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Full Text

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 cluster transfer into the dissipation process, we systematically investigated the energy spectra and angular distribution of preequilibrium clusters (n, p, d, t,

^{3}He, α, ^{6,7}Li, ^{8,9}Be) in massive transfer reactions of ^{12}C+^{209}Bi, ^{14}N+^{159}Tb, ^{14}N+^{169}Tm, ^{14}N+^{181}Ta, ^{14}N+^{197}Au, ^{14}N+^{209}Bi, and ^{58,64,72}Ni+^{198}Pt near Coulomb barrier energies. We find that neutron emission is 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 dinuclear system evolution. The kinetic energy spectra manifest Boltzmann distributions, with Coulomb potential influencing 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 ones, which can be treated as a whole without considering its internal structure [1]. In 1968, Ikeda proposed that nuclear cluster states tend to occur in excited states near the cluster threshold energy [2]. 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 ^{6}Li being composed of an α particle and a deuteron, the 2α structure for ^{8}Be, 3α for ^{12}C, and 5α for ^{20}Ne [3]. 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. Semiclassical 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. [4] 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, 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 differs from the cluster emitted during de-excitation of a composite nucleus, and the pre-equilibrium 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 [4].

Since multinucleon transfer (MNT) reactions and deep inelastic heavy ion colli-

sions were proposed in the 1970s [5–7], numerous experiments have been carried out to measure double differential cross sections, angular distributions, and energy distributions of different reaction systems. However, it is worth noting that relatively little research has been conducted 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}N+^{159}Tb, ^{169}Tm, ^{181}Ta, ^{197}Au, ^{209}Bi [8] and ^{12}C+^{209}Bi [9, 10], respectively. The angular distributions, kinetic energy spectra, and total production cross sections of emitted particles were measured in 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 = 104–118 [11] 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 the excitation energy of compound nuclei in MNT reactions distributes widely. 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 [12, 13].

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 wide species of particle beams [14], which provides a good experimental platform for the study of nuclear cluster structures and cluster emission.

In this work, we systematically investigate 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 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 [15] 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 [16–18]. The Lanzhou nuclear physics group has further developed the DNS model [19–22], e.g., introducing the barrier distribution function method in the capture pro-

cess, considering the effects of quasifission and fission in the fusion stage, 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 multinucleon transfer (MNT) reactions [23–25].

With the DNS model, we have calculated the temporal evolution, kinetic energy spectra, and angular distributions of preequilibrium clusters in transfer reactions with incident energy near the Coulomb barrier. Compared to our previous work [26], we have introduced the transfer of clusters in 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 the compound nucleus is formed, and its emission continues until the composite nucleus is formed. The cross section of preequilibrium particle emission (= n, p, d, t, ^{3}He, α, ^{6},^{7}Li and ^{8},^{9}Be) is defined as

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

Here, the reduced de Broglie wavelength $\lambda=\frac{\hbar}{\sqrt{2\mu E_{c.m.}}}$, 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

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

where $T(E_{c.m.},J,B)$ is the penetration probability for overcoming the barrier B. For light and medium systems, $T(E_{c.m.},J)$ is calculated by the well-known Hill-Wheeler formula [27],

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

with $\hbar\omega(J)$ being the width of the parabolic barrier at $R_B(J)$. For heavy systems, where the collision system does not form a potential energy pocket after overcoming the Coulomb barrier, $T(E_{c.m.},J)$ is calculated by the classical trajectory method,

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

The reduced mass is $\mu=m_nA_PA_T/(A_P+A_T)$ with m_n, A_P and A_T being the nucleon mass and mass numbers of projectile and target nuclei, respectively. R_C denotes the Coulomb radius.

The barrier distribution function is Gaussian [21, 22] with B_m as the Coulomb barrier at tip-to-tip orientation:

$$f(B)=\exp\left[-\left(\frac{B-B_m}{\Delta}\right)^2\right],\quad \int f(B)dB=1.$$

The normalization constant satisfies this condition. 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…

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 [29]. 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

$$\frac{dP(Z_1,N_1,E_1,\beta_1,B,t)}{dt}=\sum_{Z_1',N_1',\beta_1'}\Big[W_{Z_1',N_1';Z_1,N_1}(t)\times[d_{Z_1',N_1'}P(Z_1',N_1',E_1',B,t)-d_{Z_1,N_1}P(Z_1,N_1,E_1,\beta_1,B,t)$$

In this equation, $W_{Z_1,N_1;Z_1',N_1'}$ is the mean transition probability from 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,β_1).

In this process, the transfer of nucleons or clusters satisfies the relationships $Z_1' = Z_1 \pm Z_\nu$ and $N_1' = N_1 \pm N_\nu$, each representing the transfer of a neutron, proton, deuteron, tritium, ^{3}He, or α. Note that we ignore the quasifission of DNS and fission of heavy fragments in the dissipation process. The initial probabilities of projectile and target nuclei are set to $P(Z_{\rm proj}, N_{\rm proj}, E_1 = 0, t = 0) = P(Z_{\rm targ}, N_{\rm targ}, E_1 = 0, t = 0) = 0.5$. The nucleon transfer process satisfies the unitary condition $\sum P(Z_1, N_1, E_1, t) = 1$.

Similar to the cascade transfer of nucleons [21], the transfer of clusters is also described by the single-particle Hamiltonian. 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 time. The total single-particle energy is

$$H_0(t) = \sum_K \varepsilon_K(t)\alpha_K^\dagger(t)\alpha_K(t).$$

The interaction potential is

$$V(t) = \sum_{K,K'} u_{K;K'}(t)\alpha_K^\dagger(t)\alpha_{K'}(t) = \sum_{K,K'} V_{K;K'}(t).$$

The quantity ε_K represents the single-particle energies, and $u_{K;K'}$ is the interaction matrix elements, parameterized in the following form:

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

Here, the calculation of $U_{K;K'}(t)$ and $\delta_{K;K'}(t)$ has been described in Ref. [30].

In the relaxation process of relative motion, the DNS becomes excited by dissipation of relative kinetic energy and angular momentum. The excited DNS opens a valence space in which 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:

$$\Delta\varepsilon_K = \varepsilon^*, \quad g_K = A_K/12,$$

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 $N_K = g_K\Delta\varepsilon_K$, with g_K being the single-particle level density around the Fermi surface. The number of valence nucleons is $m_K = N_K/2$. The microscopic dimension for 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

$$W^{(\nu)}_{Z_1,N_1;Z_1',N_1'} = \frac{|\langle Z_1', N_1', E_1', i'|V|Z_1, N_1, E_1, i\rangle|^2}{d_{Z_1,N_1} d_{Z_1',N_1'}} = G_\nu \tau_{\rm mem}(Z_1, N_1, E_1; Z_1', N_1', E_1').$$

G_ν represents the spin-isospin statistical factors, and we use the Wigner density approach to identify particle types [31, 32], i.e., $G_\nu = 1, 1, 3/8, 1/12, 1/12, 1/96$ for neutron, proton, deuteron, tritium, ^{3}He, and α, respectively.

The memory time is connected with the internal excitation energy [33],

$$\tau_{\rm mem}(Z_1, N_1, E_1; Z_1', N_1', E_1') = \left[\frac{2\pi}{\hbar}\langle V_{KK'} V^*_{KK'}\rangle\right]^{-1/2} = \left[\frac{2\pi}{\hbar}\sum_{KK'} g_K g_{K'} \Delta_{KK'} \Delta\varepsilon_K \Delta\varepsilon_{K'}\right]^{-1/2}.$$

The interaction matrix elements are calculated by

$$|V_{ii'}|^2 = \omega_{11}(i_1, i_1') + \omega_{22}(i_1, i_1') + \omega_{12}(i_1, i_1') + \omega_{21}(i_1, i_1'),$$

with

$$\omega_{KK'}(i, i') = \frac{\langle V_{KK'}, V^*_{KK'}\rangle}{d_{Z_1,N_1}}.$$

In the relaxation process of relative motion, the DNS becomes excited by dissipation of relative kinetic energy. The local excitation energy is determined by the dissipation energy from relative motion and the potential energy surface of the DNS [22, 24],

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

The excitation energy of DNS fragment (Z_1, N_1) is $E_1 = \varepsilon^*(t = \tau_{\rm int})A_1/A$. $\tau_{\rm int}$ denotes the interaction time, which is associated with the reaction system and relative angular momentum, and can be obtained from the deflection function [34]. The energy dissipated into the DNS is

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

The radial energy is $\langle E_{\rm rad}(J,t)\rangle = E_{\rm rad}(J,0)\exp(-t/\tau_r)$, with the relaxation time of radial motion being $\tau_r = 5\times10^{-22}$ s and the initial radial energy being $E_{\rm rad}(J,0) = E_{c.m.} - B - J_i(J_i+1)\hbar^2/(2\zeta_{\rm rel})$. The dissipation of relative angular momentum is described by

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

with the angular momentum at the sticking limit $J_{\rm st} = J_i\zeta_{\rm rel}/\zeta_{\rm tot}$ and relaxation time $\tau_J = 15\times10^{-22}$ s. $\zeta_{\rm rel}$ and $\zeta_{\rm tot}$ are the relative and total moments of inertia of the DNS, respectively. The initial angular momentum is set to $J_i = J$ in Eq. (1). The relaxation time of radial kinetic energy and angular momentum is associated with friction coefficients in binary collisions. The values in this work are taken from empirical analysis in deeply inelastic heavy-ion collisions [34, 35].

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 $N_1+N_2=N$ [36, 37]. 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, where the DNS is assumed to be formed. $B(Z_i,N_i)$ $(i=1,2)$ and $B(Z,N)$ are the negative binding energies of fragment (Z_i,N_i) and the compound nucleus (Z,N), respectively. β_i represents the quadrupole deformations of the two fragments at ground state, and θ_i $(i=1,2)$ denote the angles between collision orientations and symmetry axes of deformed nuclei. The interaction potential between fragments (Z_1,N_1) and (Z_2,N_2) is derived from

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

where V_C is the Coulomb potential using the Wong formula [38], V_N is the nucleus-nucleus potential using the double folding potential [39], and $V_{\rm def}(t)$ denotes the deformation energy of the DNS at reaction time t,

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

The quantities C_i $(i=1,2)$ denote the stiffness parameters of the nuclear surface, calculated by the liquid drop model [41]. Detailed calculations of $V_{\rm def}(t)$ can be obtained from Ref. [40] and references therein.

Shown in Fig. 1 [Figure 1: see original paper] is the PES for collisions of ^{14}N+^{209}Bi and ^{64}Ni+^{198}Pt. The zigzag lines are the driving potentials, estimated by minimal PES values during nucleon transfer. 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

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

Here the time step is set to $\Delta t = 0.5 \times 10^{-22}$ s for reactions induced by ^{12}C and ^{14}N, but $\Delta t = 0.25 \times 10^{-22}$ s for reactions induced by ^{58},^{64},^{72}Ni isotopes.

Based on the Weisskopf evaporation theory [42, 43], we have the particle decay widths as follows:

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

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 $\sigma_{\rm inv} = \pi R_\nu^2 T(\nu)$, with radius $R_\nu = 1.21(A-A_\nu)^{1/3} + A_\nu^{1/3}$. The penetration probability is set to $T(\nu) = 1$ 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 [44]:

$$E_i^* = \varepsilon^* \frac{A_i}{A}.$$

The level density is calculated from the Fermi-gas model as

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

with $\sigma^2 = 6\bar{m}^2A^{2/3}/\pi^2$ and $\bar{m} \approx 0.24A^{2/3}$. The pairing correction energy δ is set to $12/A^{1/2}$ for even-even, even-odd, and odd-odd nuclei, respectively. The level density parameter is related to the shell correction energy $E_{\rm sh}(Z, N)$ and excitation energy E^* of the nucleus as

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

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 0.45, respectively [36, 37].

The kinetic energy of the preequilibrium particle is sampled by the Monte Carlo method within the energy range $\varepsilon_\nu \in (0, E^* - B_\nu - V_C - E_{\rm rot})$. Here, V_C represents the Coulomb force that outgoing particles must overcome, and for neutrons, $V_C = 0$. The Watt spectrum is used for neutron emission [45] and expressed as

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

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

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

with $T_\nu = \sqrt{E^*/a}$ and $a = A/8$ being the level density parameter.

We use the deflection function method [34, 46] 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

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

with incident energy $E_{c.m.}$ and impact parameter b.

The nuclear deflection is calculated by

$$\Theta_N(J_i) = -\beta \Theta_C^{\rm gr}(J_i)\left(\frac{J_i}{J_{\rm gr}}\right)^\delta.$$

Here $\Theta_C^{\rm gr}(J_i)$ is the Coulomb scattering angle at the grazing angular momentum $J_{\rm gr} = 0.22R_{\rm int}\sqrt{A_{\rm red}(E_{c.m.} - V(R_{\rm int}))}$. The quantity J_i is the incident angular momentum, $A_{\rm red}$ is the reduced mass of the collision system, and $V(R_{\rm int})$ denotes the interaction potential with $R_{\rm int}$ being the Coulomb radius. The parameters δ and β are parameterized by fitting deep inelastic scattering in massive collisions as

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

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

with $f(\eta) = [1 + \exp(\eta - 235)]^{-1}$. The quantity $\eta = Z_1Z_2e^2/\hbar v$ is the Sommerfeld parameter, and the relative velocity is calculated by $v = \sqrt{2(E_{c.m.} - V(R_{\rm int}))/\mu}$. For the i-th DNS fragment, the emission angle is determined by

$$\Theta_i(J_i) = \Theta(J_i)\frac{\xi_i}{\xi_1 + \xi_2},$$

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

III. RESULTS AND DISCUSSION

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

The temporal evolution of emission probabilities for n, p, d, t, ^{3}He, and α from transfer reactions of ^{14}N + ^{159}Tb, ^{169}Tm, ^{181}Ta, and ^{197}Au at $E_{\rm lab} = 115$ 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 preequilibrium process lasts only several zeptoseconds. The figures show that preequilibrium cluster emission continues until composite nucleus formation. At the beginning of the reaction, the emission probability increases rapidly, reaching a maximum at about $(20 - 40) \times 10^{-22}$ s, then remaining stable or decreasing gradually. The emission probabilities of α and hydrogen isotopes are comparable, with yields about 3-4 orders of magnitude lower than neutrons but much larger than ^{3}He. The local excitation energy of DNS fragments increases with time, and emitted clusters

can carry away part of this energy, which is conducive to forming 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. These cross sections for different particles are shown in Table I . It is obvious that 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 transfer reactions of ^{14}N + ^{159}Tb, ^{169}Tm, ^{181}Ta at $E_{\rm lab}$ = 115 MeV. The kinetic energy spectra show similar shapes across different reactions, presenting Boltzmann distributions. Neutron emission is most important. Compared with previous work [26], we have introduced Coulomb barrier corrections. Hydrogen isotopes have similar emission probabilities due to identical charge, with spectral peaks around 10 MeV. Since α and ^{3}He are more highly charged, their kinetic energy spectra shift toward higher energies (i.e., move rightward in the figures). Additionally, Fig. 4 shows that α emission probability is about three to five orders of magnitude higher than ^{3}He because the former has lower separation energy and is more easily emitted from DNS fragments. These calculations are consistent with experimental data [8, 10].

In Fig. 5 [Figure 5: see original paper], we exhibit kinetic energy spectra of preequilibrium clusters (n, p, d, t, ^{3}He, α, ^{6},^{7}Li, ^{8},^{9}Be) in transfer reactions induced by ^{12}C and ^{14}N on the same target nucleus ^{209}Bi. These kinetic energy spectra reveal nuclear structure effects and dynamic characteristics of nuclear reactions. Available experimental data for α emission from HIRFL for the massive transfer reaction ^{12}C+^{209}Bi [10] and from RIKEN for ^{14}N+^{209}Bi [8] are nicely reproduced by 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 formation probability and emission probability. In our calculation, assuming clusters already exist in the DNS, emission cross sections of different clusters are primarily determined by emission probabilities. Higher charge on emitted particles leads to higher Coulomb barriers. Conversely, larger separation energy of the cluster results in smaller decay width and lower emission probability. Kinetic energy spectra of clusters are strongly related to Coulomb barriers and excitation energies of the composite system.

Preequilibrium cluster emission depends on both the reaction system and incident energy. Shown in Fig. 6 [Figure 6: see original paper] is a comparison of time evolution and kinetic energy distribution for the transfer reaction ^{58}Ni+^{198}Pt at incident energies of 220 MeV and 240 MeV. The left panel shows temporal evolution, while the right panel shows 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, with high local excitation energy benefiting 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 preequilibrium cluster emission probability increases with incident energy.

In Fig. 7 [Figure 7: see original paper], we compare transfer reactions bombarding target nucleus ^{198}Pt with heavier Ni isotopes at $E_{c.m.} = 240$ MeV. The left panel shows kinetic energy spectra of preequilibrium clusters emitted in the ^{64}Ni+^{198}Pt reaction, while the right panel shows the ^{72}Ni+^{198}Pt reaction. Compared to the ^{64}Ni+^{198}Pt system, the reaction induced by ^{72}Ni appears more likely to emit neutrons, while the former is more likely to emit protons. In both systems, the peak of kinetic energy spectra for proton isotopes is about 9 MeV, while the peak of α kinetic energy spectra is about 17 MeV.

Particles emitted in the preequilibrium process differ from those from compound nucleus formation in both kinetic energy and angular distributions [47]. Direct particles primarily emit in the same direction as incident particles with similar energies, while particles from compound processes emit isotropically in equal amounts forward and backward. Preequilibrium particles tend to be emitted forward and are generally more energetic than those from composite nuclei.

Shown in Fig. 8 [Figure 8: see original paper] are angular distributions of emitted preequilibrium clusters in ^{58},^{64},^{72}Ni+^{198}Pt at $E_{c.m.} = 240$ MeV. Angular distributions differ for different reaction systems. For the same reaction system, angular distributions of different clusters are roughly similar because different clusters may evaporate from the same excited DNS fragment. The figure also shows that angular distributions of preequilibrium particles are anisotropic, with shape characteristics similar to angular distributions of fragments in multinucleon transfer reactions [34, 46]. Under all three reaction systems, particle angular distributions increase rapidly when the center-of-mass angle is about 26°, exhibiting a window of 30°–160° for preequilibrium emission. Studying angular distributions of preequilibrium clusters in transfer reactions is significant for understanding angular distributions of primary fragments in MNT reactions and is helpful for experimental measurement planning.

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: the temporal evolution, kinetic energy spectra, and angular distributions of n, p, d, t, ^{3}He, α, ^{6},^{7}Li, and ^{8},^{9}Be in collisions of ^{12}C+^{209}Bi, ^{14}N+^{159}Tb, ^{169}Tm, ^{181}Ta, ^{197}Au, ^{209}Bi, and ^{58},^{64},^{72}Ni+^{198}Pt. The model incorporates cluster transfer and dynamic deformation coupled to relative dissipation of angular momentum and kinetic energy. Preequilibrium cluster emission strongly depends on incident energy, separation energy, and Coulomb barrier from primordial DNS fragments. Yields of hydrogen isotopes and α production have similar magnitudes but are more probable than heavier particles. Kinetic energy spectra manifest differences for charged particles, with α emission having higher kinetic energy than protons. Preequilibrium clusters

follow MNT fragment emission in angular distributions and are related to nucleon correlations. This reaction mechanism is helpful for investigating MNT fragment formation—yields, shell effects, emission dynamics, etc.—which is being planned for forthcoming experiments at HIAF in Huizhou.

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REFERENCES

[1] Z. Y. Wei and Y. T. Zhu, Nucl. Phys. Rev. 3, 18-21 (1995).
[2] K. Ikeda, N. Takigawa, H. Horiuchi, Prog. Theor. Phys. Suppl. 68, 464-475 (1968).
[3] B. Zhou, Y. Funaki, H. Horiuchi, Y. G. Ma, G. Röpke, P. Schuck, A. Tohsaki, and T. Yamada, Nat. Commun. 14, 8206 (2023).
[4] P. E. Hodgson and E. Béták, Phys. Rep. 374, 1-89 (2003).
[5] A. G. Artukh, V. V. Avdeichikov, G. F. Gridnev et al., Nucl. Phys. A 176, 284-288 (1971).
[6] P. J. A. Buttle, L. J. B. Goldfarb, Nucl. Phys. A 176, 299-320 (1973).
[7] A. G. Artukh, G. F. Gridnev, V. L. Mikheev et al., Nucl. Phys. A 215, 91-108 (1973).
[8] H. Utsunomiya, T. Nomura, T. Inamura et al., Nucl. Phys. A 334, 127-143 (1980).
[9] W. Q. Shen, S. W. Xu, D. T. Wang et al., Chin. Phys. C 1, 70-78 (1977).
[10] G. M. Jin, Y. X. Xie, Y. T. Zhu et al., Nucl. Phys. A 349, 285-300 (1980).
[11] M. Thoennessen, At. Data Nucl. Data Tables 99, 312-344 (2013).
[12] H. M. Devaraja, A. V. Yeremin, S. Heinz et al., Phys. Part. Nucl. Lett. 19, 693-716 (2022).
[13] T. Niwase, Y. X. Watanabe, Y. Hirayama et al., Phys. Rev. Lett. 130, 132502 (2023).
[14] J. C. Yang, J. W. Xia, G. Q. Xiao et al., Nucl. Instrum. Methods B 317, 263 (2013).
[15] V. V. Volkov, Phys. Rep. 44, 93-157 (1978).
[16] G. G. Adamian, N. V. Antonenko, R. V. Jolos et al., Int. J. Mod. Phys. E. 05, 191-216 (1996).
[17] G. G. Adamian, N. V. Antonenko, W. Scheid, and V. V. Volkov, Nucl. Phys. A 627, 361-378 (1997).
[18] G. G. Adamian, N. V. Antonenko, W. Scheid, and V. V. Volkov, Nucl. Phys. A 633, 409-420 (1998).
[19] W. Li, N. Wang, J. F. Li et al., Europhys. Lett. 64, 750-756 (2003).
[20] Z. Q. Feng et al., Chin. Phys. Lett. 22, 846 (2005).
[21] Z. Q. Feng, G. M. Jin, F. Fu, and J. Q. Li, Nucl. Phys. A 771, 50-67 (2006).
[22] Z. Q. Feng, G. M. Jin, J. Q. Li, and W. Scheid, Phys. Rev. C 76, 044606 (2007).

[23] Z. Q. Feng, G. M. Jin, and J. Q. Li, Phys. Rev. C 80, 057601 (2008).
[24] Z. Q. Feng, G. M. Jin, J. Q. Li, and W. Scheid, Nucl. Phys. A 816, 33-51 (2009).
[25] Z. Q. Feng, G. M. Jin, and J. Q. Li, Nucl. Phys. A 836, 82-90 (2010).
[26] Z. Q. Feng, Phys. Rev. C 107, 054613 (2023).
[27] D. L. Hill and J. A. Wheeler, Phys. Rev. 89, 1102-1145 (1953).
[28] V. I. Zagrebaev, Y. Aritomo, M. G. Itkis, and Yu. Ts. Oganessian, Phys. Rev. C 65, 014607 (2001).
[29] Z. Q. Feng, Phys. Rev. C 108, L051601 (2023).
[30] G. G. Adamian, N. V. Antonenko, and W. Scheid, Phys. Rev. C 68, 034601 (2003).
[31] R. Mattiello, H. Sorge, H. Stöcker, and W. Greiner, Phys. Rev. C 55, 1443 (1997).
[32] Z. Q. Feng, Phys. Rev. C 102, 044604 (2020).
[33] C. Riedel, G. Wolschin, and W. Nörenberg, Z. Phys. A 290, 47-55 (1979).
[34] G. Wolschin and W. Nörenberg, Z. Phy. A 284, 209-216 (1978).
[35] J. Q. Li and G. Wolschin, Phys. Rev. C 27, 590-601 (1983).
[36] Z. Q. Feng, G. M. Jin, and J. Q. Li, Phys. Rev. C 80, 067601 (2009).
[37] Z. Q. Feng, Phys. Rev. C 95, 024615 (2017).
[38] C. Y. Wong, Phys. Rev. Lett. 31, 766 (1973).
[39] I. I. Gontchar, D. J. Hinde, M. Dasgupta, and J. O. Newton, Phys. Rev. C 69, 024610 (2004).
[40] P. H. Chen, C. Geng, Z. X. Yang et al., Nucl. Sci. Tech. 34, 160 (2023).
[41] W. D. Myers and W. J. Swiatecki, Nucl. Phys. 81, 1-60 (1966).
[42] V. Weisskopf, Phys. Rev. 52, 295 (1937).
[43] P. H. Chen, Z. Q. Feng, J. Q. Li, and H. F. Zhang, Chin. Phys. C 40, 091002 (2016).
[44] P. Möller, J. R. Nix, W. D. Myers, and W.J. Swiatecki, At. Data Nucl. Data Tables 59, 185-381 (1995).
[45] H. Rossner, Phys. Rev. C 45, 719 (1992).
[46] C. Peng and Z. Q. Feng, Eur. Phys. J. A 58, 162 (2022).
[47] P. Hodgson, Nature 292, 671-672 (1981).

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