Dynamical Study of Neutron-Rich Projectile-Like Fragments in ^{18}O+^{238}U Reactions

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Abstract

Using the improved quantum molecular dynamics model (ImQMD) combined with the GEMINI++ statistical decay model, we investigate the deep inelastic collision process of the ($^{\{18\}O+}${238}U) system at an incident energy of 8.5 MeV/u. By analyzing the total kinetic energy-mass distribution of the reaction products, we clearly identify that projectile-like fragments mainly originate from the deep inelastic collision mechanism. This study calculates the differential cross sections, emission angles, and projectile-target contact times during the collision for isotopes of projectile-like products including carbon (C), oxygen (O), and fluorine (F). The results demonstrate that the differential cross sections of neutron-rich projectile-like fragments peak at emission angles approaching zero degrees. Further analysis reveals that a larger neutron-to-proton ratio (N/Z) of the projectile-like products corresponds to longer projectile-target contact times and smaller emission angles. The dynamical mechanism can be described as follows: after the projectile contacts the target nucleus, a dinuclear system with a neck is formed, which rotates about the center of mass for a duration exceeding 200 fm/c with a rotation angle of approximately 90 degrees. During this rotational contact period, extensive nucleon transfer occurs between the projectile and target. Since the Q-values for the transfer reaction channels 1p+2n, 1p+3n, and 1p+4n from the target nucleus ^{238}U to the projectile ^{18}O are all positive, being 4.212, 3.492, and 5.805 MeV respectively, this facilitates the occurrence of such reactions, leading to a relatively large differential cross section for $^{21-23}$F. The calculated results are in basic agreement with experimental data, thereby validating the effectiveness of the method and intuitively presenting the reaction dynamics mechanism. This research provides crucial reference for new-generation zero-degree spectrometers to conduct low-energy nuclear physics experiments and extract secondary beams of exotic nuclei.

Full Text

Preamble

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Dynamical Study of Neutron-Rich Projectile-Like Fragments Produced in the 18O+238U Reaction

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Abstract

The deep inelastic collision (DIC) process of the 18O + 238U system at an incident energy of 8.5 MeV/u was investigated using the improved quantum molecular dynamics (ImQMD) model coupled with the GEMINI++ statistical decay model. By analyzing the total kinetic energy-mass distribution of reaction products, we unambiguously demonstrate that projectile-like fragments originate primarily from deep inelastic collision mechanisms. Calculations were performed for differential cross sections, emission angles, and projectile-target contact times for projectile-like isotopes of carbon (C), oxygen (O), and fluorine (F). The results reveal that differential cross sections of neutron-rich projectile-like fragments peak at forward angles near zero degrees. Further analysis shows that larger neutron-to-proton ratios (N/Z) of projectile-like products correspond to longer projectile-target contact times and smaller emission angles. The dynamical mechanism can be described as follows: after contact between projectile and target, a dinuclear system with a neck forms and rotates about its center of mass for over 200 fm/c through approximately 90 degrees. During this rotational contact period, substantial nucleon transfer occurs. The Q-values for transfer channels from 238U to 18O (1p+2n, 1p+3n, and 1p+4n) are all positive at 4.212, 3.492, and 5.805 MeV, respectively, which thermodynamically favors these reactions and leads to large differential cross sections for 21–23F. The calculations agree well with experimental data, validating our approach and providing clear visualization of the reaction dynamics. These findings offer critical reference for next-generation zero-degree spectrometers conducting low-energy nuclear physics experiments and extracting exotic secondary beams.

Keywords: ImQMD model; deep inelastic collision; GEMINI++ model; neutron-rich projectile-like fragments; differential cross section

1. Introduction

In recent years, the nuclear physics community has conducted extensive research on heavy-ion collisions near barrier energies, particularly focusing on the production, identification, and structural properties of neutron-rich exotic nuclei far from the β-stability line. These studies hold crucial theoretical significance for topics including superheavy element synthesis, nuclear symmetry energy, and rapid neutron capture processes. Deep inelastic collisions (DIC) can facilitate substantial nucleon transfer near barrier energies, with primary products having relatively low excitation energies that typically de-excite to their ground states through emission of only a few nucleons. Consequently, DIC represents an important pathway for producing neutron-rich exotic nuclei far from stability [1-9]. The phenomenon of deep inelastic nuclear collisions was first observed in the 1960s [10], though its importance as a reaction mechanism was not fully recognized by nuclear physicists until the 1970s. Since then, numerous theoretical frameworks have been developed, including time-dependent Hartree-Fock (TDHF) theory [11-14], the GRAZING model [15-16], multi-dimensional Langevin dynamics models [2,17-19], dinuclear system models [20-27], and the improved quantum molecular dynamics model [28-29].

The primary characteristics of deep inelastic collisions include: formation of a nearly rigidly rotating dinuclear system between projectile and target, nucleon transfer driven by the asymmetry in neutron-to-proton ratio (N/Z), rapid dissipation of relative kinetic energy, and substantial conversion of angular momentum into the intrinsic spins of reaction products. Due to the strong dissipation of total kinetic energy, these reactions are also referred to as strongly damped collisions. Studies indicate that projectile-like fragments (PLF) produced through few-nucleon transfer typically originate from short interaction times and are emitted near grazing angles, while massive nucleon transfer corresponds to longer contact times during which the projectile may undergo significant deflection. Consequently, the angular distribution maxima of multi-nucleon transfer reaction products shift toward smaller angles as the number of exchanged nucleons increases, suggesting that the probability of producing exotic fragments via deep inelastic collisions may increase at emission angles approaching zero degrees. However, definitive experimental verification remains lacking.

Although measurements and identification of multi-nucleon transfer reaction products near zero degrees have attracted considerable attention, experiments face challenges including difficulty in effectively separating low-energy beams and the broad momentum distributions of deep inelastic collision products, which hinder precise cross-section measurements near zero degrees. Available experimental data can be found in references [30-31]. The Super Separator Spectrometer (S3) at France's GANIL laboratory is a high-precision instrument specialized for separating and analyzing atomic and molecular ions, widely applied in nuclear and particle physics research. Capable of producing and utilizing high-intensity low-energy heavy-ion beams with energies of 5–15 MeV/u, S3 can filter exotic deep inelastic collision products at zero degrees for constructing low-energy exotic secondary beams, making it significant for nuclear experimental research. Therefore, predicting reaction cross sections for exotic deep inelastic collision products near zero degrees is crucial. To explore the characteristics of neutron-rich exotic products in deep inelastic collisions, Stefan et al. conducted a nuclear reaction experiment in 2018 using 18O bombarding a 238U target [32].

The experiment was performed at GANIL's LISE spectrometer with an angular acceptance of approximately 1 degree, using an 18O ion beam at 8.5 MeV/u to bombard a 238U target with thickness (1.0 ± 0.1) mg/cm^2. The high N/Z ratio of 238U among stable isotopes facilitates neutron transfer. By measuring the kinetic energy distributions of selected projectile-like products near zero degrees and integrating them, differential reaction cross sections were obtained. Comparisons with deep inelastic transport (DIT) model and nucleus-nucleus collision model based on Langevin equations (NNCLE) revealed that neutron-rich projectile-like products (produced via neutron transfer or proton removal) have maximum cross sections near zero degrees. However, the emission mechanism of fragments near zero degrees and the competition between nucleon pickup and stripping between projectile and target remain unclear and require theoretical investigation.

2. Model Description

Over the past decades, various transport models have achieved remarkable success in describing nuclear reactions, among which the quantum molecular dynamics (QMD) model stands out. Since its introduction by Aichelin's group in the 1980s [33-34], the QMD model has served as a semi-classical microscopic transport theory, playing an important role in intermediate-energy heavy-ion collision research and providing crucial tools for exploring the nuclear equation of state and symmetry energy properties. However, conventional QMD models exhibit significant limitations in treating low-energy nuclear reactions, such as overestimated fusion cross sections due to nuclear surface diffuseness, fixed wave packet widths that restrict dynamical degrees of freedom, and inability to accurately represent fermionic properties. To overcome these limitations, Wang Ning et al. developed the improved quantum molecular dynamics (ImQMD) model [28-29], which incorporates three key improvements: (1) surface energy and surface symmetry energy terms in the potential energy density functional, (2) system-size-dependent wave packet widths, and (3) phase-space occupation number constraints to improve nuclear fermionic properties [35]. These enhancements significantly improve ImQMD's predictive capability for describing heavy-ion fusion reactions near the Coulomb barrier and the dynamical processes and energy dissipation mechanisms in intermediate-energy heavy-ion collisions, advancing heavy-ion collision physics from phenomenological description to mechanistic understanding.

In the ImQMD model, the wave function of a single nucleon is represented as a

Gaussian wave packet:

$$\phi_i(\mathbf{r}) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{4\sigma_r^2} + \frac{i\mathbf{p}_i\cdot\mathbf{r}}{\hbar}\right]$$

where $\mathbf{r}_i$ denotes the wave packet center in coordinate space for the i-th nucleon, $\mathbf{p}_i$ represents the wave packet center in momentum space, and σ_r is the wave packet width in coordinate space. We employ a system-size-dependent wave packet width $\sigma_r = 0.09A^{1/3} + 0.88$ fm [29]. Each nucleon in the collision system moves in the mean field generated by the whole system, with the evolution of the coordinate and momentum centers for the i-th nucleon governed by canonical equations:

$$\dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}, \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}$$

The Hamiltonian of the system consists of potential and kinetic energy components:

$$H = T + U_{\text{Coul}} + U_{\text{loc}}$$

The kinetic energy expression is:

$$T = \sum_i \frac{\mathbf{p}_i^2}{2m} + \frac{3\hbar^2}{8m\sigma_r^2}$$

The Coulomb energy comprises direct and exchange terms:

$$U_{\text{Coul}} = \frac{e^2}{2}\int d\mathbf{r}d\mathbf{r}' \frac{\rho_p(\mathbf{r})\rho_p(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} - \frac{3e^2}{4}\left(\frac{3}{\pi}\right)^{1/3}\int d\mathbf{r}\,\rho_p^{4/3}(\mathbf{r})$$

where ρ_p is the proton density distribution. The local nuclear interaction potential energy is:

$$U_{\text{loc}} = \int V_{\text{loc}}(\mathbf{r})d\mathbf{r}$$

The nuclear interaction potential takes the form:

$$V_{\text{loc}} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^\gamma} + \frac{g_{\text{sur}}}{2\rho_0}(\nabla\rho)^2 + \frac{C_s}{2\rho_0}\left[\rho^2 - \kappa_s(\nabla\rho)^2\right]\delta^2 + g_\tau\frac{\rho^{\gamma+1}}{\rho_0^\gamma}$$

The first term represents the two-body contribution, the second term is the nonlinear density-dependent term, the third term accounts for surface energy, the fourth term includes symmetry and surface symmetry energy contributions, and the fifth term represents momentum dependence. Here $\rho = \rho_n + \rho_p$ denotes nucleon density, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ represents isospin asymmetry, and the interaction potential parameters used in this work are listed in .

A key advantage of QMD models over mean-field approaches is their inclusion of two-body collision terms. For a given reaction event, the energy in the two-nucleon center-of-mass frame is:

$$\sqrt{s} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^{2c^2}}$$

The center-of-mass velocity of colliding particles is:

$$\beta = \frac{\mathbf{p}_1 + \mathbf{p}_2}{E_1 + E_2}$$

In the two-body center-of-mass frame, the momentum of the first particle is:

$$\mathbf{p}^* = \gamma \left[\mathbf{p}_1 - \beta \left(\frac{\mathbf{p}_1 \cdot \beta}{\beta^2} \right) (\gamma - 1) - \beta E_1 \right]$$

where $\gamma = 1/\sqrt{1-\beta^2}$. The second particle has momentum $-\mathbf{p}^*$. The distance between two nucleons is:

$$\Delta \mathbf{r} = (\mathbf{r}_1 - \mathbf{r}_2) + (\gamma - 1) \frac{(\mathbf{r}_1 - \mathbf{r}_2) \cdot \beta}{\beta^2} \beta$$

Two conditions must be satisfied for a nucleon-nucleon collision: first, within the time interval $[-\delta t/2, \delta t/2]$, the particles must reach their minimum distance satisfying $\Delta \mathbf{r} \cdot \mathbf{p}^* = 0$; second, the impact parameter $b = \sqrt{(\Delta \mathbf{r})^2 - [(\Delta \mathbf{r} \cdot \mathbf{p}^*)/p^*]^2}$ must be smaller than the maximum impact parameter corresponding to the total nucleon-nucleon cross section, $b_{\max} = \sqrt{\sigma_{\text{tot}}^{nn}/\pi} \approx 1.32$ fm. For collisions below 150 MeV/u, the elastic channel dominates and only non-relativistic dynamics are considered. With an incident energy of 8.5 MeV/u in this work, we only consider the elastic scattering channel $n + n \to n + n$. The scattering angle is determined via Monte Carlo sampling, and after calculating the scattered momenta in the two-body center-of-mass frame, we transform back to the two-nucleus center-of-mass frame for Pauli blocking evaluation.

3. Results and Discussion

To accurately simulate the production mechanism of neutron-rich projectile-like fragments in the 18O+238U reaction, proper preparation of the initial projectile and target nuclei is crucial, as it directly affects the reliability of low-energy nuclear reaction simulations. We first employ the ImQMD model to sample a large number of initial nuclei and evolve them for 1000 fm/c. Initial nuclei that remain stable during evolution—exhibiting no nucleon emission and maintaining root-mean-square radii and binding energies consistent with experimental values—are selected for subsequent reaction simulations. At the initial reaction time, randomly assigned Euler angles rotate the selected projectile and target nuclei, generating a total of 3 million distinct reaction events to ensure statistical reliability. The ImQMD model evolves the reaction for 700 fm/c, by which time the dynamical process is complete, before coupling to the GEMINI++ statistical decay model. Throughout the simulation, the initial center-of-mass distance between projectile and target is set to 20 fm, with positions and momenta of all nucleons recorded to provide essential data for analyzing the reaction dynamics.

3.1 Optimal Impact Parameters and Reaction Mechanism

In nuclear reaction studies, the impact parameter serves as a key physical quantity for distinguishing different reaction mechanisms. However, due to fluctuation effects, no sharp boundaries exist between mechanisms, making precise definitions challenging. Current understanding suggests that low-energy heavy-ion reactions in the energy regime above the Coulomb barrier but below the Fermi energy exhibit two primary mechanisms: fusion reactions at small impact parameters, and deep inelastic collisions accompanied by fast fission at larger impact parameters. To investigate neutron-rich projectile-like fragment production in the 18O+238U reaction, we estimate the optimal impact parameter range based on empirical nuclear radius formulas. [Figure 1: see original paper] presents the probability of two-fragment events generated by the ImQMD model at various impact parameters (with a minimum fragment mass number of A=5). The figure clearly shows that when the impact parameter is less than 8 fm, the probability of two-fragment events is extremely low, with fusion being the dominant reaction mechanism. Since our focus is on neutron-rich projectile-like products to which fusion contributes negligibly, we select a minimum impact parameter of 8 fm with a step size of 0.5 fm to reduce computational cost. The maximum impact parameter is calculated using the empirical formula:

$$b_{\max} = r_P + r_T + 0.5 \text{ fm}$$

where $r_P = 1.2A_P^{1/3}$ and $r_T = 1.2A_T^{1/3}$ represent the radii of projectile and target, respectively, and the 0.5 fm term accounts for Coulomb excitation effects. For each impact parameter set, 3 million reaction events are simulated to ensure statistical precision. In ImQMD calculations, the initial center-of-mass distance between projectile and target is set to 20 fm, with an evolution time of 700 fm/c and time step of 1 fm/c. The simulation is terminated at 700 fm/c and coupled with the GEMINI++ statistical decay model to handle the de-excitation of primary projectile-like products, yielding final fragment yields and properties. Detailed information about the GEMINI++ statistical decay model can be found in reference [36].

[Figure 2: see original paper] shows the fragment mass distribution from ImQMD+GEMINI++ simulations for the 18O+238U reaction at 8.5 MeV/u. Red squares represent primary products from ImQMD simulations. Three prominent peaks are visible from left to right: the first near A 18 corresponds to projectile-like fragments, the second near A 236 corresponds to target-like fragments, and the third near A 250 arises from fusion-formed compound nuclei. The discrete distribution between A=50 and A=200 corresponds to massive multi-nucleon transfer products. Black solid triangles show the final projectile-like fragment distribution after GEMINI++ statistical decay processing (with primary projectile-like mass numbers restricted to A=5–35). Analysis reveals that the projectile-like fragment distribution remains essentially unchanged after de-excitation, indicating low excitation energies and limited influence from statistical decay.

The total kinetic energy distribution represents a critical observable for understanding reaction mechanisms. However, experimental information on fragment cross sections remains very limited for deep inelastic collisions between light heavy ions (mass numbers A=10–24) and medium-mass or heavy targets at low energies. References [37-38] investigated projectile-like production mechanisms in low-energy 14N+159Tb collisions, revealing that fragments heavier than lithium originate primarily from deep inelastic collisions through analysis of total kinetic energy distributions. In this study, we use the ImQMD model to calculate the total kinetic energy distribution of primary two-fragment events from 18O+238U at 8.5 MeV/u. The total kinetic energy of these primary products mainly derives from Coulomb repulsion. As shown in [Figure 3: see original paper], the dashed line represents the laboratory-frame incident energy, while contour lines indicate the laboratory-frame total kinetic energy distribution. ImQMD simulations show a broad total kinetic energy distribution significantly lower than the incident energy, exhibiting strong damping characteristics consistent with deep inelastic collisions. When impact parameters b$ $8 fm, the probability of two-fragment events increases, excluding fusion dominance. Combined with good agreement with experimental cross sections, this confirms that projectile-like products originate mainly from deep inelastic collision mechanisms.

3.2 Differential Cross Sections of Projectile-Like Fragments

Using the ImQMD model, we calculated key information including charge distributions, mass distributions, and momentum distributions of primary fragments from the 18O+238U reaction. To comprehensively describe the final state, we terminate ImQMD simulations at an appropriate time and introduce the GEMINI++ statistical decay model to process primary products statistically, obtaining final fragment information. The coupling at 700 fm/c is chosen because the dynamical process is essentially complete by this time, with projectile-like fragments having low excitation energy and no longer undergoing significant nucleon emission. Based on these simulations, we calculated differential cross sections for projectile-like isotopes of carbon (C), oxygen (O), and fluorine (F) after GEMINI++ de-excitation, and statistically analyzed the projectile-target contact times and average laboratory-frame emission angles during their formation. In the ImQMD model, the total cross section is expressed as:

$$\sigma = 2\pi \int_{b_{\min}}^{b_{\max}} bP(b)db$$

where b is the impact parameter, $P(b)$ is the production probability of a given fragment at impact parameter b, b_{min} is the minimum impact parameter, and b_{max} is the maximum impact parameter. The angular range is divided into bins starting from 0.5° with 1° steps. Using equation (14), cross sections for each angular bin are calculated and converted to angular differential cross sections by dividing by $2\pi \sin\theta$ (where θ is the left boundary of the angular bin) for comparison with experimental data.

[Figure 4: see original paper] presents experimental differential cross sections for projectile-like isotopes of carbon (C), oxygen (O), and fluorine (F), compared with three theoretical models. The red line shows ImQMD+GEMINI++ results, the black line represents the nucleus-nucleus collision model based on Langevin equations (NNCLE) coupled with the NRV evaporation model, and blue dashed lines correspond to the deep inelastic transport (DIT) model combined with GEMINI++. Red solid points are experimental measurements, with experimental data and DIT/NNCLE model results taken from reference [32]. ImQMD calculations demonstrate that differential cross sections of neutron-rich projectile-like fragments peak at emission angles near zero degrees, then gradually decrease with increasing angle, rapidly approaching zero near grazing angles. All three models show that neutron-rich projectile-like fragment cross sections maximize near zero degrees. Compared to ImQMD, NNCLE and DIT models exhibit a second peak near grazing angles for fragments with lower N/Z ratios, with zero-degree predictions closer to experimental values. For fragments with larger N/Z ratios, NNCLE and DIT model predictions drop rapidly away from zero degrees. ImQMD shows excellent agreement with experimental data near zero degrees, particularly for high N/Z products (22,23F; 21,22O; 17,18C), without the “second peak” at grazing angles seen in other models. This indicates that ImQMD better captures the nucleon transfer dynamics in deep inelastic collisions and reduces dependence on secondary mechanisms like particle evaporation.

To further understand the dynamics of neutron-rich projectile-like fragment emission near zero degrees, [Figure 5: see original paper] shows the time evolution of a typical deep inelastic reaction at impact parameter $b = 10$ fm from ImQMD simulations for the 18O+238U system producing 23F, with total evolution time of 700 fm/c. Red and magenta open circles represent protons from projectile and target, respectively, while black and blue solid points represent neutrons from projectile and target. The projectile 18O shows no significant change in direction between initial and final states. At 200 fm/c, projectile and target contact forms a dinuclear system with a neck. Due to the large impact parameter, the dinuclear system possesses significant angular momentum and clearly rotates about its center of mass from 200 fm/c to 450 fm/c, with rotation duration of approximately 250 fm/c through about 90 degrees. Subsequently, the dinuclear system separates into projectile-like and target-like fragments. During the dinuclear system’s lifetime, the target 238U has N/Z=1.587, greater than the projectile 18O’s N/Z=1.52, and the neutron skin effect of 238U causes its surface N/Z to exceed its central value. Consequently, the neutron density is higher on the neck side near 238U, driving neutrons from the target surface to flow toward the lower-density 18O region. Furthermore, the Q-values for transfer reactions from 238U to 18O (1p+2n, 1p+3n, and 1p+4n) are all positive (4.212, 3.492, and 5.805 MeV, respectively, as shown in from the AME2020 database), thermodynamically favoring these channels and resulting in large differential cross sections for 21–23F. At 450 fm/c, the combined action of Coulomb repulsion and centrifugal force causes the dinuclear system to split into two fragments. Throughout the reaction, 18O transferred 3 neutrons to 238U while receiving 7 neutrons and 2 protons, resulting in a net transfer of 4 neutrons and 2 protons from 238U to 18O. Coulomb excitation during rotation causes minor proton evaporation, with the projectile 18O emitting one proton in this event, ultimately transforming into the more neutron-rich projectile-like fragment 23F. Additionally, Q-values for transfer channels -1p-1n, -1p, and -1p+1n from 238U to 18O are negative and progressively decreasing, corresponding to decreasing cross sections for 16–18C. Positive Q-values for 2n and 4n transfer channels indicate that two- and four-neutron transfers are more favorable. However, ImQMD simulations show no clear systematic trend for 2n and 4n transfer differential cross sections, possibly indicating model limitations.

3.3 Contact Time and Emission Angle

To further investigate characteristics of projectile-like fragments in deep inelastic collisions, we calculated emission angles in the laboratory frame for oxygen isotopes as an example. Figure 6: see original paper shows that neutron-to-proton ratio (N/Z) correlates negatively with emission angle—more extreme N/Z values (either larger or smaller) correspond to smaller average emission angles. This indicates that as the number of exchanged nucleons increases, the angular distribution maximum shifts to smaller angles. We define contact time as the duration from neck formation after projectile-target contact until final separation. Figure 6: see original paper reveals that projectile-like products with more extreme N/Z ratios have longer projectile-target contact times, demonstrating that greater nucleon exchange requires longer contact. For instance, 23F with the largest N/Z ratio has a contact time of approximately 250 fm/c. Extended contact enhances the dinuclear system's rotational effects, causing products to emerge at smaller angles. This study thus reveals the dynamic correlation "more extreme N/Z → longer contact time → smaller emission angle," providing important theoretical guidance for experimental selection of high N/Z exotic nuclei through angular filtering.

Based on this theory, we additionally predicted cross sections near zero degrees (0.5°–1.5°) for nitrogen (N) and neon (Ne) isotopes 18,19,20N and 24,25,26Ne beyond those shown in [Figure 4: see original paper]. These predictions are presented in and will provide crucial theoretical support for extracting exotic secondary beams using the "zero-degree advantage" strategy.

4. Conclusion

Using the improved quantum molecular dynamics (ImQMD) model coupled with the GEMINI++ statistical decay model, we systematically studied the deep inelastic collision process of the 18O+238U system at 8.5 MeV/u. By analyzing two-fragment event probability distributions and empirical nuclear radius formulas, we determined the optimal impact parameter range to be 8–11 fm. The total kinetic energy distribution of primary products exhibits clear energy dissipation and strong damping characteristics, confirming that neutron-rich projectile-like fragments originate primarily from deep inelastic mechanisms with maximum yields in the zero-degree direction. At 700 fm/c evolution time, GEMINI++ de-excitation simulations produce stable final products. Calculated differential cross sections for neutron-rich isotopes of carbon (C), oxygen (O), and fluorine (F) show excellent agreement with experimental values, validating the feasibility of producing exotic secondary beams using low-energy deep inelastic collision products. Furthermore, the study reveals the correlation that more extreme N/Z ratios correspond to longer projectile-target contact times and smaller emission angles (e.g., ~250 fm/c for 23F). This dynamical correlation enhances understanding of isospin effects and nucleon transfer mechanisms in deep inelastic collisions and provides experimental constraints for calibrating microscopic transport models. In summary, this work theoretically supports the "zero-degree cross-section advantage" strategy for extracting exotic secondary beams and provides a solid theoretical foundation for next-generation low-energy spectrometers conducting experiments on extreme nuclear matter.

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