Production of neutron-rich actinide isotopes in isobaric collisions via multinucleon transfer

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Abstract

We have calculated the multinucleon transfer reactions of 208Os, 208Pt, 208Hg, 208Pb,208Po, 208Rn, 208Ra,132,136Xe bombarding on 232Th and 248Cm at Coulomb barrier energies within the dinuclear system model, systematically. The results are in good agreement with the available experimental data. The Coulomb effect and shell effect on the production of actinides in these reactions have been investigated thoroughly. Potential energy surface and total kinetic energy mass distributions in the reactions 208Hg, 208Pb and208Po colliding on 248Cm and 232Th are calculated and analyzed, respectively. It is found that PES and TKE spectra manifest the fragment formation mechanism in the multinucleon transfer reactions. The isospin effect and shell effect are shown in PES and TKE. Production cross-sections of multinucleon transfer products are highly dependent on the isobar projectiles with the mass number A = 208. The isobar projectiles with larger N/Z ratios are favorable for creating neutron-rich target-like fragments. The isobar projectiles with larger charge number induced products tend to shift to proton-rich regions. Coulomb potential coupled with the shell effect is shown in production cross-sections of actinide isotopes. Based on the radioactive projectiles induced reactions, we have predicted massive new actinide isotopes around nuclear drip lines, even could access the superheavy nuclei region.

Full Text

Preamble

Production of neutron-rich actinide isotopes in isobaric collisions via multinucleon transfer reactions

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We have systematically calculated the multinucleon transfer reactions of ^{208}Os, ^{208}Pt, ^{208}Hg, ^{208}Pb, ^{208}Po, ^{208}Rn, ^{208}Ra, and ^{132,136}Xe bombarding ^{232}Th and ^{248}Cm at Coulomb barrier energies within the dinuclear system model. The results are in good agreement with available experimental data. The Coulomb effect and shell effect on actinide production in these reactions have been thoroughly investigated. Potential energy surfaces and total kinetic energy mass distributions for the reactions of ^{208}Hg, ^{208}Pb, and ^{208}Po colliding with ^{248}Cm and ^{232}Th have been calculated and analyzed, respectively. We find that both PES and TKE spectra manifest the fragment formation mechanism in multinucleon transfer reactions, with isospin and shell effects clearly exhibited. Production cross sections of multinucleon transfer products are highly dependent on the isobaric projectiles with mass number $A = 208$. Isobaric projectiles with larger N/Z ratios favor the creation of neutron-rich target-like fragments, while those with larger charge numbers tend to shift products toward proton-rich regions. The Coulomb potential coupled with the shell effect is evident in the production cross sections of actinide isotopes. Based on reactions induced by radioactive projectiles, we have predicted numerous new actinide isotopes around nuclear drip lines, with potential access even to the superheavy nuclei region.

Keywords: Dinuclear system model, Isobaric collisions, Multinucleon transfer reactions, Neutron-rich actinides

Introduction

To date, 3,327 nuclides have been identified in the nuclide chart, including the synthesis of eleven isotopes (^{149}Lu [?], ^{207}Th [?], ^{251,264}Lr [?, ?], ^{166}Pm, ^{168}Sm, ^{170}Eu, ^{172}Gd [?], ^{204}Ac [?], ^{39}Na [?], and ^{286}Mc [?]) in the past year alone. These consist of 288 natural nuclides (254 stable isotopes with lifetimes longer than Earth' s age and 34 unstable nuclides) and 3,039 species synthesized in laboratories worldwide through various methods including fusion-evaporation (FE), multinucleon transfer (MNT) or deep inelastic reactions (DIR), projectile fragmentation (PF), spallation, spontaneous fission (SF), neutron capture (NC), and thermonuclear tests (TT) [?]. However, theoretical models predict that 8,000-10,000 unknown bound isotopes may exist \cite{10-12}, meaning at least 5,000 nuclides remain to be discovered, particularly in regions near nuclear drip lines and the stability island of superheavy nuclei.

In recent years, laboratories worldwide have synthesized several new species from the experimental side, such as ^{207}Th, ^{235}Cm, ^{214}U, ^{222}Np, ^{211}Pa, and ^{280}Ds produced via FE reactions \cite{2,13-15}; ^{110}Zr, ^{121}Tc, and ^{129}Pd via PF [?]; and ^{223,229}Am and ^{233}Bk via MNT [?]. This has drawn significant interest from facilities including the Lanzhou Heavy Ion Research Facility (HIRFL) in China, the Joint Institute for Nuclear Research (JINR) in Russia, the Helmholtz Centre for Heavy Ion Research (GSI) in Germany, the Grand Accélérateur National d' Ions Lourds (GANIL) in France, and Argonne National Laboratory (ANL) in the United States, all aiming to synthesize new nuclides around drip lines and in the superheavy region.

To describe the damped collision mechanism and predict synthesis cross sections for target nuclides, theorists have developed sophisticated and practical models for multinucleon transfer reactions at incident energies near the Coulomb barrier. These include the GRAZING model \cite{18-20}, the dinuclear system (DNS) model \cite{21-30}, and a dynamical model based on Langevin equations [?, ?]. Microscopic methods based on nucleonic degrees of freedom include the time-dependent Hartree-Fock (TDHF) approach \cite{33-35} and the improved quantum molecular dynamics model (ImQMD) [?, ?]. Generally, all these models can nicely reproduce available experimental data through their unique characteristics. The DNS model is particularly advantageous as it can better account for shell effects, dynamical deformation, fission, quasi-fission, deep-inelastic mechanisms, and odd-even effects, while maintaining high computational efficiency.

In this work, we compare calculated cross sections for target-like fragments in MNT reactions of ^{132,136}Xe + ^{248}Cm at incident energies around the Coulomb barrier with available experimental data using the DNS model. To investigate the Coulomb force coupled with shell effects in the MNT process, we select isobaric projectiles with mass number $A = 208$ around the doubly magic nucleus ^{208}Pb to bombard targets ^{232}Th and ^{248}Cm at Coulomb barrier energies. We analyze production cross sections for unknown actinide isotopes in these isobaric collisions. The article is organized as follows: Section II provides a brief description of the DNS model. Calculated results and discussions are presented in Section III. A summary is concluded in Section IV.

II. Model Description

The DNS concept was initially proposed by Volkov for depicting deep inelastic heavy-ion collisions [?]. G.G. Adamian later added a quasifission component in the massive fusion process [?, ?]. Finally, modifications coupling the relative motion energy and angular momentum of two colliding nuclei to nucleon transfer within the DNS concept were developed by the Lanzhou Group [?]. The production cross sections of superheavy nuclei (SHN), quasi-fission, and fusion-fission dynamics have been extensively investigated within the dynamical DNS model. The dynamical evolution of the colliding system sequentially proceeds through the capture process by overcoming the Coulomb barrier to form the DNS, the relaxation process of relative motion energy, angular momentum, mass, charge asymmetry, etc., within the potential energy surface, and the de-excitation of primary fragments [?]. The production cross section of MNT fragments was evaluated by

$$\sigma_{\mathrm{tr}}(Z_1, N_1, E_{\mathrm{c.m.}}) = \sigma_{\mathrm{cap}}(E_{\mathrm{c.m.}}, J) \int f(B) \sum_{J_{\max}} \times P(Z_1, N_1, J_1, B) \times W_{\mathrm{sur}}(E_1, J_1, s)\, dB.$$

Here $\sigma_{\mathrm{cap}}(E_{\mathrm{c.m.}}, J)$ represents the cross sections for DNS formation derived from the Hill-Wheeler formula with a barrier distribution function [?], while $W_{\mathrm{sur}}(E_1, J_1, s)$ denotes the survival probability of fragment formation in the MNT process. The symbol s stands for decay channels for fragments (Z_1, N_1), such as neutron, proton, deuteron, alpha, gamma rays, etc. $E_{\mathrm{c.m.}}$ is the incident energy in the center-of-mass frame. The maximum angular momentum $J_{\max}$ was calculated at the grazing configuration for the colliding system, with angular momentum J taken at the initial colliding configuration before dissipation. E_1 and J_1 represent the excitation energy and angular momentum for the fragment with proton number Z_1 and neutron number N_1 in the DNS model, respectively. $P(Z_1, N_1, J_1, B)$ is the formation probability of fragments (Z_1, N_1). For the barrier distribution function, we adopt an asymmetric Gaussian form [?]:

$$f(B) = \exp\left[-\frac{(B - B_m)^2}{2\Delta^2}\right].$$

The quantities Δ and B_m were evaluated by $\Delta = (B_t + B_s)/2$ and $B_m = (B_t + B_s)/2$, where B_t and B_s represent the height of the Coulomb barrier and the minimum point of deformation under tip-tip collision, respectively. The normalization constant satisfies $\int f(B)\, dB = 1$.

In the DNS model, the solution for nucleon transfer and relative motion is carried out through a set of microscopic derivations, with master equations distinguishing protons and neutrons. The fragment distribution probability $P(Z_1, N_1, E_1)$, representing the proton number Z_1, neutron number N_1, and excitation energy E_1 for DNS fragment 1, is described by the following master equation:

$$\frac{dP(Z_1, N_1, E_1, \beta, t)}{dt} = \sum_{Z_1', N_1', \beta'} W_{Z_1, N_1, \beta; Z_1', N_1', \beta'}(t) \left[d_{Z_1', N_1'} P(Z_1', N_1', E_1', \beta', t) - d_{Z_1, N_1} P(Z_1, N_1, E_1, \beta, t)\right] - \Big[\Lambda$$

Here $W_{Z_1, N_1, \beta; Z_1', N_1', \beta'}$ is the mean transition probability from the channel (Z_1, N_1, E_1, β) to $(Z_1', N_1', E_1', \beta')$ [or (Z_1, N_1, E_1, β) to (Z_1, N_1', E_1', β)], 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 fragment (Z_1, N_1) may take, but 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 quasi-fission width Λ_{qf} and fission width Λ_{fis} are calculated using the Kramers formula [?, ?].

The excited DNS opens a valence space in which the valence nucleons have a symmetrical distribution around the Fermi surface. Only particles in states within the valence space are active for nucleon transfer. The transition probability is related to the local excitation energy and nucleon transfer, which is microscopically derived from the interaction potential in the valence space as described in [?, ?]:

$$W_{Z_1,N_1,\beta;Z_1',N_1',\beta'} = \frac{d_{Z_1,N_1} d_{Z_1',N_1'}}{\tau_{\mathrm{mem}}(Z_1,N_1,\beta,E_1;Z_1',N_1',\beta',E_1')} \sum_{i,i'} \left|\langle Z_1',N_1',E_1',i'|V|Z_1,N_1,E_1,i\rangle\right|^2 .$$

The neutron transition coefficient has the same formula. The relaxation time is calculated using the deflection function method [?]. Memory time τ_{mem} and interaction matrix elements V can be found in Ref. [?].

The motion of nucleons in the interacting potential is governed by the single-particle Hamiltonian [?, ?]:

$$H(t) = H_0(t) + V(t),$$

$$H_0(t) = \sum_{\nu,K} \varepsilon_{\nu K}(t) \alpha^+_{\nu K}(t) \alpha_{\nu K}(t),$$

$$V(t) = \sum_{\alpha K,\beta K'} u_{\alpha K,\beta K'}(t) \alpha^+_{\alpha K}(t) \alpha_{\beta K'}(t) = \sum_{\alpha K,\beta K'} V_{K,K'}(t).$$

Here the indices K, K' ($K, K' = 1, 2$) denote fragments 1 and 2. The quantities $\varepsilon_{\nu K}$ and $u_{\alpha K,\beta K'}$ represent the single-particle energies and interaction matrix elements, respectively. The single-particle states are defined with respect to the centers of the interacting nuclei and are assumed to be orthogonalized in the overlap region, making the annihilation and creation operators time-dependent. The single-particle matrix elements are parameterized by:

$$u_{\alpha K,\beta K'}(t) = \begin{cases} U_{K,K'}(t) & \text{if } |\varepsilon_{\alpha K}(t) - \varepsilon_{\beta K'}(t)| \leq \Delta_{K,K'}(t), \\ 0 & \text{otherwise.} \end{cases}$$

Detailed calculations of these parameters and mean transition probabilities are described in Refs. [?, ?]:

$$\Delta\varepsilon_K = \sqrt{\frac{\varepsilon_K^*}{g_K}}, \quad g_K = \frac{A_K}{12},$$

where ε_K^* is the local excitation energy of the DNS. The microscopic dimension for fragment (Z_K, N_K) is evaluated by the valence states $N_K = g_K \Delta\varepsilon_K$ and the valence nucleons $m_K = N_K/2$ $(K = 1, 2)$ as:

$$d(m_1, m_2) = \binom{N_1}{m_1}\binom{N_2}{m_2}.$$

The local excitation energy E_1 was derived from the dissipation energy coupled to the potential energy surface (PES) of the relative motion of the DNS. In the equilibrium stage, the excitation energy is shared by the fragments according to their masses. The angular momentum of the main fragment is determined by the moment of inertia. The local excitation energy is evaluated by [**?**, **?**]:

$$\varepsilon^*(t) = E_{\text{diss}}(t) - \left(U(\{\alpha\}) - U(\{\alpha_{\text{EN}}\})\right).$$

The entrance channel quantities $\{\alpha_{\text{EN}}\}$ include the proton and neutron numbers, quadrupole deformation parameters, and orientation angles for projectile and target nuclei, denoted by $Z_P, N_P, Z_T, N_T, R, \beta_P, \beta_T, \theta_P, \theta_T$, respectively. The interaction time τ_{int} is obtained from the deflection function method [**?**]. The energy dissipated into the DNS increases exponentially. The potential energy surface (PES) of the DNS is evaluated by:

$$U_{\text{dr}}(t) = Q_{gg} + V_C(Z_1, N_1; \beta_1, Z_2, N_2, \beta_2, t) + V_N(Z_1, N_1, \beta_1; Z_2, N_2, \beta_2, t) + V_{\text{def}}(t),$$

$$V_{\text{def}}(t) = C_1(\beta_1 - \beta_T'(t))^2 + C_2(\beta_2 - \beta_P'(t))^2,$$

$$C_i = \frac{(\lambda-1)(\lambda+2)R_N^2}{4\pi}\frac{Z^2e^2}{A},$$

where Q_{gg} is derived from the negative binding energies of fragments (Z_i, N_i) calculated by the liquid drop model plus shell correction [**?**]. The θ_i denote the angles between collision orientations and symmetry axes of deformed nuclei. V_C and V_N are calculated using the Wong formula [**?**] and double-folding potential [**?**], respectively. Quadrupole deformations of ground-state nuclei are taken from Ref. [**?**]. $V_{\text{def}}(t)$ represents the deformation energy of the DNS at reaction time t. The evolution of quadrupole deformations for projectile-like and target-like fragments from the initial configuration follows:

$$T(t) = \beta_T \exp(-t/\tau_\beta) + \beta_1[1-\exp(-t/\tau_\beta)], \quad P(t) = \beta_P \exp(-t/\tau_\beta) + \beta_2[1-\exp(-t/\tau_\beta)],$$

with the deformation relaxation time $\tau_\beta = 4 \times 10^{-21}$ s.

The total kinetic energy (TKE) of the primary fragment is evaluated by:

$$\mathrm{TKE} = E_{\mathrm{c.m.}} + Q_{gg} - E_{\mathrm{diss}},$$

where $Q_{gg} = M_P + M_T - M_{\mathrm{PLF}} - M_{\mathrm{TLF}}$, and $E_{\mathrm{c.m.}}$ is the incident energy in the center-of-mass frame. The masses M_P, M_T, M_{PLF}, and M_{TLF} correspond to the projectile, target, projectile-like fragment, and target-like fragment, respectively.

The survival probability $W_{\mathrm{sur}}(E_1, J_1, s)$ is particularly important in evaluating the cross section and is usually calculated with the statistical model. While the physical process of understanding the excited nucleus is clear, the magnitude of the survival probability strongly depends on ingredients in the statistical model such as the level density parameter [?], separation energy [?], shell correction [?], fission barrier [?, ?], etc. The excited fragments cool by evaporating γ-rays and light particles (neutrons, protons, α, etc.) in competition with fission [?]. The probability for the channel of evaporating the x-th neutron, y-th proton, and z-th alpha particle is expressed as:

$$W_{\mathrm{sur}}(E_1^*, x, y, z, J) = P(E_1^*, x, y, z, J) \prod_{i=1}^{x} \frac{\Gamma_n(E_i^*, J)}{\Gamma_{\mathrm{tot}}(E_i^*, J)} \prod_{j=1}^{y} \frac{\Gamma_p(E_j^*, J)}{\Gamma_{\mathrm{tot}}(E_j^*, J)} \prod_{k=1}^{z} \frac{\Gamma_\alpha(E_k^*, J)}{\Gamma_{\mathrm{tot}}(E_k^*, J)}.$$

Here E_1^* and J are the excitation energy evaluated from the mass table in Ref. [?] and the spin of the excited nucleus, respectively. The total width Γ_{tot} is the sum of partial widths for particle evaporation, γ-emission, and fission. The excitation energy E_s^* before evaporating the s-th particle is evaluated by:

$$E_{s+1}^* = E_s^* - B_n^i - B_p^j - B_\alpha^k - 2T_s,$$

with the initial condition E_1^* and $s = i+j+k$. The B_n^i, B_p^j, and B_α^k are separation energies for the i-th neutron, j-th proton, and k-th alpha particle, respectively. The nuclear temperature T_i is given by $E_i^* = aT_i^2$ with a being the level density parameter. The fission width and particle decay width are calculated using the Weisskopf evaporation theory and the Bohr-Wheeler formula, respectively. The realization probability $P(E_1^*, x, y, z, J)$ is calculated using the Jackson formula [?].

III. Results and Discussion

We calculated the production cross sections of actinide isotope chains with atomic numbers $Z = 93 - 100$ in collisions of ^{132,136}Xe + ^{248}Cm at incident energy $E_{\mathrm{lab}} = 699 - 790$ MeV, as shown in Fig. 1 [Figure 1: see original paper]. Compared to available experimental data for ^{129,132,136}Xe + ^{248}Cm [**?**, **?**], our calculations for ^{136}Xe + ^{248}Cm (solid black lines) and ^{132}Xe + ^{248}Cm (dashed red lines) basically reproduce the tendency of cross-section distributions for actinide isotopic chains. The experimental data show that reactions induced by ^{129,132,136}Xe isotopes with target ^{248}Cm produce actinide products with a large overlapping distribution area in the neutron-rich region, which is not as clearly distinguishable as expected. Our calculations based on the deep-inelastic mechanism indicate that relatively proton-rich projectiles like ^{132}Xe tend to shift toward the proton-rich region compared to experimental results. Target-like fragments exhibit production cross sections spanning from 100 millibarns to 10 nanobarns. Far from the target, the formation cross section of target-below products decreases more slowly than trans-target products, indicating that quasi-fission dominates these collisions relatively. It should be noted that the limitations of our calculation lie in the free-parameter model dependence for primary fragment cross sections and in the estimation of survival probability against fission.

To investigate the competition between Coulomb repulsive potential and shell effects in MNT reactions, we calculated reactions of isobaric projectiles with $A = 208$ bombarding targets ^{248}Cm and ^{232}Th at incident energy $E_{\mathrm{c.m.}} = 1.1 \times V_B$. The interaction potential between colliding partners combines Coulomb and nuclear potentials. In Fig. 2 Figure 2: see original paper, the interaction potential V_{CN} for ^{208}Pt + ^{248}Cm, ^{208}Hg + ^{248}Cm, ^{208}Pb + ^{248}Cm, ^{208}Po + ^{248}Cm, and ^{208}Rn + ^{248}Cm reactions are marked by solid black, dashed red, dash-dot blue, dash-dot-dot green, and short-dash olive lines, respectively. The V_{CN} distributions for these collisions show similar trends, with larger Coulomb potentials leading to larger interaction potentials. V_{CN} increases exponentially as the distance R decreases, rising slowly in the attraction region of the nuclear force where nucleon transfer occurs at the touching configuration. Based on the deflection function, the sticking time of colliding partners was calculated for all impact parameters [**?**], as shown in Fig. 2 Figure 2: see original paper, which decreases exponentially with increasing angular momentum. In these collisions, a relatively larger Coulomb potential causes a longer sticking time for a fixed impact parameter. During the sticking time, kinetic energy dissipates into the composite system, heating it with internal excitation energy that increases exponentially with reaction time and reaches equilibrium around 2×10^{-21} s, as shown in Fig. 2 Figure 2: see original paper.

After capture, the dissipating kinetic energy coupled to angular momentum in the DNS enables fragments to diffuse along the potential energy surface (PES), followed by nucleon rearrangement between the colliding partners, calculated by solving a set of master equations. PES and driving potential were calculated using Eq. (12), composed of Coulomb potential, binding energy, and nuclear potential, computed via the Wong formula, liquid-drop model plus shell correction, and double-folding method [?], respectively. The driving potential for projectiles ^{208}Hg, ^{208}Pb, and ^{208}Po on targets ^{248}Cm and ^{232}Th at tip-tip collision with fixed distance is plotted as a function of mass asymmetry $\eta = (A_T - A_P)/(A_T + A_P)$ in Figs. 3(a) and 3(e), represented by solid black, dashed red, and dash-dot blue lines, respectively. Open circles and open stars indicate projectile-target injection points. The driving potential trajectories for these collisions show similar trends, with two pockets appearing at $\eta = 0.2$ and $\eta = 0$ for target ^{248}Cm-based reactions, while one pocket appears at $\eta = 0.2$ for target ^{232}Th-based reactions. The neutron subshell number $N = 162$ might play a crucial role in pocket formation. For projectiles ^{208}Po far from the β^- stable line, their injection points are far from their driving potential trajectories, tending rapidly toward the driving potential trajectory when diffusion begins. Generally, based on PES, the spectral distribution trend of each isotope chain can be roughly predicted.

Production probabilities of primary fragments with excitation energies were derived by solving a set of master equations, classified by mass number and kinetic energy using Eq. (16), as illustrated in Fig. 4 [Figure 4: see original paper], where driving potential trajectories are added as solid grey lines. Two peaks in large kinetic regions are located around projectile-target injection points, and cross sections preferentially populate around pockets of driving potential trajectories. All reactions of ^{208}Hg, ^{208}Pb, and ^{208}Po induced with targets ^{248}Cm and ^{232}Th at incident energy $E_{\mathrm{c.m.}} = 1.1 \times V_B$ yield similar TKE-mass distributions with symmetric and broad shapes. The TKE-mass distribution spans a wide kinetic range of 500–800 MeV and mass region of 160–280, suggesting transfers of more than 30 nucleons.

Based on the statistical evaporation program, the survival probability of excited primary fragments has been calculated, yielding production cross sections for secondary fragments. Production cross sections of primary and secondary fragments as functions of mass number and charge number in collisions of ^{208}Hg, ^{208}Pb, and ^{208}Po induced reactions with target ^{248}Cm at $E_{\mathrm{c.m.}} = 1.1 \times V_B$ are listed in Figs. 5 Figure 5: see original paper–(f). Solid blue and dashed red lines indicate secondary and primary fragments, respectively, with the superheavy nuclei region covered by rectangular shadows. Primary fragments can cover very large charge regions, even accessing the superheavy region, while secondary fragments are strongly suppressed by de-excitation. Highly excited primary trans-target fragments with small fission barriers undergo fission easily. Predicted cross sections for superheavy nuclei with $Z = 104 - 116$ exceed 10 picobarns, where the neutron subshell $N = 162$ might play a crucial role, especially in the ^{208}Po + ^{248}Cm collision.

Calculated secondary production cross sections for actinide target-like fragments of Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, and Lr isotopes in collisions of projectiles ^{208}Pt, ^{208}Hg, ^{208}Pb, ^{208}Po, ^{208}Rn, ^{208}Ra bombarding target ^{248}Cm at $E_{\text{c.m.}} = 1.1 \times V_B$ are illustrated in Fig. 6 [Figure 6: see original paper], corresponding to solid black, dashed red, dash-dot green, dash-dot-dot blue, and short-dash olive lines, respectively. Collisions with smaller Coulomb forces preferentially shift toward the neutron-rich region, while those with larger Coulomb forces tend toward neutron-deficient areas. Massive unknown actinide isotopes have been predicted by all reactions ^{208}Pt+^{248}Cm, ^{208}Hg+^{248}Cm, ^{208}Pb+^{248}Cm, ^{208}Po+^{248}Cm, ^{208}Rn+^{248}Cm, and ^{208}Ra+^{248}Cm, as listed in Table 1 . For new neutron-rich actinide isotopes, ^{208}Pt+^{248}Cm reactions preferentially produce the largest cross sections, though ^{208}Pt itself remains an unknown nucleus. Unknown actinide products are highly dependent on the Coulomb potential, with ^{208}Rn+^{248}Cm reactions favoring production of new neutron-deficient actinide isotopes with the largest cross sections. Open circles represent new neutron-rich actinide nuclides.

Figure 7 [Figure 7: see original paper] shows secondary production cross sections for formed fragments in collisions of ^{208}Os+^{248}Cm, ^{208}Pt+^{248}Cm, ^{208}Hg+^{248}Cm, ^{208}Pb+^{248}Cm, ^{208}Po+^{248}Cm, ^{208}Rn+^{248}Cm, ^{208}Ra+^{248}Cm and primary production cross sections for ^{208}Pb+^{248}Cm at incident energy $E_{\text{c.m.}} = 1.1 \times V_B$ in N-Z panels. Panels (g) and (h) clearly show the de-excitation effect. Panels (a)-(f) and (h) reveal that massive new isotopes have been predicted, including both neutron-rich and neutron-deficient isotopes, even extending to superheavy nuclei. Projectile-target injection points and all existing isotopes in the nuclide chart are represented by solid black-up triangles and open squares, respectively.

IV. Conclusion

Within the DNS model framework, we have systematically calculated production cross sections for MNT fragments in reactions of projectiles ^{208}Os, ^{208}Pt, ^{208}Hg, ^{208}Pb, ^{208}Po, ^{208}Rn, ^{208}Ra, and ^{132,136}Xe bombarding targets ^{232}Th and ^{248}Cm around Coulomb barrier energies. To investigate isospin diffusion in actinide product formation during the MNT process, we selected projectiles with the same mass number $A = 208$. Our calculations for ^{132,136}Xe + ^{248}Cm show nice consistency with available experimental data. The sticking time of colliding systems derived from deflection functions is highly dependent on the Coulomb force, particularly at small impact parameters. PES and TKE for these reactions are discussed, contributing to predicting cross-section diffusion tendencies. Relatively large cross sections appear around pockets in the PES, where the neutron subshell $N = 162$ is evident. The de-excitation process strongly suppresses primary cross sections for actinide isotopes by up to four orders of magnitude. Production cross sections for new actinides are highly dependent on the N/Z ratio of the isobaric projectile. We find that Coulomb force coupled with shell effects plays a crucial role in actinide product production cross sections in MNT reactions. Massive unknown heavy isotopes have been predicted with accessible cross-section values for these five colliding systems, even for superheavy nuclei with charge numbers $Z = 104 - 110$.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Peng-Hui Chen, Chang Geng, and Zu-Xing Yang. The first draft of the manuscript was written by Peng-Hui Chen, and all authors commented on previous versions. All authors read and approved the final manuscript.

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