Entrance channel effect on the formation time of nuclei using HICOL code calculations

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Introduction

Heavy-ion-induced fusion-fission (HIFF) dynamics represent a significant area of contemporary research due to the notable impact of entrance channel effects on both fission-fragment mass distributions and particle multiplicities. Many studies have been conducted to examine the influence of shell effects and dissipative forces within the HIFF process, using different projectile-target combinations near the Coulomb barrier [1–5]. These reactions can be studied using two distinct approaches: the statistical model and the dynamical model. The statistical model assumes a fully equilibrated compound nucleus (CN) after fusion and describes its decay using statistical distributions, effectively capturing average fission behavior. However, it may overlook important transient dynamics, especially in cases where the CN is not fully formed. In contrast, the dynamical model provides a more detailed time-dependent description, tracking the system from the initial contact through its evolution and capturing non-equilibrium processes like quasi-fission and fast-fission, providing deeper insight into CN formation and time scales.

For the present study, calculations using the dynamical model HICOL code [6] were performed to investigate formation delay time τ_{fo} (time taken from the start of interaction to CN formation), and shape evolution of the ^{11}B + ^{237}Np ($\alpha = 0.911 > \alpha_{BG} = 0.897$) and ^{16}O + ^{232}Th ($\alpha = 0.871 < \alpha_{BG} = 0.897$) systems, where α represents the entrance channel mass asymmetry and α_{BG} is the critical Businaro-Gallone mass asymmetry, leading to the formation of CN ^{248}Cf. These reactions, having different entrance channel properties, exhibit variations in τ_{fo}, critical for understanding the fusion-fission process.

Dynamical Model Calculations

In the present work, dynamical trajectory calculations were performed using the HICOL code, developed by Feldmeier et al., to simulate the evolution of two colliding nuclei across different angular momentum values (ℓ). The model describes the system as two spherical bodies connected by a neck, characterized by a quadratic surface of revolution, evolving through a one-body dissipation mechanism. The system's evolution is tracked by solving Langevin equations of motion.

The HICOL code focuses on three key parameters: (a) the distance between the nuclei (S), (b) the neck coordinate (σ), and (c) the asymmetry coordinate (Δ). These parameters are defined as follows:

$$\sigma = \frac{V_0 - \left(\frac{4\pi}{3}\right) R_1^3 - \left(\frac{4\pi}{3}\right) R_2^3}{V_0} \tag{1}$$

$$\Delta = \frac{R_1 - R_2}{R_1 + R_2} \tag{2}$$

where V_0 represents the total system volume, and R_1, R_2 are the radii of the interacting nuclei.

Results

This study presents dynamical trajectory calculations for the reactions ^{11}B + ^{237}Np and ^{16}O + ^{232}Th at an excitation energy of 60 MeV. Figures 1(a) and 1(b) includes fusion and non-fusion trajectories on the (S, σ) plane for selected angular momentum values. For

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the ^{16}O + ^{232}Th system, the HICOL code predicts fusion for $\ell \leq 39\hbar$, while for ^{11}B + ^{237}Np, fusion is predicted for $\ell \leq 38\hbar$. At higher ℓ, non-equilibrated systems reseparate into projectile-like and target-like fragments, corresponding to quasi-elastic events with minimal mass exchange. The formation time, as calculated using the HICOL code, is 15.8×10^{-21} sec for ^{16}O + ^{232}Th and 8.54×10^{-21} sec for ^{11}B + ^{237}Np.

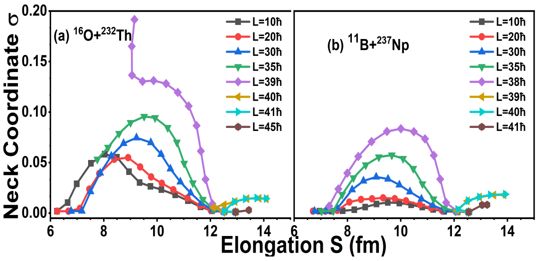

FIG. 1: Neck coordinate vs. elongation for fusion and non-fusion trajectories for the reactions (a) ^{16}O + ^{232}Th and (b) ^{11}B + ^{237}Np.

Figures 2(a) and 2(b) illustrate how elongation S (in femtometers) evolves with time (in 10^{-22} seconds) for both systems. Experimentally, the ^{11}B + ^{237}Np system shows shorter formation time (5-10 $\times 10^{-21}$ s) compared to ^{16}O + ^{232}Th (10-15 $\times 10^{-21}$ s) [7]. The larger formation time in later case is due to large mass transfer from target to projectile which leads to increase in formation time scale. This suggests a gradual increase in CN formation time when moving from the asymmetric to a symmetric system in the entrance channel. Considering that the emission of neutrons also takes place from the dinuclear system before it attains the equilibrium configuration, the number of neutrons emitted during the formation time for ^{16}O + ^{232}Th will be larger due to its longer formation time, as also observed experimentally by A. Saxena et al. [7]. These findings imply that the observed pre-scission neutron multiplicity and fission delay for ^{11}B + ^{237}Np and ^{16}O + ^{232}Th reactions can be understood quantitatively by considering the different formation time values as predicted by the dynamical code HICOL. A comparison of τ_{fo} for these reactions indicates the presence of entrance channel effects, which significantly influence the fusion-fission dynamics. In conclusion, dynamical model calculations using the HICOL code for the ^{11}B + ^{237}Np and ^{16}O + ^{232}Th reactions predict different CN formation times for the two systems. The HICOL code further predicts that fusion occur for $\ell \leq 38\hbar$ for ^{11}B + ^{237}Np and $\ell \leq 39\hbar$ for ^{16}O + ^{232}Th, while at higher angular momentum values, non-compound events dominate.

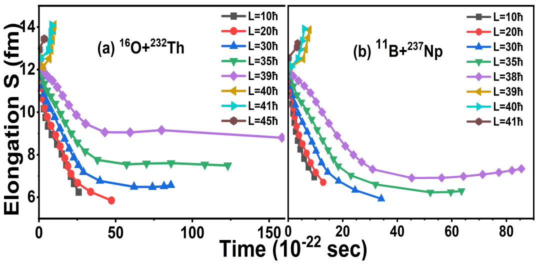

FIG. 2: Elongation vs. time for various values of angular momentum for the reactions (a) ^{16}O + ^{232}Th and (b) ^{11}B + ^{237}Np.

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References

[1] Prashant N. Patil et al., Phys. Rev. C **102**, 034618 (2020).
[2] M. Thakur et al., Eur. Phys. J. A **53**, 133 (2017).
[3] K. S. Golda et al., Nucl. Phys. A **913**, 157 (2013).
[4] M. Thakur et al., Phys. Rev. C **98**, 014606 (2018).
[5] C. Sharma et al., Phys. Rev. C **107**, 064615 (2023).
[6] H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).
[7] A. Saxena et al., Phys. Rev. C **49**, 932 (1994).