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Full Text

Preamble

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Exploring the Feasibility of Producing Superheavy Nuclei in the Proton Evaporation Channel

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Abstract

The feasibility of producing superheavy nuclei in proton evaporation channels was systematically studied within the dinuclear system (DNS) model. Due to the Z=114 proton shell, Fl isotopes can be synthesized through proton evaporation channels. In this work, we only considered the case of evaporating one proton first followed by n neutrons; other cases were ignored due to their small cross sections. The production cross sections of unknown isotopes ^{290},^{291}Fl in the ^{38}S+^{255}Es reaction are the highest compared with ^{50}Ti+^{243}Np and ^{54}Cr+^{239}Pa reactions, with maximum cross sections of 1.1 pb and 15.1 pb, respectively. The reaction ^{42}S+^{254}Es represents a promising candidate for approaching the island of stability as radioactive beam facilities are upgraded in the future, with estimated production cross sections for $^{291-294}$Fl of 3.2, 6.0, 4.0, and 0.1 pb, respectively.

Keywords: DNS model; superheavy nuclei; fusion reaction; proton evaporation channel; production cross section

Introduction

The synthesis of superheavy nuclei has always been a crucial task and significant challenge in nuclear physics, essential for expanding the nuclear chart, investigating the origin of heavy elements, and testing the shell model. Current research on superheavy nuclei synthesis can be divided into two main directions: synthesizing new elements to explore the charge limit of superheavy nuclei [1-3], and moving toward the doubly magic nucleus ^{298}Fl, which is the center of the island of stability [4-7]. Because the β-stability line bends toward the neutron axis, the superheavy nuclei currently produced through fusion-evaporation reactions are neutron-deficient and lie far from the island of stability. This necessitates the development of radioactive beam facilities and the search for new production mechanisms.

Several models have been developed to study the fusion mechanism and predict production cross sections for superheavy nuclei. Semi-classical models such as multidimensional Langevin-type dynamical equations [8], the nuclear collectivization model [9], the fusion-by-diffusion model [10], and the dinuclear system model [11-13] have been successfully applied to calculate evaporation-residue (ER) cross sections for superheavy nuclei. Microscopic models like the TDHF approach [14-15] and ImQMD model [16-17] can effectively describe dynamical dissipation during the fusion process. In this work, we explore the production of superheavy nuclei in proton evaporation channels. To this end, we have developed the de-excitation component of the DNS model and found that the production of Fl isotopes through proton evaporation channels is considerable.

1 The DNS Model

Within the DNS framework, the ER cross sections for superheavy nuclei at incident energy $E_{\mathrm{c.m.}}$ are calculated by [18]:

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

Here, T, P_{CN}, and W_{sur} represent the transmission, fusion, and survival probabilities, respectively. Due to the complexity of the actual Coulomb barrier, an analytical expression for the transmission probability is difficult to obtain; however, it can be calculated using the WKB method after making a parabolic approximation of the Coulomb barrier [19]:

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

In this expression, $\hbar\omega$ is the width of the parabolic barrier and R_B defines the barrier position. Considering the multidimensional character of the realistic barrier, the barrier distribution function $f(B)$ should be introduced, which we take to have an asymmetric Gaussian form [9].

The interaction potential after accounting for deformation can be written as:

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

where V_C and V_N are the Coulomb and nuclear potentials, given by Wong' s formula and the double-folding method, respectively. $\beta_{1,2}^0$ is the static deformation (for nuclei 1 and 2), usually taken as the quadrupole deformation, while $\beta_{1,2}$ represents dynamical deformation. Assuming the deformation energy is proportional to the mass number, i.e., $C_1\beta_1^2/C_2\beta_2^2 = A_1/A_2$, only one deformation parameter $\beta = \beta_1 + \beta_2$ is needed to represent the dynamical deformation. The coefficients $C_{1,2}$ characterize nuclear hardness and are given by:

$$C = \frac{1}{(2\lambda+1)}\left[(\lambda-1)(\lambda+2)R_N\sigma - \frac{3Z^{2e^2}}{2\pi(2\lambda+1)R_N}\right],$$

where R_N is the nuclear radius, λ is the deformation order (taken as 2 for quadrupole deformation), and σ is the surface tension coefficient given by $4\pi R_N^2\sigma = a_s A^{2/3}$, with a_s taken as 18.32 MeV.

The distribution probability $P(Z_1, N_1, t)$ for fragment (Z_1, N_1) at time t is determined by solving the master equation [20]:

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

Here, d_{Z_1,N_1} describes the microscopic dimension corresponding to the macroscopic state (Z_1, N_1). Λ_{qf} and Λ_{fis} are the quasifission and fission rates, calculated using the one-dimensional Kramers equation [21]. $\Theta(t) = \sqrt{\varepsilon^*/a}$ is the local temperature, obtained from the Fermi gas model, where ε^* is the local excitation energy of the dinuclear system and a is the level density parameter. $W_{Z_1,N_1;Z_1',N_1'}(t)$ represents the transition probability from state (Z_1, N_1) to (Z_1', N_1'), which can be written as:

$$W_{Z_1,N_1;Z_1',N_1'}(t) = \frac{2\pi}{\hbar^2 d_{Z_1,N_1}} \left|\langle Z_1', N_1', E_1', i|V(t)|Z_1, N_1, E_1, i\rangle\right|^2 \tau_{\mathrm{mem}}(Z_1, N_1, E_1, Z_1', N_1', E_1'; t).$$

Here, i represents the remaining quantum numbers, E_1 denotes the local excitation energy, and τ_{mem} is the memory time given by [22]:

$$\tau_{\mathrm{mem}}(A_1, E_1, A_1', E_1'; t) = \frac{\hbar}{\sum_{KK'}\langle V_{KK'}V_{KK'}^*\rangle}.$$

The compound nucleus formed by fusion reaction possesses high excitation energy and de-excites through emission of γ-rays, light particles, and fission. According to Weisskopf's evaporation theory [23], the evaporation width for particle ν can be written as:

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

where B_ν, m_ν, and s_ν are the binding energy, mass, and spin of the particle, respectively. The pairing correction δ is set to $12/\sqrt{A}$, 0, and $-12/\sqrt{A}$ for even-even, odd-A, and odd-odd nuclei, respectively, while δ_n is the neutron correction energy. If the neutron number of the compound nucleus is odd, $\delta_n = 12/\sqrt{A}$; otherwise, $\delta_n = 0$. The level density ρ is calculated using the Fermi-gas model, with the level density parameter a given by:

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

where $\tilde{a}(A) = \alpha A + \beta A^{2/3} b_s$ is the asymptotic Fermi-gas value. $E_{\rm sh}(Z, N)$ is the shell correction energy, and $f(E^*)$ is the shell damping factor. The parameters α, β, and b_s are taken as 0.114, 0.098, and 1.0, respectively.

The inverse cross section $\sigma_{\rm inv}$ is given by:

$$\sigma_{\rm inv}(\varepsilon) = \begin{cases} \pi R_\nu^2 \left(1 - \frac{V_\nu}{\varepsilon}\right) & \varepsilon > V_\nu, \\ 0 & \varepsilon < V_\nu, \end{cases}$$

where R_ν can be expressed as $R_\nu = 1.16[(A - A_\nu)^{1/3} + A_\nu^{1/3}]$ fm, with A_ν being the mass number of the evaporated particle. For proton evaporation, the Coulomb barrier V_ν is parameterized by $V_\nu = \frac{1.15 Z_\nu (Z - Z_\nu)}{R_\nu + 1.6}$ MeV.

The survival probability of a superheavy nucleus can be expressed as [23]:

$$W_{\rm sur}(E^*_{\rm CN}, x, y, J) = P(E^*_{\rm CN}, x, y, J) \frac{\Gamma_p(E^*_1, J)}{\Gamma_{\rm tot}(E^*_1, J)} \prod_{j=x+1}^{y} \frac{\Gamma_n(E^*_j, J)}{\Gamma_{\rm tot}(E^*_j, J)},$$

where $\Gamma_{\rm tot} = \Gamma_n + \Gamma_p + \Gamma_f$. The fission width Γ_f is given by the Bohr-Wheeler formula:

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

Here, $P(E^*_{\rm CN}, x, y, J)$ is the realization probability given by the Jackson formula [24], E^*_i is the excitation energy before evaporating the i-th particle, B_ν is the separation energy of the i-th particle, and T_i is the nuclear temperature before evaporation of the i-th particle, obtained from $T_i = \sqrt{E^*_i/a}$.

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2 Results and Discussion

To identify compound nuclei with the largest cross sections in proton evaporation channels, we first defined a ratio B_f/B_p to evaluate the strength of proton evaporation. Figure 1 [Figure 1: see original paper] shows the calculated B_f/B_p ratios for nuclei $^{286-297}$Nh, $^{286-297}$Fl, $^{285-296}$Mc, and $^{286-297}$Lv, denoted by circles, squares, triangles, and pentagrams, respectively. The ratios for $^{285-296}$Mc are the highest, with the fission barrier approximately 2-4 times the proton separation energy, indicating that proton evaporation is most favorable for $^{285-296}$Mc during de-excitation, resulting in larger proton evaporation probabilities. In contrast, the B_f/B_p ratios for $^{286-297}$Fl are the smallest, demonstrating that $^{286-297}$Fl isotopes are resistant to proton evaporation due to the proton closed shell at $Z = 114$. Consequently, one can first synthesize compound nuclei with $Z = 115$ and then obtain Fl isotopes by evaporating one proton and n neutrons.

To verify the reliability of the DNS model, we calculated the ER cross sections for ^{40}Ar+^{179}Hf reactions, as shown in Figure 2 [Figure 2: see original paper]. The solid, dashed, and dash-dotted lines represent the calculated ER cross sections for $p2n$, $p3n$, and $p4n$ evaporation channels, respectively, while circles, squares, and triangles represent the corresponding experimental data with error bars [25]. The calculated results are in good agreement with experimental data, though at low incident energies the calculations are significantly lower than the data. This discrepancy arises because charged-particle evaporation in the de-excitation process is treated classically without considering quantum tunneling effects.

For producing superheavy nuclei via proton evaporation, it is necessary to consider both the number and order of evaporated protons. Figure 3 [Figure 3: see original paper] shows the calculated evaporation widths for the ^{48}Ca+^{243}Am reaction, which produces Mc compound nuclei. The proton evaporation width is the smallest, and compared to neutron evaporation width, the survival probability decreases by 1-2 orders of magnitude after each proton emission. Therefore, in this work we only consider the case of evaporating one proton first followed by n neutrons; the survival probability for multiple proton emission is too small and can be neglected. Additionally, as excitation energy decreases, the proton evaporation width decreases rapidly and the ratio Γ_p/Γ_n diminishes.

The ER cross sections for producing Fl isotopes in ^{38}S+^{255}Es, ^{50}Ti+^{243}Np, ^{54}Cr+^{239}Pa, and ^{42}S+^{254}Es reactions are shown in Figure 4 [Figure 4: see original paper]. Solid, dashed, dash-dotted, and dotted lines represent $p1n$, $p2n$, $p3n$, and $p4n$ evaporation channels, respectively. For these reactions, the ER cross sections in $p2n$ and $p3n$ channels are relatively larger. The ER cross sections in the ^{38}S+^{255}Es reaction are the highest among the first three reactions, which correspond to the same compound nucleus. This is because the mass asymmetry for ^{38}S+^{255}Es is the largest, leading to the highest fusion probability. The maximum ER cross sections for the unknown isotopes ^{290}Fl and ^{291}Fl are 1.1 pb and 15.1 pb at $E^*_{\rm CN} = 38.2$ MeV and 39.4 MeV, respectively. The ^{38}S beam can be produced by fragmenting ^{40}Ar at a projectile fragmentation facility [26], and fusion reactions ^{38}S + ^{181}Ta and ^{38}S + ^{208}Pb have been successfully conducted with a ^{38}S beam.

To produce additional unknown Fl isotopes, we also predicted ER cross sections for the radioactive beam-induced reaction ^{42}S+^{254}Es. Four unknown isotopes, $^{291-294}$Fl, are synthesized with cross sections of 3.2, 6.0, 4.0, and 0.1 pb at $E^*_{\rm CN} = 42.2$, 28.6, 20.2, and 15.0 MeV, respectively. Notably, the ER cross sections in the $p4n$ channel for ^{42}S+^{254}Es are comparable to those in the $p2n$ and $p3n$ channels, unlike the other three reactions. This occurs because the compound nucleus in ^{42}S+^{254}Es has more neutrons than in the other reactions, leading to the highest survival probability in the $p4n$ channel. If radioactive beam facilities are upgraded and the intensity of the ^{42}S beam increases substantially in the future, the ^{42}S+^{254}Es reaction could become a promising candidate for approaching the island of stability.

Considering the sensitivity of the DNS model to certain parameters, it is necessary to evaluate the theoretical uncertainties to determine the reliability of predictions. Among the model parameters, the shell damping factor E_d plays a vital role in determining ER cross sections [27]. This factor cannot be precisely determined experimentally or theoretically, and its uncertainty is estimated based on experimental data from Ref. [28]. The resulting calculation uncertainties are shown as shaded regions in Figure 4. The uncertainties in ER cross sections for Fl isotopes are no better than one order of magnitude, while the uncertainties in the optimal excitation energy are only on the order of 0.1 MeV.

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3 Summary

In summary, we have investigated the production of Fl isotopes in proton evaporation channels within the DNS model. Among isotopes around $Z = 114$, proton evaporation is easiest for Mc isotopes but most difficult for Fl isotopes due to the proton closed shell at $Z = 114$. Therefore, one can synthesize Fl isotopes in proton evaporation channels by first forming compound nuclei with $Z = 115$. The DNS model reproduces experimental data very well. The synthesis of unknown isotopes ^{290,291}Fl was studied via ^{38}S+^{255}Es, ^{50}Ti+^{243}Np, and ^{54}Cr+^{239}Pa reactions, which correspond to the same compound nucleus. The ER cross sections for ^{290}Fl and ^{291}Fl are largest in the ^{38}S+^{255}Es reaction, reaching 1.1 pb and 15.1 pb at $E^*_{\mathrm{CN}} = 38.2$ MeV and 39.4 MeV, respectively. In the radioactive beam-induced reaction ^{42}S+^{254}Es, four new isotopes $^{291-294}$Fl are predicted with ER cross sections of 3.2, 6.0, 4.0, and 0.1 pb at $E^*_{\mathrm{CN}} = 42.2$, 28.6, 20.2, and 15.0 MeV, respectively. The uncertainties in these predictions arising from the shell damping factor are estimated to be no better than one order of magnitude for ER cross sections.

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