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Abstract

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Isospin Equilibration in Multinucleon Transfer Reactions at Near-Barrier Energies

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The isospin equilibration process in multinucleon transfer reactions is investigated using the improved quantum molecular dynamics (ImQMD) model. We study collisions of ^{124}Xe+^{208}Pb at near-barrier energies with different symmetry energy coefficients. Our findings reveal that neutron transfer is enhanced during the early stages of collisions under strong symmetry potentials, with neutron transfer occurring earlier than proton transfer. The neutron flow trajectory follows a low-density path from the target to the projectile. We also examine the average N/Z values of primary products in the ^{58}Ni+^{208}Pb reaction and compare them with available experimental data, which show that the average N/Z values of projectile-like products increase rapidly with increasing mass transfer. In quasi-elastic collisions, the isospin equilibration process remains incomplete due to short contact times between reaction partners, while complete isospin equilibration occurs in symmetric quasi-fission reactions.

I. INTRODUCTION

Isospin transport effects in heavy-ion collisions have been studied extensively for many years [?]. These effects encompass two distinct facets: isospin diffusion and isospin drift. Isospin diffusion relates to the isospin asymmetry of a system where the projectile and target have different N/Z values [?], whereas isospin drift is associated with density gradients expected to exist in the low-density neck region, even between two identical nuclei [?].

In nuclear reactions, isospin transport initiates and continues until the system disintegrates or the chemical potentials for neutrons and protons in both nuclei become equal. If the interaction time between projectile and target is sufficiently long, the system will reach isospin equilibration. At intermediate energies, isospin transport effects have been investigated in mid-peripheral collisions by analyzing the N/Z values of reconstructed primary quasi-projectile, quasi-target, and mid-velocity sources. For instance, in the ^{40}Ca+^{48}Ca reaction [?], isospin diffusion effects lead to an increase in the N/Z ratio of the quasi-projectile source. In collisions between nuclei with identical N/Z values (such as ^{58}Ni+^{58}Ni [?]), the isospin drift phenomenon can be observed without contamination from mid-velocity sources.

At low incident energies, multinucleon transfer (MNT) reactions represent one of the most important mechanisms and have attracted widespread interest in recent years, both experimentally [?] and theoretically [?]. Unlike at intermediate energies, collisions between reaction partners are not violent. The major products in MNT reactions consist only of quasi-projectile and quasi-target fragments with nucleon transfers of up to 30 or more; no mid-velocity fragments are formed. In general, MNT reactions include quasi-elastic, deep-inelastic, and quasi-fission processes, which can be distinguished by analyzing the total-kinetic-energy-mass (TKE-Mass) distributions combined with the total kinetic energy loss (TKEL) distributions of the products [?]. The contact times between reaction partners differ significantly among these reaction types. MNT reactions thus provide an opportunity to study the isospin equilibration process across different time scales. In quasi-fission reactions, typical time scales can reach 10^{-21} s or longer [?, ?], allowing nucleon transfer processes to potentially lead to a uniform distribution of the N/Z ratio.

Many experiments on isospin equilibration effects at low energies have been performed over the past decades by analyzing the N/Z values of reconstructed primary products [?, ?]. For example, Królas et al. investigated the reactions

^{64}Ni+^{130}Te at $E_{\mathrm{lab}} = 275$ MeV and ^{58}Ni+^{208}Pb at $E_{\mathrm{lab}} = 345$ MeV at Laboratori Nazionali di Legnaro (INFN) [**?**], finding that the isospin equilibration process is closely related to the number of nucleons transferred between reaction partners. However, it is difficult to separate the contributions of isospin diffusion and drift at low energies. Isospin equilibration represents an important mechanism in MNT reactions and offers a promising approach for producing new neutron-rich nuclei. For instance, Guerreau et al. produced new isotopes ^{54}Ti, ^{56}V, ^{58,59}Cr, ^{61}Mn, and ^{63,64}Fe using a 340 MeV ^{40}Ar beam from the Orsay ALICE accelerator facility bombarding a ^{238}U target [**?**].

The neck represents an important characteristic in MNT reactions, even in the early stages of fusion. It forms in the dinuclear system and is characterized by sub-saturation densities. Isospin transport and energy dissipation processes are closely related to nucleon transfer between reaction partners through the neck, requiring dynamical calculations to understand these processes in detail. The improved quantum molecular dynamics (ImQMD) model [**?**, **?**] describes nuclear reactions based on effective nucleon-nucleon interactions and is self-consistent in describing neck evolution and nucleon transport during collisions. In this work, we apply the ImQMD model to investigate the isospin equilibration process in ^{124}Xe+^{208}Pb and ^{58}Ni+^{208}Pb reactions at near-barrier energies.

This paper is organized as follows: Section II briefly introduces the ImQMD model, Section III presents results and discussion, and Section IV provides conclusions.

II. THE MODEL

The ImQMD model is an improved version of the quantum molecular dynamics (QMD) model [**?**]. It adopts the standard Skyrme interaction (omitting the spin-orbit term) to describe the bulk and surface properties of nuclei [**?**]. The stochastic two-body collision process is incorporated into the time evolution via Hamilton's equations of motion. To describe the fermionic nature of the N-body system, the Fermi constraint proposed by Papa et al. in the constrained molecular dynamics (CoMD) model [**?**, **?**] is introduced, which greatly improves the stability of individual nuclei. The final state of the two-body collision process is checked to ensure it obeys the Pauli principle. Detailed descriptions of the ImQMD model can be found in Refs. [**?**, **?**].

The nuclear interaction potential can be expressed as:

$$V_{\mathrm{loc}} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_0}{2\rho_0}(\nabla\rho)^2 + \frac{C_s}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_0}\rho\delta^2 + \frac{C_s^{\mathrm{surf}}}{2\rho_0}(\nabla\rho)^2\delta^2 + g_\tau\frac{\rho^{\eta+1}}{\rho_0^{\eta}}$$

Here $\rho = \rho_n + \rho_p$ is the nucleon density, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry. The first three terms are obtained directly from the potential energy functional of the Skyrme interaction. The fourth term represents the symmetry potential energy, including both bulk and surface symmetry potential energies. The surface symmetry potential energy term, related to the density gradient, is important for describing the neutron skin of nuclei. The last term is a small correction term.

The density distribution function ρ of a system is given by:

$$\rho(\mathbf{r}) = \frac{1}{(2\pi\sigma_r^2)^{3/2}} \sum_i \exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{2\sigma_r^2}\right]$$

where σ_r is the wave-packet width of the nucleon in coordinate space. The IQ2 parameter sets (see Table 1) adopted in this work are the same as those in Refs. [**?**, **?**]. The incompressibility coefficient K_∞ is 195 MeV. These parameter sets have been successfully applied to heavy-ion collisions in fusion reactions [**?**, **?**], multinucleon transfer reactions [**?**, **?**], and ternary breakup reactions [**?**].

TABLE I. The model parameters (IQ2) adopted in this work.

Parameter	Value
α (MeV · fm^2)	-356
β (MeV)	303
γ	7/6
g_0 (MeV)	12.5
γ_0	2/3
C_s (MeV)	32.0
C_s^{surf} (MeV)	0.08
ρ_0 (fm^{-3})	0.165

In this work, we set the z-axis as the beam direction and the x-axis as the impact parameter direction. The wave-packet width is set to $\sigma_r = 1.3$ fm for calculating the isospin equilibration process in ^{124}Xe+^{208}Pb and ^{58}Ni+^{208}Pb. The initial distance between the centers of mass of the projectile and target is 30 fm.

III. RESULTS AND DISCUSSION

We first test the ImQMD model's ability to describe MNT reactions by simulating ^{58}Ni+^{208}Pb collisions at $E_{\mathrm{lab}} = 328.4$ MeV. A total of 39,000 simulation events are calculated with impact parameters ranging from 0 to b_{max} fm, where $b_{\mathrm{max}} = R_P + R_T$ (with R_P and R_T denoting the radii of projectile and target, respectively). Each event is simulated until $t = 2000$ fm/c with a time step of $\Delta t = 1$ fm/c. Figure 1 [Figure 1: see original paper] shows the isotope production cross sections from Mn to Ni, excluding fusion and elastic scattering events. Experimental data are taken from Ref. [**?**]. The thick folding lines and thick solid lines represent calculations from the ImQMD+GEMINI combination and the GRAZING model [?] with evaporation included, respectively. Nuclear level densities in the GEMINI code [?] are taken in Fermi-gas form with default parameters. Figure 1 demonstrates that the measured isotope distributions for Co and Ni are reasonably well reproduced by ImQMD+GEMINI calculations, though discrepancies increase with the number of proton transfers. The GRAZING calculations exhibit similar behavior.

For simplicity, we investigate the isospin equilibration process in head-on collisions of ^{124}Xe+^{208}Pb at $E_{\text{c.m.}} = 450$ MeV. For this reaction, the incident energy is slightly above the Coulomb barrier, and compound nucleus formation is highly unlikely due to the large $Z_P Z_T$ value. The typical reaction process involves the colliding nuclei exchanging nucleons before re-separating. Figure 2 [Figure 2: see original paper] shows the single-particle potentials for neutrons and protons in ^{124}Xe+^{208}Pb along the beam direction at $t = 200$ and 300 fm/c. The single-particle potential is defined as $U_q(\mathbf{r}) = \int \rho(\mathbf{r}')V(\mathbf{r}-\mathbf{r}')d\mathbf{r}'$, where $q = n, p$, $\rho(\mathbf{r})$ is the density distribution, and $V(\mathbf{r}-\mathbf{r}')$ is the effective nucleon-nucleon interaction. The Coulomb interaction plays a crucial role in isospin transport processes during the early stages of MNT reactions. At $t = 200$ fm/c, neutron transfer is permitted due to the low barrier between reaction partners (Fig. 2(a)), whereas proton transfer is forbidden at this time because the barrier is very high (Fig. 2(c)). Consequently, neutron transfer occurs earlier than proton transfer in MNT reactions. By $t = 300$ fm/c, the barriers between reaction partners are reduced for both neutrons and protons, allowing both to transfer between target and projectile (Figs. 2(b) and 2(d)).

Figure 3 [Figure 3: see original paper] displays the time evolution of density profiles for ^{124}Xe+^{208}Pb at $E_{\text{c.m.}} = 450$ MeV. The central nuclear densities in the reactions are reasonable, and density diffuseness is clearly visible on the system surface. Figure 4 [Figure 4: see original paper] shows contour plots of isospin asymmetry ($\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$) for ^{124}Xe+^{208}Pb during system evolution. The average isospin asymmetry values for ^{124}Xe and ^{208}Pb nuclei are 0.13 and 0.21, respectively. The isospin asymmetry distributions in the cores of both reaction partners remain uniform, with corresponding δ values of 0.1 and 0.17 in the quasi-projectile and quasi-target, respectively. However, isospin asymmetry values on nuclear surfaces are significantly larger than in the cores. The ^{208}Pb core is covered by a neutron skin with maximal $\delta = 0.54$ at $t = 50$ fm/c. Neutron enrichment is also evident in the low-density neck region, a phenomenon known as isospin drift resulting from density gradients. Neutrons are preferentially driven to low-density areas [?], and Fig. 4 clearly shows neutron flow forming along the low-density path.

To investigate isospin transport during dinuclear system evolution, we introduce a separation plane to divide quasi-projectile and quasi-target nuclei, defined as the plane where iso-contours of projectile and target densities intersect. This method was adopted in TDHF calculations [?, ?]. Figure 5 [Figure 5: see original paper] shows neutron and proton transfer coefficients in head-on ^{124}Xe+^{208}Pb collisions with symmetry energy coefficients $C_s = 28$ and 32 MeV. The transfer coefficient is defined as $\nu_{n,p} = dN_{n,p}/dt$, where $N_{n,p}$ denotes the net neutron or proton flux through the separation plane, with transfer direction from target to projectile. Neutron transfer is enhanced for $C_s = 32$ MeV during early collision stages due to the strong symmetry potential, with a peak neutron transfer coefficient of approximately 1×10^{-2} per fm/c, comparable to TDHF calculations [**?**]. Proton transfer coefficients are insensitive to symmetry energy in ^{124}Xe+^{208}Pb reactions because symmetry energy primarily influences neutron transport when projectile and target have large N/Z differences. Additionally, neutron transfer begins at $t = 150$ fm/c, earlier than proton transfer, as proton transfer is hindered by a high barrier between reaction partners during early collision stages (see Figs. 2(a) and 2(c)).

In MNT reactions, contact time between reaction partners is related to collision mode, with different mechanisms distinguishable through TKE-Mass distributions combined with TKEL distributions of products. Figure 6 [Figure 6: see original paper] shows TKE-Mass distributions and corresponding TKEL distributions of primary binary fragments in ^{58}Ni+^{208}Pb at $E_{\text{lab}} = 345$ MeV for contact time ranges of $0 < t_{\text{con}} \leq 400$, $400 < t_{\text{con}} \leq 1000$, and $0 < t_{\text{con}} \leq 1000$ fm/c. Contour plots show fragment counts on a logarithmic scale for impact parameters from 0 to b_{max} fm. Quasi-elastic and deep-inelastic collisions occur when contact time is less than 400 fm/c. As shown in Fig. 6(b), quasi-elastic collision events can be extracted by fitting the TKEL distribution peak with a Gaussian curve. Generally, contact times for quasi-elastic collisions are shorter than for deep-inelastic collisions, with only a few nucleons transferred between projectile and target. The TKEL for quasi-elastic events is less than 30 MeV. Differences between ImQMD calculations and the Gaussian curve correspond primarily to deep-inelastic events. Most quasi-fission events occur for $400 < t_{\text{con}} \leq 1000$ fm/c, with masses distributed over a broad range and extensive nucleon transfer that may lead to isospin equilibration between quasi-projectile and quasi-target fragments.

Figure 7 [Figure 7: see original paper] shows average N/Z values of primary products in ^{58}Ni+^{208}Pb at $E_{\text{lab}} = 345$ MeV. The solid line in Fig. 7(a) denotes ImQMD calculations with $0 < t_{\text{con}} \leq 1000$ fm/c for impact parameters from 0 to b_{max} fm, excluding elastic scattering and fusion-fission events. The N/Z values for projectile, target, and compound nucleus are 1.071, 1.537, and 1.418, respectively. Experimental data are reasonably well reproduced by ImQMD calculations. The average N/Z values of projectile-like products increase rapidly with nucleon transfer due to isospin transport from target to projectile. A steep valley and peak are clearly visible near projectile and target masses, a feature also observed in ^{64}Ni+^{130}Te and ^{64}Ni+^{208}Pb reactions [**?**, **?**]. The isospin equilibration process depends strongly on contact time, as shown in Fig. 7(b) for contact time regions of $0 < t_{\text{con}} \leq 200$, $200 < t_{\text{con}} \leq 400$, and $400 < t_{\text{con}} \leq 1000$ fm/c. For $0 < t_{\text{con}} \leq 200$ fm/c, most primary products result from quasi-elastic collisions. Strong neutron flow from target to projectile causes a sharp increase in N/Z values of projectile-like fragments, but complete isospin equilibration cannot be achieved due to short contact time. With increasing contact time, enhanced isospin equilibration becomes evident. Products of complete isospin equilibration are produced in symmetric quasi-fission reactions. The isospin equilibration process in MNT reactions can produce very neutron-rich projectile-like fragments, with experiments observing strong neutron absorption by the projectile (^{58}Ni) [?]. For example, after neutron evaporation, ^{67}Ni with a production cross section of about 15 μb was detected in γ-γ coincidence analysis.

IV. CONCLUSIONS

In summary, we have calculated isotope production cross sections in the ^{58}Ni+^{208}Pb reaction at $E_{\text{lab}} = 328.4$ MeV using the ImQMD model, demonstrating its suitability for describing MNT reactions at near-barrier energies. The isospin equilibration process in head-on ^{124}Xe+^{208}Pb collisions shows uniform isospin asymmetry values in the cores of both reaction partners throughout the collision. Neutrons are preferentially driven to low-density areas, with isospin asymmetry values on nuclear surfaces exceeding those in the cores. Neutron flow proceeds from target to projectile along a low-density path and is highly sensitive to symmetry energy, with enhanced neutron flow observed under larger symmetry energy coefficients. The isospin equilibration process depends strongly on contact time between reaction partners. Analysis of average N/Z values of primary binary products in ^{58}Ni+^{208}Pb at $E_{\text{lab}} = 345$ MeV reveals that projectile-like product N/Z values increase rapidly with nucleon transfer. In quasi-elastic collisions, complete isospin equilibration cannot be achieved due to short contact times, whereas complete isospin equilibration occurs in symmetric quasi-fission reactions characterized by massive nucleon transfer and large energy dissipation.

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