

Dynamics of light nuclei produced in massive transfer reactions

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Abstract

Within the framework of the dinuclear system (DNS) model by implementing the cluster transfer into the dissipation process, we systematically investigated the energy spectra and the angular distribution of the preequilibrium clusters (n, p, d, t, ^3He , α , $^6,^7\text{Li}$, $^8,^9\text{Be}$) in the massive transfer reactions of $^{12}\text{C}+^{209}\text{Bi}$, $^{14}\text{N}+^{159}\text{Tb}$, $^{14}\text{N}+^{169}\text{Tm}$, $^{14}\text{N}+^{181}\text{Ta}$, $^{14}\text{N}+^{197}\text{Au}$, $^{14}\text{N}+^{209}\text{Bi}$, $^{58,64,72}\text{Ni}+^{198}\text{Pt}$ near the Coulomb barrier energies. It is found that the neutron emission is the most probable in comparison with the charged particles and the α yields are comparable with the hydrogen isotopes in magnitude. The preequilibrium clusters are mainly produced from the projectile-like and target-like fragments in the evolution of dinuclear system. The kinetic energy spectra manifest the Boltzmann distribution and the Coulomb potential influences the structure. The preequilibrium clusters follows the angular distribution of multinucleon transfer fragments.

Full Text

Preamble

Dynamics of Light Nuclei Produced in Massive Transfer Reactions

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Within the framework of the dinuclear system (DNS) model by implementing cluster transfer into the dissipation process, we systematically investigated the energy spectra and angular distributions of preequilibrium clusters (n, p, d, t,

^3He , α , $^6,^7\text{Li}$, $^8,^9\text{Be}$) in massive transfer reactions of $^{12}\text{C}+^{209}\text{Bi}$, $^{14}\text{N}+^{159}\text{Tb}$, $^{14}\text{N}+^{169}\text{Tm}$, $^{14}\text{N}+^{181}\text{Ta}$, $^{14}\text{N}+^{197}\text{Au}$, $^{14}\text{N}+^{209}\text{Bi}$, and $^{58,64,72}\text{Ni}+^{198}\text{Pt}$ near Coulomb barrier energies. It is found that neutron emission is the most probable compared with charged particles, and the α yields are comparable in magnitude with hydrogen isotopes. The preequilibrium clusters are mainly produced from projectile-like and target-like fragments during the evolution of the dinuclear system. The kinetic energy spectra manifest Boltzmann distributions, and the Coulomb potential influences the structure. The preequilibrium clusters follow the angular distribution of multinucleon transfer fragments.

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I. INTRODUCTION

The cluster structure in an atomic nucleus is a spatially localized subsystem consisting of strongly correlated nucleons with much greater internal binding energy than external binding energies, which can be treated as a whole without considering its internal structure [?]. In 1968, Ikeda proposed that nuclear cluster states tend to occur in excited states near the cluster threshold energy [?]. In some weakly bound nuclei, the cluster structure is more obvious, and cluster structure is also ubiquitous in light nuclei—for example, the configuration of ^6Li being composed of an α particle and a deuteron, the 2α structure for ^8Be , 3α for ^{12}C , and 5α for ^{20}Ne [?]. The most convenient way to study cluster structure inside a nucleus is to separate the cluster via pick-up or stripping reactions.

The theoretical explanation of preequilibrium reactions was initially developed through the exciton model. Semi-classical theories were less successful in explaining the angular distribution of emitted particles. The Boltzmann master equation theory was mainly used to calculate the energy spectra of particles emitted in nucleon-induced reactions and heavy-ion reactions; details can be found in the review Ref. [?] and its references. On the other hand, the emission of preequilibrium clusters in transfer reactions around the Coulomb barrier is also an important physical problem. The emission of preequilibrium clusters is a complex process, which is related not only to the cluster structure of the collision system but also to the dynamics of the reaction. In the treatment of nuclear structure, the cluster state is the overlap of single-particle wave functions. In a nuclear reaction, the formation of a preequilibrium particle is different from the cluster emitted during the de-excitation of a composite nucleus, and the preequilibrium cluster is formed before the formation of the compound nucleus. Its emission continues until the formation of the composite nucleus, and the preequilibrium cluster may be emitted from any fragments during the reaction. Cluster emission provides important information for the study of single-particle states or multiparticle correlations of nuclei and is a powerful tool for nuclear spectroscopy [?].

Since multinucleon transfer (MNT) reactions and deep inelastic heavy-ion collisions were proposed in the 1970s [?, ?, ?], numerous experiments have been carried out to measure the double differential cross sections, angular distributions, and energy distributions of different reaction systems. However, it is worth noting that there has been relatively little research on preequilibrium cluster emission in transfer reactions, both experimentally and theoretically. In the 1980s, scientists at RIKEN in Japan and at IMP in China measured the preequilibrium cluster emission from transfer reactions of $^{14}\text{N}+^{159}\text{Tb}$, ^{169}Tm , ^{181}Ta , ^{197}Au , ^{209}Bi [?] and $^{12}\text{C}+^{209}\text{Bi}$ [?, ?], respectively. The angular distributions, kinetic energy spectra, and total production cross sections of the emitted particles were measured in these experiments. As is well known, since the concept of the superheavy stable island was proposed in the 1960s, the synthesis of superheavy nuclei has become an important frontier in nuclear physics. In the past few decades, 15 kinds of superheavy elements with $Z = 104\text{--}118$ [?] have been synthesized artificially by hot fusion or cold fusion reactions. However, due to limitations of projectile-target materials and experimental conditions, the fusion-evaporation reaction is difficult to reach the next period of the periodic table. With MNT reactions, we can generate many nuclei depending on the transfer channels, and with the development of separation and detection technology, MNT reactions may be the most promising method to synthesize unknown superheavy elements. This mechanism has been applied to the production of heavy and superheavy isotopes [?, ?].

The study of preequilibrium cluster emission in MNT reactions is not only of great significance for understanding the cluster structure of the collision system but also for exploring the formation mechanism of clusters, the kinetic information of the reaction process, and nuclear astrophysical processes. The High Intensity Accelerator Facility (HIAF) built in Huizhou, China, has a large energy range and a wide variety of particle beams [?], which provides an excellent experimental platform for the study of nuclear cluster structures and cluster emission.

In this work, we have systematically investigated preequilibrium cluster emission in transfer reactions. The article is organized as follows. In Section II we give a brief description of the DNS model for describing preequilibrium cluster production. In Section III, the production cross sections, kinetic energy spectra, and angular distributions of the preequilibrium clusters are analyzed and discussed. Summary and perspectives are presented in Section IV.

II. BRIEF DESCRIPTION OF THE MODEL

The dinuclear system (DNS) model was first proposed by Volkov [?] to describe deep inelastic heavy-ion collisions. Adamian et al. applied the DNS model to fusion-evaporation reactions in competition with the quasifission process to study the synthesis of superheavy nuclei for the first time [?, ?, ?]. The Lanzhou nuclear physics group has further developed the DNS model [?, ?, ?, ?], e.g., introducing the barrier distribution function method in the capture process,

considering the effects of quasifission and fission in the fusion stage, and using statistical evaporation theory and the Bohr-Wheeler formula to calculate the survival probability of superheavy nuclei. The DNS model has been widely used to study production cross sections, quasifission, fusion dynamics, etc., in the synthesis of superheavy nuclei based on fusion-evaporation (FE) reactions and MNT reactions [?, ?, ?].

With the DNS model, we have calculated the temporal evolution, kinetic energy spectra, and angular distributions of preequilibrium clusters in transfer reactions with incident energies near the Coulomb barrier. Compared to our previous work [?], we have introduced cluster transfer into the master equation of the DNS model, and the Coulomb force is considered in the preequilibrium cluster emission process. The preequilibrium particle is formed before compound nucleus formation, and its emission continues until the composite nucleus is formed. The cross section of preequilibrium particle emission ($\nu = n, p, d, t, {}^3\text{He}, \alpha, {}^6\text{Li}$ and ${}^8, {}^9\text{Be}$) is defined as

$$\sigma_\nu(E_k, \theta, t) = \sum_{J=0}^{J_{\max}} \sum_{Z_1=Z_\nu}^{Z_{\max}} \sum_{N_1=N_\nu}^{N_{\max}} (2J+1) \int f(B) \times T(E_{c.m.}, J, B) P(Z_1, N_1, E_1(E_{c.m.}, J), t, B) \times P_\nu(Z_\nu, N_\nu, E_k) dB.$$

Here, E_k and θ are the kinetic energy and emission angle of the particles when they are ejected from the projectile-like or target-like fragments, t is the time of the reaction process. The reduced de Broglie wavelength $\lambda = \hbar/\sqrt{2\mu E_{c.m.}}$, and $P(Z_1, N_1, E_1(E_{c.m.}, J), t, B)$ denotes the realization probability of the DNS fragment (Z_1, N_1) . $P_\nu(Z_\nu, N_\nu, E_k)$ is the emission probability of the preequilibrium particles. E_1 is the excitation energy for the fragment (Z_1, N_1) , which is associated with the center-of-mass energy $E_{c.m.}$ and incident angular momentum J . The maximal angular momentum $J_{\max}$ is taken to be the grazing collision of two colliding nuclei. The DNS fragments (Z_1, N_1) range from the light one (Z_ν, N_ν) to the composite system $(Z_{\max}, N_{\max})$, with $Z_{\max} = Z_T + Z_P$ and $N_{\max} = N_T + N_P$ being the total proton and neutron numbers, respectively.

2.1 The Capture Cross Section of Binary System Overcoming the Coulomb Barrier

In the capture stage, the collision system overcomes the Coulomb barrier to form a composite system. The capture cross section is given by

$$\sigma_{\text{cap}}(E_{c.m.}) = \pi\lambda^2 \sum_{J=0}^{J_{\max}} (2J+1) \int f(B) T(E_{c.m.}, J, B) dB,$$

where $T(E_{c.m.}, J, B)$ is the penetration probability for overcoming the barrier B .

For light and medium systems, $T(E_{c.m.}, J, B)$ is calculated by the well-known Hill-Wheeler formula [?]:

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

with $\hbar\omega(J)$ being the width of the parabolic barrier at $R_B(J)$. Due to the effect of multidimensional quantum penetration, the Coulomb barrier exhibits a distribution. By introducing a barrier distribution function based on the original Hill-Wheeler formula [?], the penetration probability can be written as

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

with $\hbar\omega(J)$ being the width of the parabolic barrier at $R_B(J)$.

For heavy systems, the collision system does not form a potential energy pocket after overcoming the Coulomb barrier, so $T(E_{c.m.}, J)$ is calculated by the classical trajectory method:

$$T(E_{c.m.}, J) = \begin{cases} 0, & E_{c.m.} < B + \frac{J(J+1)\hbar^2}{2\mu R_C^2} \\ 1, & E_{c.m.} > B + \frac{J(J+1)\hbar^2}{2\mu R_C^2} \end{cases}$$

The reduced mass is $\mu = m_n A_P A_T / (A_P + A_T)$ with m_n , A_P and A_T being the nucleon mass and the mass numbers of projectile and target nuclei, respectively. R_C denotes the Coulomb radius, and $R_C = r_{0c} \times (A_T^{1/3} + A_P^{1/3})$ with $r_{0c} = 1.4 \sim 1.5$ fm.

The barrier distribution function is of Gaussian form [?, ?]:

$$f(B) = \frac{1}{\sqrt{\pi}\Delta} \exp \left[- \left(\frac{B - B_m}{\Delta} \right)^2 \right].$$

The normalization constant satisfies $\int f(B) dB = 1$. The quantities B_m and Δ are evaluated by $B_m = (B_C + B_S)/2$ and $\Delta = (B_C - B_S)/2$, respectively. B_C is the Coulomb barrier at waist-to-waist orientation and B_S is the minimum barrier by varying the quadrupole deformation of the colliding partners. Here we take B_S as the Coulomb barrier at tip-to-tip orientation.

2.2 The Nucleon and Cluster Transfer Dynamics

In the nucleon transfer process, the distribution probability of DNS fragments is obtained by numerically solving a set of master equations [?]. A fragment (Z_1, N_1) has proton number Z_1 , neutron number N_1 , internal excitation energy E_1 , and quadrupole deformation β_1 . The time evolution equation of its distribution probability can be described as

$$\frac{dP(Z_1, N_1, E_1, \beta_1, B, t)}{dt} = \sum_{Z'_1, N'_1, \beta'_1} \left[W_{Z'_1, N'_1, \beta'_1; Z_1, N_1, \beta_1}(t) \times d_{Z'_1, N'_1} P(Z'_1, N'_1, E'_1, \beta'_1, B, t) - W_{Z_1, N_1, \beta_1; Z'_1, N'_1, \beta'_1}(t) \right]$$

In the equation, $W_{Z'_1, N'_1, \beta'_1; Z_1, N_1, \beta_1}$ is the mean transition probability from the channel (Z_1, N_1, E_1, β_1) to $(Z'_1, N'_1, E'_1, \beta'_1)$. The quantity $d_{Z'_1, N'_1}$ indicates the microscopic dimension corresponding to the macroscopic state $(Z'_1, N'_1, E'_1, \beta'_1)$. In this process, the transfer of nucleons or clusters satisfies the relationships $Z'_1 = Z_1 \pm N_\nu$ and $N'_1 = N_1 \pm N_\nu$, each representing the transfer of a neutron, proton, deuteron, tritium, ^3He , or α particle. Note that we ignored the quasifission of DNS and the fission of heavy fragments in the dissipation process. The initial probabilities of projectile and target nuclei are set to be $P(Z_{\text{proj}}, N_{\text{proj}}, E_1 = 0, t = 0) = P(Z_{\text{targ}}, N_{\text{targ}}, E_1 = 0, t = 0) = 0.5$. The nucleon transfer process satisfies the unitary condition $\sum_{Z_1, N_1} P(Z_1, N_1, E_1, t) = 1$.

Similar to the cascade transfer of nucleons [?], the transfer of clusters is also described by the single-particle Hamiltonian $H(t) = H_0(t) + V(t)$. Single-particle states are defined with respect to the centers of the interacting nuclei and are assumed to be orthogonalized in the overlap region. Thus, the annihilation and creation operators depend on the reaction time. The total single-particle energy is $H_0(t) = \sum_{\nu K} \varepsilon_{\nu K}(t) \alpha_{\nu K}^+(t) \alpha_{\nu K}(t)$. The interaction potential is $V(t) = \sum_{\nu K; \nu' K'} u_{\nu K; \nu' K'}(t) \alpha_{\nu K}^+(t) \alpha_{\nu' K'}(t) V_{K; K'}(t)$.

The cluster formation probability is related to the cluster structure, cluster potential, cluster binding energy, Mott effect, etc. More improvements are still needed in future work. The memory time is connected with the internal excitation energy [?]. The quantity $\varepsilon_{\nu K}$ represents the single-particle energies, and $u_{\nu K; \nu' K'}$ is the interaction matrix elements, parameterized in the following form:

$$u_{\nu K; \nu' K'} = \frac{U_{K; K'}(t)}{\varepsilon_{\nu K}(t) - \varepsilon_{\nu' K'}(t)} \Delta_{K; K'}(t) - \delta_{\nu K; \nu' K'}.$$

The calculation of $U_{K; K'}(t)$ and $\delta_{\nu K; \nu' K'}(t)$ has been described in Ref. [?].

In the relaxation process of the relative motion, the DNS will be excited by the dissipation of relative kinetic energy and angular momentum. 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 actively excited and undergo transfer. The averages on these quantities are performed in the valence space as follows:

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

where the symbol ε^* is the local excitation energy of the DNS fragments, which provides the excitation energy for the mean transition probability. The number of valence states in the valence space is $N_K = g_K \Delta\varepsilon_K$, where g_K is the single-particle level density around the Fermi surface. The number of valence nucleons is $m_K = N_K/2$. The microscopic dimension for the fragment (Z_K, N_K) is evaluated as

$$d(m_1, m_2) = \frac{(m_1 + m_2)!}{m_1! m_2!}.$$

The mean transition probability is related to the local excitation energy and the transfer of nucleons or clusters, and it can be microscopically derived from the interaction potential in valence space as

$$W_{Z_1, N_1; Z'_1, N'_1}^\nu = \frac{G_\nu}{\tau_{\text{mem}}(Z_1, N_1, E_1; Z'_1, N'_1, E'_1)} \frac{|\langle Z'_1, N'_1, E'_1, i' | V | Z_1, N_1, E_1, i \rangle|^2}{d_{Z_1, N_1} d_{Z'_1, N'_1}}.$$

G_ν represents the spin-isospin statistical factors, and we use the Wigner density approach to identify particle types [?, ?], i.e., $G_\nu = 1, 1, 3/8, 1/12, 1/12, 1/96$ for neutron, proton, deuteron, tritium, ^3He , and α , respectively. It is noted that the cluster transition probability is related to $\tau_{\text{mem}}(Z_1, N_1, E_1; Z'_1, N'_1, E'_1)$. The interaction matrix elements are calculated by

$$|V_{ii'}|^2 = \omega_{11}(i_1, i'_1) + \omega_{22}(i_1, i'_1) + \omega_{12}(i_1, i'_1) + \omega_{21}(i_1, i'_1) + \sum_{KK'} \langle V_{KK'}, V_{KK'}^* \rangle,$$

in which $\omega_{KK'}(i, i') = d_{Z_1, N_1} \langle V_{KK'}, V_{KK'}^* \rangle$, with the states $i(Z_1, N_1, E_1)$ and $i'(Z'_1, N'_1, E'_1)$.

In the relaxation process of the relative motion, the DNS will be excited by the dissipation of relative kinetic energy. The local excitation energy is determined by the dissipated energy from the relative motion and the potential energy surface of the DNS [?, ?]:

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

where $\alpha_{EN} = \{Z_P, N_P, Z_T, N_T, J, R, \beta_P, \beta_T, \theta_P, \theta_T\}$ for the projectile-target system. The excitation energy of the DNS fragment (Z_1, N_1) is $E_1 = \varepsilon^*(t = \tau_{\text{int}})A_1/A$. τ_{int} denotes the interaction time, which is associated with the reaction system and the relative angular momentum, and can be obtained from the deflection function [?]. The energy dissipated into the DNS is

$$E_{\text{diss}}(t) = E_{c.m.} - B - \frac{\langle J(t) \rangle (\langle J(t) \rangle + 1) \hbar^2}{2\zeta_{\text{rel}}} - \langle E_{\text{rad}}(J, t) \rangle.$$

The radial energy is $\langle E_{\text{rad}}(J, t) \rangle = E_{\text{rad}}(J, 0) \exp(-t/\tau_r)$, with the relaxation time of radial motion being $\tau_r = 5 \times 10^{-22}$ s and the initial radial energy being $E_{\text{rad}}(J, 0) = E_{c.m.} - B - J_i(J_i + 1)\hbar^2/(2\zeta_{\text{rel}})$. The dissipation of relative angular momentum is described by

$$\langle J(t) \rangle = J_{\text{st}} + (J_i - J_{\text{st}}) \exp(-t/\tau_J),$$

where the angular momentum at the sticking limit is $J_{\text{st}} = J_i \zeta_{\text{rel}}/\zeta_{\text{tot}}$ and the relaxation time $\tau_J = 15 \times 10^{-22}$ s. The ζ_{rel} and ζ_{tot} are the relative and total moments of inertia of the DNS, respectively. The initial angular momentum is set to be $J_i = J$ in Eq. (1). The relaxation times of radial kinetic energy and angular momentum are associated with the friction coefficients in binary collisions. The values in this work are taken from empirical analysis of deeply inelastic heavy-ion collisions [?, ?].

The potential energy surface (PES) of the DNS is evaluated as

$$U(\{\alpha\}) = B(Z_1, N_1) + B(Z_2, N_2) - B(Z, N) + V(\{\alpha\}),$$

with the relationship $Z_1 + Z_2 = Z$ and $N_1 + N_2 = N$ [?, ?]. The symbol $\{\alpha\}$ denotes the quantities $\{Z_1, N_1, Z_2, N_2, J, R, \beta_1, \beta_2, \theta_1, \theta_2\}$. In the calculation, the distance R between the centers of the two fragments is chosen to be the value at the touching configuration, in which the DNS is assumed to be formed, and $R = r_0 \times (A_T^{1/3} + A_P^{1/3})$ with $r_0 = 1.2 \sim 1.3$ fm.

The $B(Z_i, N_i)$ ($i = 1, 2$) and $B(Z, N)$ are the negative binding energies of the fragment (Z_i, N_i) and the compound nucleus (Z, N) , respectively. The β_i represent the quadrupole deformations of the two fragments at ground state, and θ_i ($i = 1, 2$) denote the angles between the collision orientations and the symmetry axes of deformed nuclei. The interaction potential between fragment (Z_1, N_1) and (Z_2, N_2) is derived from

$$V(\{\alpha\}) = V_C(\{\alpha\}) + V_N(\{\alpha\}) + V_{\text{def}}(t),$$

where V_C is the Coulomb potential using the Wong formula [?], V_N is the nucleus-nucleus potential using the double folding potential [?], and $V_{\text{def}}(t)$ denotes the deformation energy of the DNS at reaction time t :

$$V_{\text{def}}(t) = C_1(\beta_1 - \beta_T(t))^2 + C_2(\beta_2 - \beta_P(t))^2.$$

The quantities C_i ($i = 1, 2$) denote the stiffness parameters of the nuclear surface, which are calculated by the liquid drop model [?]. Detailed calculations of $V_{\text{def}}(t)$ can be obtained from Ref. [?] and the references therein.

Shown in Fig. 1 [Figure 1: see original paper] is the PES in collisions of $^{14}\text{N} + ^{209}\text{Bi}$ and $^{64}\text{Ni} + ^{198}\text{Pt}$. The zigzag lines are the driving potentials, which are estimated by the minimal PES values in the process of transferring nucleons. The incident point is denoted by the star symbol.

2.3 The Preequilibrium Cluster Emission

The emission probabilities of preequilibrium clusters with kinetic energy E_k are calculated by the uncertainty principle within the time step $t \sim t + \Delta t$ via

$$P_\nu(Z_\nu, N_\nu, E_k) = \frac{\Delta t \Gamma_\nu}{\hbar}.$$

Based on the Weisskopf evaporation theory [?, ?], we have the particle decay widths as follows:

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

with s_ν , m_ν , and B_ν being the spin, mass, and binding energy of the evaporating particles, respectively.

The inverse cross section is given by $\sigma_{\text{inv}} = \pi R_\nu^2 T(\nu)$, with the radius $R_\nu = 1.21(A - A_\nu)^{1/3} + A_\nu^{1/3}$. The penetration probability is set to be $T(\nu) = 1$ for neutrons and $T(\nu) = [1 + \exp(2\pi(V_C(\nu) - \varepsilon)/\hbar\omega)]^{-1}$ for charged particles with $\hbar\omega = 5$ MeV and 8 MeV for hydrogen isotopes and other charged particles, respectively.

It should be mentioned that local equilibrium of the DNS is assumed to be formed and the excitation energy for the i -th fragment is associated with the local excitation energy with the mass table [?]. The level density is calculated from the Fermi-gas model as

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

with $\sigma^2 = 6\bar{m}^2 A/\pi^2$ and $\bar{m} \approx 0.24A^{2/3}$. The pairing correction energy δ is set to be 0, Δ , and 2Δ for even-even, even-odd, and odd-odd nuclei, respectively, where $\Delta = 12/\sqrt{A}$. The level density parameter is related to the shell correction energy $E_{\text{sh}}(Z, N)$ and the excitation energy E^* of the nucleus as

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

The asymptotic Fermi-gas value of the level density parameter at high excitation energy is $\tilde{a}(A) = \alpha A + \beta A^{2/3} b_s$, and the shell damping factor is given by $f(E^*) = 1 - \exp(-\gamma E^*)$ with $\gamma = \tilde{a}/(\epsilon A^{4/3})$. The parameters α , β , b_s , and ϵ are taken to be 0.114, 0.098, 1, and 0.4, respectively [?, ?].

The kinetic energy of the preequilibrium particle is sampled by the Monte Carlo method within the energy range $\varepsilon_\nu \in (0, E^* - B_\nu - E_{\text{rot}} - V_C)$ and $E_k = \varepsilon_\nu + V_C$. Here, V_C represents the Coulomb force that the outgoing particles need to overcome, and for neutrons, $V_C = 0$.

The Watt spectrum is used for neutron emission [?] and expressed as

$$\frac{dN_n}{d\varepsilon_n} = C_n \exp\left(-\frac{\varepsilon_n}{T_w}\right) \sinh\left(\sqrt{2\varepsilon_n/T_w}\right) T_w^{-3/2},$$

with $T_w = 1.7 \pm 0.1$ MeV and normalization constant C_n .

For charged particles, the Boltzmann distribution is taken into account as

$$\frac{dN_\nu}{d\varepsilon_\nu} = \frac{8\pi\varepsilon_\nu m_\nu}{(2\pi T_\nu)^{3/2}} \exp\left(-\frac{\varepsilon_\nu}{T_\nu}\right),$$

with the mass m_ν and local temperature $T_\nu = \sqrt{E^*/a}$, where $a = A/8$ is the level density parameter.

The parameters δ and β are parameterized by fitting the deep inelastic scattering in massive collisions as

$$\delta = \begin{cases} 0.07f(\eta) + 0.11, & \eta < 375 \\ 0.117 \exp(-1.34 \times 10^{-4}\eta), & \eta \geq 375 \end{cases}, \quad \beta = \begin{cases} 75f(\eta) + 15, & \eta < 375 \\ 36 \exp(-2.17 \times 10^{-3}\eta), & \eta \geq 375 \end{cases},$$

with $f(\eta) = [1 + \exp(\eta - 235)]^{-1}$. The quantity $\eta = Z_1 Z_2 e^2 / \hbar v$ is the Sommerfeld parameter, and the relative velocity is calculated by $v = \sqrt{2(E_{c.m.} - V(R_{\text{int}})) / \mu}$.

We use the deflection function method [?, ?] to calculate the angular distribution of preequilibrium particles emitted from DNS fragments as

$$\Theta(J_i) = \Theta_C(J_i) + \Theta_N(J_i).$$

The Coulomb deflection is given by the Rutherford function as

$$\Theta_C(J_i) = 2 \arctan \left(\frac{Z_p Z_t e^2}{2 E_{c.m.} b} \right),$$

with the incident energy $E_{c.m.}$ and impact parameter b . The nuclear deflection is calculated by

$$\Theta_N(J_i) = -\beta \Theta_C^{\text{gr}}(J_i) \frac{J_i}{J_{\text{gr}}},$$

where $\Theta_C^{\text{gr}}(J_i)$ is the Coulomb scattering angle at the grazing angular momentum $J_{\text{gr}} = 0.22 R_{\text{int}} \sqrt{A_{\text{red}}(E_{c.m.} - V(R_{\text{int}}))}$. The quantity J_i is the incident angular momentum, A_{red} is the reduced mass of the collision system, and $V(R_{\text{int}})$ denotes the interaction potential with R_{int} being the Coulomb radius. For the i -th DNS fragment, the emission angle is determined by

$$\Theta_i(J_i) = \Theta(J_i) (\xi_1 + \xi_2),$$

with the moment of inertia ξ_i for the i -th fragment.

III. RESULTS AND DISCUSSION

Preequilibrium cluster emission in transfer reactions is very complicated, being related not only to the structure of the collision system (e.g., formation factor) but also to the dynamic evolution of the reaction process, i.e., the dissipation of relative motion and the coupling of internal degrees of freedom. The emission of preequilibrium clusters is a non-equilibrium process of time and space evolution, which serves as a powerful probe for deeply investigating MNT reaction dynamics.

The temporal evolution of the emission probability of n, p, d, t, ^3He , and α from the transfer reactions of $^{14}\text{N} + ^{159}\text{Tb}$, ^{169}Tm , ^{181}Ta , and ^{197}Au at $E_{\text{lab}} = 115$ MeV is shown in Fig. 2 [Figure 2: see original paper] and Fig. 3 [Figure 3: see original paper], respectively. It is noted that compound nucleus formation occurs on the order of a few hundred zeptoseconds, while the reaction time of the preequilibrium process is about several zeptoseconds. The figures show that preequilibrium cluster emission continues until the formation of the composite nucleus. At the beginning of the reaction, the emission probability of preequilibrium clusters increases rapidly, reaching a maximum value at about $20\text{--}40 \times 10^{-22}$ s, and then remaining stable or decreasing gradually. The emission probabilities of α and hydrogen isotopes are comparable, and their yields are

about 3–4 orders of magnitude lower than that of neutrons but much larger than that of ^3He . The local excitation energy of DNS fragments increases with time, and the emitted clusters can carry away part of the energy, which is conducive to the formation of compound nuclei with lower excitation energy. The total emission cross sections of preequilibrium clusters can be obtained by counting the temporal evolution of cluster yields. The total emission cross sections of different preequilibrium particles are shown in Table I. It is obvious that the α yields are comparable with proton emission.

Shown in Fig. 4 [Figure 4: see original paper] are the kinetic energy spectra of light nuclei produced in the transfer reactions of $^{14}\text{N} + ^{159}\text{Tb}$, ^{169}Tm , and ^{181}Ta at $E_{\text{lab}} = 115$ MeV. The kinetic energy spectra of different reactions show similar shapes, presenting Boltzmann distributions. Neutron emission is the most important. Compared with previous work [?], we have introduced Coulomb barrier corrections in this work. Hydrogen isotopes have similar emission probabilities due to having the same amount of charge, and the peak of their kinetic energy spectrum is about 10 MeV. Since α and ^3He are more highly charged, their kinetic energy spectra shift toward higher energies (i.e., move to the right in the figure). Additionally, Fig. 4 shows that the emission probability of α is about three to five orders of magnitude higher than that of ^3He , because the former has lower separation energy and is more easily emitted from DNS fragments. These calculation results are consistent with experimental data [?, ?].

In Fig. 5 [Figure 5: see original paper], we exhibit the kinetic energy spectra of preequilibrium clusters (n, p, d, t, ^3He , α , ^6Li , ^8Be) in transfer reactions induced by ^{12}C and ^{14}N on the same target nucleus ^{209}Bi . The kinetic energy spectra of these preequilibrium particles in transfer reactions show nuclear structure effects and dynamic characteristics of nuclear reactions. The available experimental data for α emission from HIRFL for the massive transfer reaction $^{12}\text{C} + ^{209}\text{Bi}$ [?] and from RIKEN for $^{14}\text{N} + ^{209}\text{Bi}$ [?] are nicely reproduced with the DNS model. The excitation energy of DNS fragments, transition probability, binding energy, and separation energy of transferred nucleons (clusters) affect the kinetic energy spectra. The emission cross section of preequilibrium clusters is mainly related to their formation probability and emission probability. In our calculation, it is assumed that clusters already exist in the DNS, so the emission cross sections of different clusters are mainly determined by the emission probabilities. The higher the charge of the emitted particle, the higher the Coulomb barrier. On the other hand, the larger the separation energy of the cluster, the smaller the decay width and the lower the emission probability. The kinetic energy spectra of clusters are strongly related to the Coulomb barriers and excitation energies of the composite system.

The emission of preequilibrium clusters depends not only on the reaction system but also on the incident energy. Shown in Fig. 6 [Figure 6: see original paper] is the comparison of the time evolution and kinetic energy distribution for the transfer reaction $^{58}\text{Ni} + ^{198}\text{Pt}$ at different incident energies of 220 MeV and 240

MeV. The left part of the figure shows the temporal evolution, and the right part shows the kinetic energy spectra of preequilibrium particles. The kinetic energy of preequilibrium clusters is mainly determined by the local excitation energy of projectile-like and target-like fragments, and high local excitation energy is beneficial for cluster emission. The emission probability at $E_{c.m.} = 240$ MeV is about 2–3 orders of magnitude higher than at $E_{c.m.} = 220$ MeV, indicating that the emission probability of preequilibrium clusters increases with incident energy. In Fig. 7 [Figure 7: see original paper], we compare transfer reactions bombarding the target nucleus ^{198}Pt with heavier Ni isotopes at $E_{c.m.} = 240$ MeV; the left panel shows the kinetic energy spectra of preequilibrium clusters emitted in the $^{64}\text{Ni}+^{198}\text{Pt}$ reaction, and the right panel shows the reaction of $^{72}\text{Ni}+^{198}\text{Pt}$. It can be found that compared to the $^{64}\text{Ni}+^{198}\text{Pt}$ system, the reaction induced by ^{72}Ni seems more likely to emit neutrons, while the former is more likely to emit protons. In both reaction systems, the peak of the kinetic energy spectra for proton isotopes is about 9 MeV, while the peak of the α kinetic energy spectra is about 17 MeV.

Particles emitted in the preequilibrium process and from the compound nucleus have different kinetic energy and angular distributions [?]. Direct particles primarily emit in the same direction as incident particles and have similar energies, while particles from the compound process emit isotropically in equal amounts forward and backward. Preequilibrium particles tend to be emitted forward and are generally more energetic than those from the composite nucleus. Shown in Fig. 8 [Figure 8: see original paper] are the angular distributions of emitted preequilibrium clusters in $^{58,64,72}\text{Ni}+^{198}\text{Pt}$ at $E_{c.m.} = 240$ MeV. The angular distribution differs for different reaction systems. For the same reaction system, the shape of the angular distributions of different clusters is quite similar, because different clusters may be evaporated from the same excited DNS fragment. The figure also shows that the angular distributions of preequilibrium particles are anisotropic, and their shape exhibits similar characteristics to the angular distributions of fragments in multinucleon transfer reactions [?, ?]. In the program calculation, we ignored values where the output was less than $1\text{E-}10$. Under the three reaction systems, the angular distributions of particles increase rapidly when the center-of-mass angle is about 26° , reaching maximum values between 32° and 36° . There exhibits a window of $32^\circ\text{--}160^\circ$ for preequilibrium neutron emission. The study of angular distributions of preequilibrium clusters in transfer reactions is of great significance for investigating the angular distributions of primary fragments in MNT reactions and is helpful for the management of experimental measurements.

IV. CONCLUSIONS

In summary, within the framework of the DNS model, we have investigated the emission mechanism of preequilibrium clusters in massive transfer reactions near Coulomb barrier energies, i.e., the temporal evolution, kinetic energy spectra, and angular distributions of n, p, d, t, ^3He , α , ^6Li , ^7Li , and $^8,^9\text{Be}$ in collisions of

$^{12}\text{C}+^{209}\text{Bi}$, $^{14}\text{N}+^{159}\text{Tb}$, ^{169}Tm , ^{181}Ta , ^{197}Au , ^{209}Bi , and $^{58,64,72}\text{Ni}+^{198}\text{Pt}$. The cluster transfer and dynamic deformation are coupled to the relative dissipation of angular momentum and kinetic energy in the DNS model. The emission of preequilibrium clusters strongly depends on the incident energy, the separation energy, and the Coulomb barrier from the primordial DNS fragments. The yields of hydrogen isotopes and α production have similar magnitudes but are more probable than heavy particles. The kinetic energy spectra manifest differences for charged particles, i.e., α emission has higher kinetic energy than protons. The preequilibrium clusters follow the angular distribution of MNT fragment emission and are related to nucleon correlations. This reaction mechanism is helpful for investigating the cluster structure of atomic nuclei and MNT fragment formation, i.e., the yields, shell effects, emission dynamics, etc., which is being planned for forthcoming experiments at HIAF in Huizhou.

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