Production of proton-rich isotopes of Pu, Cm, Bk, Ds, Fl, Cn by fusion evaporation reactions with 40Ar projectile

Authors: Yao, Mrs. QingQing, Tianliang Zhao, Bao, Xiao-Jun, Bao, Dr. Xiao-Jun

Date: 2025-02-25T00:00:00+00:00

Abstract

The evaporation residual cross sections (ERCSs) of these reaction systems were calculated by bombarding 144Sm, 160Dy, 164Dy, 165Ho, 169Tm, 174Yb, 175Lu, 176−180Hf and 181Ta targets with 40Ar projectile in the theoretical framework of the dinuclear system model. The de-excitation process of the compound nucleus is theoretically calculated using two different statistical models, namely the statistical model 1 and statistical model 2 (GEMINI++ model). The calculated ERCSs were also compared with the experimental data. The ERCSs of synthesizing new proton-rich isotopes of Pu, Cm, Bk, Ds, Cn and Fl are investigated based on the fusion evaporation reaction. Predictions were made for the ERCSs of new isotopes of Pu, Cm and Bk in the heavy nucleus region, while the new isotopes of Ds, Cn and Fl are predicted in the superheavy nucleus region of Z$ $104.

Full Text

Preamble

Production of proton-rich isotopes of Pu, Cm, Bk, Ds, Fl, and Cn via fusion-evaporation reactions with a 40Ar projectile

Qing-Qing Yao, Tian-Liang Zhao, and Xiao-Jun Bao

Department of Physics, Collaborative Innovation Center for Quantum Effects, and Key Laboratory of Low Dimensional Quantum Structures and Quantum Control of Ministry of Education, Hunan Normal University, Changsha 410081, People' s Republic of China

The evaporation residue cross sections (ERCSs) for these reaction systems were calculated by bombarding 144Sm, 160,164Dy, 165Ho, 166Er, 169Tm, 171,174Yb,

175Lu, 176−180Hf, 181Ta, 180,182W, and 187Re targets with a 40Ar projectile within the theoretical framework of the dinuclear system (DNS) model. The de-excitation process of the compound nuclei was theoretically calculated using two different statistical models, namely statistical model 1 and statistical model 2 (the GEMINI++ model). The calculated ERCSs were also compared with experimental data. The ERCSs for synthesizing new proton-rich nuclides were investigated based on fusion-evaporation reactions. Predictions were made for the ERCSs of new isotopes of Pu, Cm, and Bk in the heavy nuclei region, while new isotopes of Ds, Cn, and Fl are predicted in the superheavy nuclei region with Z $\geq$ 104.

Keywords: Dinuclear system model, Evaporation residue cross section, Proton-rich nuclides

Introduction

The synthesis of new elements and nuclides is a prominent topic in nuclear physics [1–3]. It is not only of great significance for understanding the structure of matter but also provides crucial information for comprehending the evolution of celestial environments, making it an essential means of exploring nature. Heavy-ion fusion-evaporation (FE) reactions play a crucial role in the synthesis of new elements and nuclides [3–12]. In such reactions, heavy ions accelerated by heavy-ion accelerators collide with target nuclei, leading to nuclear fusion and subsequent evaporation processes that result in the synthesis of new nuclides.

Significant experimental progress has been made in FE reactions. In 1975, 40Ar beams with energies up to 225 MeV from the Dubna U-300 cyclotron bombarded 204Pb and 206Pb targets, leading to the synthesis of 242Fm [13]. In 1981, 206Pb and 209Bi targets were bombarded with a 40Ar beam from the GSI Universal Linear Accelerator (UNILAC) to form 243Fm and 247Md in FE reactions [14]. Similarly, the successful synthesis of new nuclides 245Md and 246Md was achieved via the 40Ar + 209Bi combination at the GSI Laboratory in 1996 [15]. An enriched 204Pb target was bombarded with 40Ar beams from the GSI UNILAC accelerator to form 241Fm in the (3n) FE reaction in 2008 [16]. The new neutron-deficient isotope 217U was produced by bombarding a 182W target with 40Ar ions and identified using a recoil-α-α correlation method in 2000 [17].

China has also achieved notable success in synthesizing new nuclides using 40Ar in recent years. For instance, the team from the Institute of Modern Physics of the Chinese Academy of Sciences (IMPCAS) successfully synthesized new uranium isotopes 215,216U using the projectile-target combination 40Ar + 180W in 2015 [18, 19]. Since 2017, IMPCAS has devoted itself to the synthesis and study of Np radioisotopes, successively producing a series of new neutron-deficient isotopes 220,223,224Np through FE reactions with 40Ar + 185,187Re [20–22]. Recent results from Dubna for the 40Ar + 238U reaction [23] demonstrated that 40Ar beams can also be used for the synthesis of superheavy nuclei.

In theoretical studies, many models have been developed to understand the formation mechanism of heavy and superheavy nuclei in FE reactions [24–28]. This work is based on the dinuclear system (DNS) model [29-32]. The synthesis of heavy and superheavy nuclei is a complex dynamic process involving mainly competition between fusion and quasi-fission. These processes can be viewed as the evolution of the DNS along two main degrees of freedom: the relative motion of nuclei in the interaction potential for DNS formation and the decay of the DNS (quasi-fission process) along the elongation degree of freedom (internuclear motion); and the transfer of nucleons between two nuclei in the mass asymmetric coordinate system = (A1−A2)/(A1+A2), which is the process of diffusion of the excited system leading to the formation of compound nuclei (CN). It is assumed that the two contacting nuclei always maintain their ground-state characteristics in the DNS [33–35]. In reality, however, the nuclei in the DNS are gradually deformed by the strong nuclear and Coulomb interactions between them. This deformation alters the masses of nuclei as well as the interactions between them, which affects the further evolution of the system [36] and is usually not negligible.

The DNS concept must therefore be improved by reducing the approximations used to simplify calculations. In this paper, we numerically investigate the time-dependent dynamical deformations of the interacting nuclei, which are coupled with nucleon transfer in heavy-ion fusion reactions to form superheavy nuclei (SHN). As mentioned in Ref. [37], in addition to the asymmetry degree variables of neutrons and protons, the quadrupole deformation of interacting nuclei is also taken as a dynamic variable, constructing new four-variable master equations (MEs). This means that deformation and nucleon transfer are always regarded as a diffusion process controlled by the master equation in the potential energy surface (PES) of the system.

Theoretical calculations were performed using the combination of DNS + statistical model 1, as well as DNS + statistical model 2 (the GEMINI++ model). The evaporation residue cross sections (ERCSs) for FE reactions were calculated by bombarding 144Sm, 160,164Dy, 165Ho, 166Er, 169Tm, 171,174Yb, 175Lu, 176−180Hf, 181Ta, 180,182W, and 187Re targets with a 40Ar projectile, and the results were compared with available experimental data. The article is organized as follows: In Sec. II we provide a brief description of the theoretical framework. Results and discussion are presented in Sec. III. A summary is given in Sec. IV.

II. Theoretical Framework

In theoretical studies, the fusion-evaporation reaction process can be divided in more detail into three successive phases. The first phase is the capture process, which can be evaluated by the capture cross section; the second phase is the evolution of the DNS from the contact configuration to the formation of a compound nucleus, which can be evaluated by the fusion probability; the final stage involves the excited compound nucleus undergoing evaporation of light particles to prevent fission, which can be evaluated by the survival probability. Finally, a small ERCS is obtained for the generation of residual nuclei. In the DNS concept, the ERCS is calculated as the sum over all partial waves [24, 25, 38]:

$$\sigma_{ER} = \sum \sigma_{cap}(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J) \tag{1}$$

where $E_{c.m.}$ and J are the incident energy and angular momentum in the center-of-mass coordinate system. The σ_{cap}, P_{CN}, and W_{sur} denote the capture cross section, fusion probability, and survival probability, respectively.

The σ_{cap} is mainly calculated using the empirical coupled-channel approach. Different potential distribution functions are constructed based on different modes of coupling between the projectile and the target. They are divided into three different cases: a fusion reaction involving two spherical nuclei, reactions with two statically deformed nuclei, and reactions with the combination of one spherical nucleus and one statically deformed nucleus, as described in detail in Ref. [39]. For a given center-of-mass energy $E_{c.m.}$, the $\sigma_{cap}(E_{c.m.}, J)$ can be expressed as [40]:

$$\sigma_{cap}(E_{c.m.}, J) = \frac{2\mu}{E_{c.m.}} \sum (2J+1) T(E_{c.m.}, J)$$

where μ denotes the reduced mass of the projectile and target nuclei. $T(E_{c.m.}, J)$ is the penetration probability of the two colliding nuclei overcoming the Coulomb barrier in the entrance channel.

By numerically solving the four-variable master equations in the corresponding potential energy surface, the time evolution of the probability distribution function $P(Z_1, N_1, \beta_{12}, \beta_{22}, \theta_1, \theta_2, \varepsilon_1, \tau_{int})$ under the directional angles (θ_1 and θ_2) can be obtained, which is mentioned in detail in Refs. [41–43]. Finally, the fusion probability P_{CN} is given by:

$$P_{CN}(E_{c.m.}, J) = \sum_{Z_{BG}} \sum_{N_{BG}} \int_0^{\infty} \int_0^{\infty} \int_0^{\pi/2} \int_0^{\pi/2} P(Z_1, N_1, \beta_{12}, \beta_{22}, \theta_1, \theta_2, \tau_{int}) \rho_1(\beta_{12}) \rho_2(\beta_{22}) \sin\theta_1 \sin\theta_2 d\beta_{12} d\beta_{22}$$

where N_{BG} and Z_{BG} are the Businaro-Gallone points. $\rho_i(\beta_{i2}) = 1/h_i$ denotes the density of the discrete dots with step length h_i ($i = 1, 2$). The interaction time τ_{int} in the dissipative process of two colliding nuclei is determined by the deflection function method [44].

The survival probability is important in evaluating the cross section. In the de-excitation process of the compound nucleus, two different statistical models are employed for theoretical calculations: statistical model 1 and statistical model 2 (the GEMINI++ model). In model 1, similar to neutron evaporation, the probability in the channel of evaporating the x-th neutron, the y-th proton, and the z-th α particle is expressed as [45]:

$$W_{sur}(E^*_{CN}, x, y, z, J) = P(E^*_{CN}, x, y, z, J) \frac{\prod_i \Gamma_n(E^*_i, J)}{\prod_j \Gamma_{tot}(E^*_j, J)} \frac{\prod_i \Gamma_p(E^*_i, J)}{\prod_j \Gamma_{tot}(E^*_j, J)} \frac{\prod_k \Gamma_\alpha(E^*_k, J)}{\prod_k \Gamma_{tot}(E^*_k, J)}$$

where $P(E^*_{CN}, x, y, z, J)$ denotes the realization probability when the excitation energy of the compound nucleus is E^*_{CN} and its angular momentum is J. The total width Γ_{tot} for CN decay is the sum of the partial widths of particle evaporation Γ_m ($m = n, p, \alpha$ for neutron, proton, and α particle, respectively), γ-emission, and fission Γ_f. The excitation energy E^* before evaporating the s-th particle is evaluated by:

$$E^*_{s+1} = E^*_s - B^i_n - B^j_p - B^k_\alpha - 2T_s$$

with the initial condition $E^*_1 = E^*_{CN}$ and $s = i + j + k$. The B^i_n, B^j_p, and B^k_α are the separation energies of the i-th neutron, j-th proton, and k-th α particle, respectively [46]. The relationship between the compound nuclear temperature T_i and the excitation energy can be expressed as:

$$E^*_i = aT^2_i - T_i$$

For one-particle evaporation, the realization probability is given by:

$$P(E^*_{CN}, J) = \exp\left(-\frac{(E^*_{CN} - B_s - 2T)^2}{2\sigma^2}\right)$$

where σ is the value obtained by experimentally measuring the width of the excitation function based on the fusion-evaporation reaction. The probability $P(E^*_{CN}, x, y, z, J)$ of evaporating x neutrons, y protons, and z α particles at excitation energy E^*_{CN} and angular momentum J is calculated using the Jackson formula [47]:

$$P(E^*_{CN}, s, J) = \frac{(2J+1)\exp\left(-\frac{E^*_{CN} - \sum_{i=1}^{s} B_{\nu_i}}{T}\right)}{I(\Delta_s, 2s-3) - I(\Delta_{s+1}, 2s-1)}$$

where the quantities I and Δ are given as follows:

$$I(z, m) = \int_0^z u^m e^{-u} du$$

$$\Delta_s = \frac{E^*_{CN} - \sum_{i=1}^{s} B_{\nu_i}}{T}$$

where B_{ν_i} is the separation energy of the i-th evaporating particle and $s(x, y, z) = x + y + z$.

The particle decay widths are evaluated with Weisskopf' s evaporation theory [48] as:

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

Here, s_ν, m_ν, and B_ν are the spin, mass, and binding energy of the evaporating particle, respectively. The inverse cross section is given by $\sigma_{inv} = \pi R_\nu^2 T(\nu)$ with the radius $R_\nu = 1.21[(A - A_\nu)^{1/3} + A_\nu^{1/3}]$, where A_ν is the mass number of the evaporated particle. The penetration probability is set to unity for neutrons and $T(\nu) = (1 + \exp(\pi(V_C(\nu) - \varepsilon)/\hbar\omega))^{-1}$ for charged particles with $\hbar\omega = 5$ and 8 MeV for proton and α, respectively. The Coulomb barrier calculation in the case of charged particle emission is:

$$V_C = \frac{(Z_{CN} - i)Z_i e^2}{r_i(A_{CN} - i)^{1/3} + A_i^{1/3}}$$

where for proton emission $r_p = 1.7$ fm, and for α emission $r_\alpha = 1.75$ fm, as described in detail in Ref. [49].

The fission width can be calculated with the Bohr-Wheeler formula as [46, 50]:

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

Here, we take $\hbar\omega = 2.2$ MeV for all nuclei considered [51], δ_f is a correction for the fission barrier, and B_f is the fission barrier consisting of macroscopic and microscopic parts, with more details given in Ref. [46].

The level density is calculated using the back-shifted Fermi-gas model [52]. The excitation energy is replaced with the equivalent excitation energy $U = E - \delta$. The back-shifts $\delta = -\Delta$ (odd-odd), 0 (odd-A), and Δ (even-even) are related to the neutron and proton pairing gap $\Delta = \frac{1}{2}[\Delta_n(Z, N) + \Delta_p(Z, N)]$. The energy level density is expressed as:

$$\rho(U, J) = \frac{2J + 1}{2\sigma^3} \sqrt{\frac{a}{4U}} \exp\left(2\sqrt{aU} - \frac{J(J + 1)}{2\sigma^2}\right)$$

with $\sigma^2 = \Theta_{rigid}\sqrt{\frac{U}{a}}$ and $\Theta_{rigid} = \frac{2}{5}m_{uAR}^2$.

The selection of the level-density parameter in Eq. (14) is crucial, as it should be applied to both low and high excitation energy regions. Only in this way can statistical model 1 be more rationally utilized to describe the de-excitation and fission processes of nuclei in excited states. It is closely related to the excitation energy of the nucleus and the shell correction:

$$a(U, Z, N) = \tilde{a}(A)\left[1 + \frac{E_{sh}}{U}f(U)\right]$$

$$\tilde{a}(A) = \alpha A + \beta A^{2/3}$$

$$f(U) = 1 - \exp(-\gamma_D U)$$

The $\tilde{a}(A)$ is the asymptotic Fermi-gas value of the level density parameter at high excitation energy. It is worth noting that in Fermi-gas models of the same type, different density of states parameters mainly depend on the different shell corrections chosen. Under the condition that the shell corrections are given by a certain mass formula, the values in the energy level density parameters are finally extracted by fitting all nuclei with experimental values of energy level densities. In this paper, the microscopic shell corrections from FRDM95 [53] are used to fit the experimental level density data, resulting in parameters $\alpha = 0.1337$, $\beta = -0.06571$, $\gamma_D = 0.04884$ [54].

Another statistical model used in this work is GEMINI++, which is the improved version of the GEMINI statistical decay model developed by R. J. Charity [55] to describe the formation of complex fragments in heavy-ion fusion experiments. The de-excitation of a compound nucleus occurs through a series of binary decays until particle emission is energetically forbidden or impossible due to competition with γ-ray emission. The evaporation process of light particles is described using the Hauser-Feshbach model in GEMINI++.

In both statistical model 1 and the GEMINI++ model, the same fission barrier is used. However, there are differences in the calculation methods for the fission widths. In the GEMINI++ model, the Bohr-Wheeler formalism is used for symmetric fission [56]. For mass-asymmetric fission outside the symmetric fission peak, the Moretto formalism is used. For statistical model 1, only Bohr-Wheeler' s formula is used. Additionally, there are differences in the treatment of level density and the parameters of level density between the two models. In GEMINI++, the level density is calculated using the Fermi-gas model: $\rho(E^*, J) \sim \exp(2\sqrt{a(U)U})$.

The level density parameter $\tilde{a}(U)$ is also related to the excitation energy and is given by:

$$\tilde{a}(U) = k_\infty - (k_\infty - k_0)\exp\left(-\frac{\kappa}{k_\infty - k_0}U\right)$$

The parameter κ defines how fast the long-range correlations wash out with excitation energy. However, the fitting range of κ is small, and the maximum compound nucleus mass is only $A = 224$ [57]. The de-excitation process in this work is simulated using the GEMINI++ model, and the default parameters of this model are used for the calculations.

III. Numerical Results and Discussions

A. Production cross sections of heavy isotopes in 40Ar-induced reactions

A variety of new nuclides have been successfully synthesized in the proton-rich region. Nevertheless, many unknown nuclides in this region remain to be explored. To further evaluate the potential of 40Ar beams in synthesizing new nuclides, we continue to use 40Ar as the projectile to bombard different targets in subsequent theoretical calculations. The ERCSs for 40Ar-induced reactions with target nuclei 144Sm, 160,164Dy, 165Ho, 166Er, 169Tm, 171,174Yb, 175Lu, 176−180Hf, 181Ta, 180,182W, and 187Re are presented in Figs. 1-5 and compared with available experimental data [18, 19, 21, 22, 58-60]. To ensure the reliability of the calculations, the same set of models and parameters are used for all projectile-target combinations in this work.

The survival probabilities calculated with the two different statistical models are shown in Figs. 1-5 for comparison. The solid lines indicate cross sections calculated via DNS + statistical model 1, the dashed lines indicate cross sections derived using DNS + GEMINI++ model, and hollow symbols represent relevant experimental data. The difference is that in Figs. 1-2 there is only evaporation of pure neutrons, while in Figs. 3-5 evaporation of charged particles is included.

As seen in Fig. 1 [Figure 1: see original paper], the calculated results obtained by DNS + statistical model 1 and DNS + GEMINI++ model are in good agreement with experimental data. The errors between the theoretical ERCSs and experimental data are basically within one order of magnitude. Fig. 2 [Figure 2: see original paper] shows the ERCSs for the 180W(40Ar, xn)220−xU, 182W(40Ar, xn)222−xU, and 187Re(40Ar, xn)227−xNp reactions. The computational results based on statistical model 1 are close to the relevant experimental data. However, when utilizing the GEMINI++ model to calculate the survival probability, a noticeable deficiency emerges in the form of a lower number of events in the neutron evaporation channels. This indicates that the GEMINI++ model has certain limitations in some reaction systems. By comprehensively comparing the theoretical calculation results of the two different models in these reactions, we can conclude that the results derived from both models are not significantly different and that statistical model 1 has a wider range of applicability.

To investigate the effect of different de-excitation processes for evaporating neutrons and charged particles on the ERCSs, we analyze different evaporation channels of the 40Ar+171,174Yb, 176−180Hf, 175Lu, and 181Ta reactions in Figs. 3-5. In general, the production of certain isotopes is more likely in the xn evaporation channel. However, the pxn and αxn evaporation channels allow access to those isotopes that are unreachable in the xn channels due to the lack of proper projectile-target combinations, as discussed in detail by Juhee Hong et al. [61]. This provides a new perspective for the synthesis of some new nuclides.

As seen in Figs. 3-5, for most channels of pure neutron evaporation, DNS + statistical model 1 calculates cross sections that are 1-2 orders of magnitude higher than those of DNS + GEMINI++ model. There is a difference of about 1-2 orders of magnitude between statistical model 1 and the experimental data, while DNS + GEMINI++ model calculations are within one order of magnitude of the experimental data. In the pxn evaporation channel, the computational results of the two models are not very different and both are in good agreement with experimental data. In the αxn evaporation channel, cross sections calculated using DNS + GEMINI++ show significantly better agreement with experimental data than those calculated using DNS + statistical model 1. Overall, in the αxn evaporation channels, cross sections from the DNS + GEMINI++ model perform better than those from DNS + statistical model 1.

By comparing ERCSs of pure neutron evaporation channels and charged particle evaporation channels (pxn and αxn) from Figs. 3-5, it is found that for the same projectile-target combination, the differences in ERCSs are mainly caused by different de-excitation modes. Specifically, these differences are primarily attributed to the survival probability. Moreover, the ERCSs in the proton evaporation channels are typically smaller than those in the neutron evaporation channel, with the α-particle evaporation channel having the smallest cross sections. This may be due to the fact that protons and α particles have higher separation energies and Coulomb potential barriers ($B_p > B_n$), and they need to overcome a larger Coulomb barrier during the evaporation process, which results in relatively smaller cross sections.

It is worth noting that, based on Figs. 1-5, there are certain discrepancies between the theoretical calculations and experimental data for some evaporation channels. These differences are caused by a combination of experimental errors and uncertainties in theoretical calculations. On the experimental side, accelerators cannot provide precise incident energies but rather a variance around that value. Additionally, the precise measurement of ERCSs is challenging, so measured ERCSs usually have upper and lower error limits. On the theoretical side, our model requires a potential energy surface as input when calculating fusion probabilities [62, 63]. However, the calculation of the multidimensional potential energy surface for the reaction system is a complicated physical problem that has not yet been fully solved. Moreover, the dependency of the fusion probability on excitation energy and the reaction entrance channel is not well established. In addition, survival probabilities are calculated based on certain nuclear data, such as nuclear masses, neutron separation energies, and fission barriers (shell correction energies), which are usually extrapolated. For instance, in the calculation of cross sections for hot fusion reactions to synthesize superheavy nuclei, the compound nucleus will evaporate 3–4 neutrons, at which point the precision of the fission barrier is critical. When the height of the fission barrier is imprecise, the calculation errors in the neutron decay width and the ratio of fission width to (xn) de-excitation cascade at each step will accumulate, leading to increased calculation error in the synthesis cross sections [64].

Research has revealed that the production of new nuclides in the superheavy region occurs primarily through neutron evaporation. The previous discussion shows that the two de-excitation models give similar results in pure neutron evaporation channels. As mentioned in Ref. [65], it was found that the GEMINI++ model is able to better represent the survival process in the $Z = 82 - 92$ nuclear region, and it also identified limitations of the GEMINI++ model in calculating survival probabilities in the actinide and superheavy nuclei regions. In addition, the number of simulations required is substantial, especially in the superheavy region where it reaches 1,000,000. Using the GEMINI++ model to simulate the de-excitation process is time-consuming. Therefore, we have chosen to use statistical model 1 for generating cross-section predictions in the following parts B and C.

B. Production cross sections of Pu, Cm, Bk proton-rich isotopes in the heavy nuclear region

Based on the reliability of theoretical calculations and to explore the potential of 40Ar in synthesizing new isotopes, we continue to use 40Ar as the incident particle to further predict the ERCSs of new nuclides that could potentially be synthesized in the laboratory. The selection of 184Os, 192Pt, and 197Au as target materials is based on the following primary reasons. Firstly, these targets possess long half-lives, which ensures their stability over extended periods during experiments, enhancing efficiency and data reliability. Furthermore, when the 40Ar beam bombards these target nuclei under current experimental conditions, there is a possibility of producing new nuclides that lie beyond the existing proton drip line. Fig. 6 [Figure 6: see original paper] shows the relevant theoretical calculations obtained by DNS + statistical model 1.

As seen in Fig. 6, for the 184Os(40Ar, xn)224−xPu reaction system, the maximum cross sections of the 3n, 4n, and 5n channels are 266.27, 176.53, and 31.63 pb, respectively, resulting in the production of 219−221Pu, and the maximum ERCS is located in the 3n channel, corresponding to an excitation energy of approximately 45 MeV. The maximum cross sections of the 3n, 4n, and 5n channels for the 192Pt(40Ar, xn)232−xCm reaction are 177.34, 40.94, and 5.54 pb, respectively, resulting in the production of 227−229Cm. The maximum ERCS is located in the 3n channel, and the corresponding excitation energy is about 47 MeV. For the 197Au(40Ar, xn)237−xBk reaction system, the maximum cross sections of the 3n, 4n, and 5n channels are 3193.41, 376.49, and 54.77 pb, respectively, resulting in the production of 232−234Bk. The maximum ERCS is located in the 3n channel, and the corresponding excitation energy is about 45 MeV.

C. Production cross sections of Ds, Cn, Fl proton-rich isotopes in the superheavy nuclear region

Similarly, we also predict the ERCSs of new nuclides in the superheavy nuclear regions that may be synthesized in the laboratory. In this study, 40Ar is utilized as the projectile to bombard actinide targets, including 238U, 244Pu, and 248Cm. In the field of superheavy nuclei research, 238U, 244Pu, and 248Cm are commonly used target nuclei that have been validated by numerous experiments, particularly those involving 48Ca beams. These studies have yielded invaluable data for understanding the properties of superheavy elements.

Fig. 7 Figure 7: see original paper shows the predicted excitation function of xn ERCSs for the reaction 238U(40Ar, xn)278−xDs. The maximal ERCSs of the 3n, 4n, and 5n channels are 1.479, 4.813, and 0.188 pb, respectively, resulting in the production of 273−275Ds. The largest ERCS is located in the 4n channel, with the corresponding excitation energy being 46 MeV. Especially noteworthy is the new nuclide 273Ds, which was produced through the combination of 40Ar + 238U with a production cross section of $\sigma = 0.18$ pb at an excitation energy of 49 MeV [23]. There is a 2.67 times difference compared to the theoretical result of 0.48 pb.

In Fig. 7(b), the maximum cross sections of the 3n, 4n, and 5n channels of the 244Pu(40Ar, xn)284−xCn reaction are 1.215, 0.897, and 0.019 pb, respectively, resulting in the production of 279−281Cn. The largest ERCS is located in the 3n channel, and its corresponding excitation energy is about 43 MeV. Similarly, for the 248Cm(40Ar, xn)288−xFl reaction system in Fig. 7(c), the maximum cross sections of the 3n, 4n, and 5n channels are 1.142, 2.699, and 0.071 pb, respectively, resulting in the production of 283−285Fl, and the maximum residual evaporation cross section is located in the 4n channel, corresponding to an excitation energy of approximately 45 MeV. The new nuclides such as 273−275Ds, 280,281Cn, and 284,285Fl are the most probable isotopes given the current experimental detection limit of 0.1 pb [4].

IV. Summary

Despite the fact that many areas of the nuclide chart have been filled in recent years, many unknown nuclides remain in the proton drip line region. To search for proton-rich isotopes in heavy and superheavy regions, we have systematically investigated 40Ar-induced fusion-evaporation reactions within the theoretical framework of the DNS model. In calculating survival probabilities, two different statistical models were employed. The results indicated no significant differences between the two models in computations for neutron and proton evaporation channels. However, the GEMINI++ model showed superior performance in calculations for α-particle evaporation channels. Statistical model 1 is more broadly applicable.

Based on statistical model 1, we used 40Ar as the projectile to predict the ERCSs of new isotopes of actinide elements such as Pu, Cm, and Bk, and the cross sections of new isotopes of Ds, Cn, and Fl in the superheavy nuclei region with $Z \geq 104$. The production cross sections of 273−275Ds, 279−281Cn, and 283−285Fl are 0.488, 4.813, 1.479 pb; 0.019, 0.89, 0.215 pb; and 0.071, 2.699, 1.142 pb, respectively. Since the current experimental limit is 0.1 pb, 273−275Ds, 280,281Cn, and 284,285Fl are more likely to be detected. We hope these results will inspire further experimental synthesis studies of new isotopes.

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