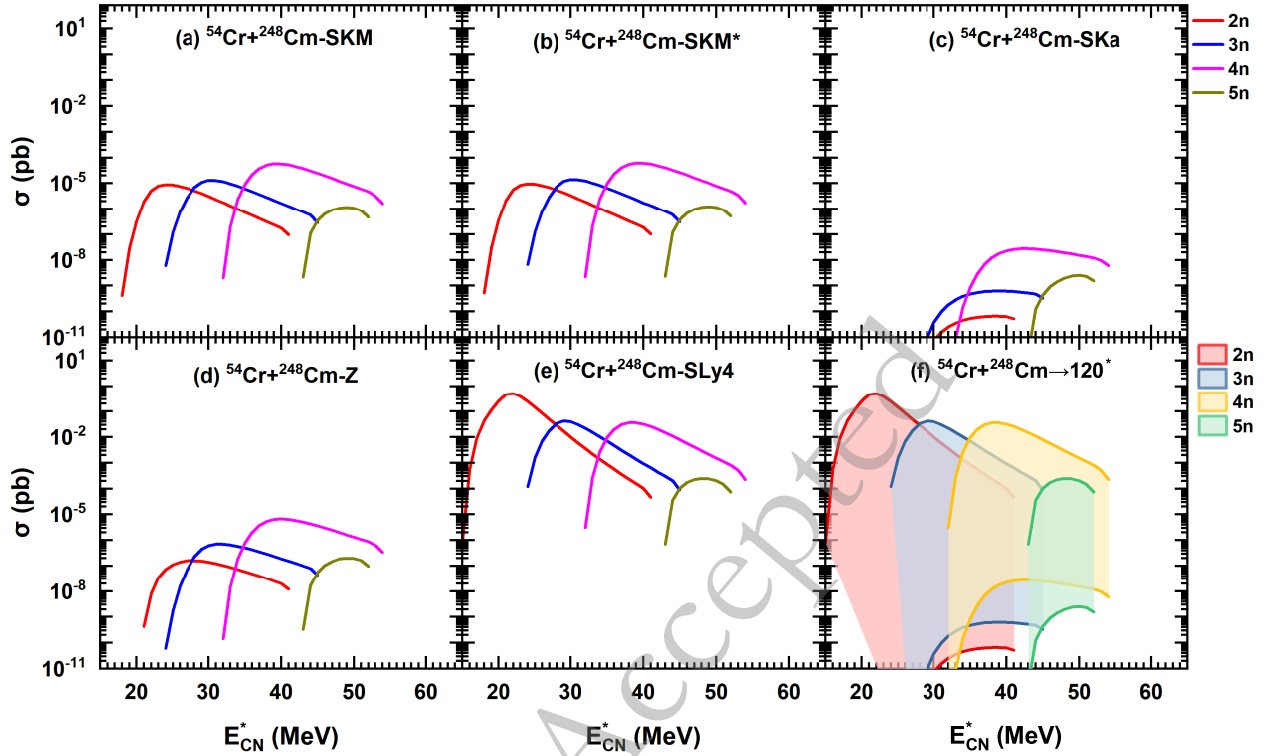


Fig. 13. (color online) Same as shown in Fig. 12, but for the production of the new SHE with $Z = 120$ in the reaction $^{54}\text{Cr}+^{248}\text{Cm}$.

It is evident that the production cross sections of 119 and 120 are below 1 fb for the Skyrme forces SKM, SKM*, SKa, and Z, except for SLy4. With the SKM parameter set, the predicted cross sections are 0.83 fb (2n), 2.1 fb (3n), 1.7 fb (4n), and 0.07 fb (5n) at excitation energies of 24 MeV, 31 MeV, 41 MeV, and 50 MeV, respectively, for the reaction $^{54}\text{Cr}+^{243}\text{Am}$. The fission barrier is strongly correlated with the survival probability of SHN and, consequently, with the production cross section. The depth and width of the potential pocket of the NN potential are correlated with the nuclear matter properties of the equation of state and the diffuseness of the proton and neutron density profiles. It has also been shown that the mass tables of nuclides influence the PES and separation energies and, consequently, SHN production [75].

IV. CONCLUSIONS

In summary, the nucleus-nucleus potential is calculated using the Skyrme energy density functional, which is correlated with the different properties of isospin-symmetric nuclear matter for the Skyrme forces SKM, SKM*, SKa, Z, and SLy4. The NN potential and PES in the DNS model are calculated with these Skyrme forces. The fusion-evaporation excitation functions for the ^{48}Ca -, ^{50}Ti -, ^{51}V -, and ^{54}Cr -induced reactions on actinide nuclei are systematically investigated for the production of SHN within the DNS model. It is demonstrated that the discrepancy in SHN production cross sections among the

different Skyrme forces is correlated with the nuclear matter properties and the inner fusion barriers in the PES. The available data from Dubna, GSI, and RIKEN for the fusion-evaporation residue excitation functions in the reactions $^{48}\text{Ca}+^{243}\text{Am}$ and $^{48}\text{Ca}+^{248}\text{Cm}$ have been well reproduced by the DNS model with the parameters SKM, SKM*, and Z. The larger cross section obtained with SLy4 arises from the lower inner fusion barrier. The predicted cross sections for the synthesis of new SHEs with $Z=119$ and 120 differ among the Skyrme forces, e.g., 10^{-8} -1 pb (2n), 5×10^{-7} -0.4 pb (3n), 2×10^{-6} -0.1 pb (4n), and 2×10^{-7} - 3×10^{-3} pb (5n) for $^{54}\text{Cr}+^{243}\text{Am}$, and 10^{-10} -0.8 pb (2n), 10^{-9} - 3×10^{-2} pb (3n), 2×10^{-8} - 3×10^{-2} pb (4n), and 2×10^{-9} - 2×10^{-4} pb (5n) for $^{54}\text{Cr}+^{248}\text{Cm}$, respectively. The credible cross sections with the SKM parameter are 0.83 fb (2n), 2.1 fb (3n), 1.7 fb (4n), and 0.07 fb (5n), at excitation energies of 24 MeV, 31 MeV, 41 MeV, and 50 MeV, respectively, for the synthesis of element 119 in the reaction $^{54}\text{Cr}+^{243}\text{Am}$. Very low cross sections are predicted for the production of element 120 in the reaction $^{54}\text{Cr}+^{248}\text{Cm}$, i.e., 8.8×10^{-6} pb (2n), 1.3×10^{-5} pb (3n), 5.8×10^{-5} pb (4n), and 1.1×10^{-6} pb (5n), respectively. The calculations of the mass table and fission barrier in the survival probability should be improved using the Skyrme energy density functional in future work. The shape evolution and density rearrangement of the binary nuclei might be improved by one-body density evolution and the time-dependent Schrödinger equation.

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