

Investigating entrance channel effect through the measurement of neutron multiplicity in mass region $a \approx 200$

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ABSTRACT

In this study, we measured both the pre-scission and post-scission neutron multiplicities for the $^{31}\text{P} + ^{170}\text{Er}$ reaction at excitation energies in the range of 62–84 MeV, using the National Array of Neutron Detectors (NAND) at Inter University Accelerator Centre (IUAC), New Delhi. Theoretical calculations to reproduce the measured neutron multiplicities have been performed using the dynamical model code VECLAN. These calculations show that the dissipation strength parameter (β) increases with excitation energy. Dynamical model calculations also have been performed using HICOL code to understand the fusion dynamics and formation time. It has been observed that transitioning from an asymmetric to a symmetric entrance channel leads to a gradual increase in the compound nucleus formation time, accompanied by more emission of neutrons during its formation.

1. Introduction

In the field of nuclear physics, the examination of heavy-ion induced fusion-fission reactions is an intriguing area of research using both theoretical and experimental methods. In such reactions, the projectile is captured by the target nucleus, leading to the creation of a compound nucleus (CN) that is equilibrated in all degrees of freedom. Sometime before a completely equilibrated CN formation, the dinuclear system may segregate prematurely. Such types of events with various degrees of equilibration are known as non-compound nuclear (NCN) processes such as Quasi-fission and the entrance channel mass asymmetry is roughly maintained in NCN processes, although large kinetic energy and angular momentum dissipation may occur [1–6]. In contrast, CN formation (fusion process) is characterized by the complete loss of entrance channel information due to the equilibration in all degrees of freedom.

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The emission of light particles, including alpha particles, protons, neutrons, gamma rays, and fission fragments provides valuable insights into the fusion-fission process of the excited compound nucleus. The multiplicities of these particles can serve as a clock to determine the lifetime of the composite nucleus before fission occurs. The term pre-scission neutron multiplicity (M_{pre}) is used to describe the number of neutrons released from the fused system moving with the compound nucleus velocity [7–9], while post-scission neutron multiplicity (M_{post}) is used to describe the neutrons released from the completely accelerated fission fragments [10,11]. The pre-scission neutron multiplicity is also affected by neutron evaporation taking place from the dinuclear system before it reaches its equilibrium configuration. The excess yield of the particle multiplicity from the heavy compound nucleus is explained by the transition-state model of fission, which indicates the slowing down of the fission process [12].

The concept of nuclear dissipation plays a crucial role in fusion-fission dynamics, influencing fusion-fission hindrance. Reproducing the experimental pre-scission neutron multiplicities (M_{pre}) using statistical model codes allows one to derive the dissipation strength and fission time of the reaction [13,14].

It has been observed that the charge product ($Z_P \cdot Z_T$) and the entrance channel mass asymmetry influence the contribution of non-compound nucleus (NCN) processes to fusion-fission. The entrance channel mass asymmetry is expressed as:

$$\alpha = \frac{A_T - A_P}{A_T + A_P}$$

where A_P and A_T are the mass numbers, and Z_P and Z_T are the atomic numbers of the projectile and target nuclei, respectively [15,16].

Experimental studies have demonstrated that the entrance channel characteristics affect pre-scission neutron multiplicities. A. Saxena et al. [17] reported this effect, while neutron multiplicity measurements for the $^{19}\text{F} + ^{209}\text{Bi}$ reaction [18] provided additional insights. Further studies on the entrance channel effect have been conducted for $^{12}\text{C} + ^{204}\text{Pb}$ and $^{19}\text{F} + ^{197}\text{Au}$ reactions at laboratory energies of 75–95 MeV [19], as well as for $^{18}\text{O} + ^{186}\text{W}$ and $^{16}\text{O} + ^{181}\text{Tl}$ reactions, which populate the ^{204}Pb and ^{197}Tl compound nuclei, respectively [20].

In a previous experiment, C. Sharma et al. [21] observed variations in pre-scission neutron yields for two different entrance channels, $^{12}\text{C} + ^{198}\text{Pt}$ and $^{18}\text{O} + ^{192}\text{Os}$, both forming the same compound nucleus (^{210}Po) at the same excitation energy. Their findings suggest that the longer formation time for a more symmetric system might explain the entrance channel effect on pre-scission neutron yields.

To further examine the interplay between fusion-fission and non fusion-fission, several experimental techniques are employed, including the analysis of mass distribution (MD) [22,23], mass-energy distribution (MED) [23,24], and mass-angle distribution (MAD) [25] of fission fragments. B. B. Back et al. [26] studied the entrance channel effect by measuring the MD for $^{32}\text{S} + ^{182}\text{W}$, $^{48}\text{Ti} + ^{166}\text{Er}$, and $^{60}\text{Ni} + ^{154}\text{Sm}$ reactions. G. N. Knyazheva et al. [27] investigated non fusion-fission processes in $^{40,48}\text{Ca} + ^{144,154}\text{Sm}$ reactions through MED measurements. Similarly, R. G. Thomas et al. [28] explored the entrance channel effect by measuring the MAD for $^{16}\text{O} + ^{204}\text{Pb}$, $^{34}\text{S} + ^{186}\text{W}$, and $^{48}\text{Ti} + ^{170}\text{Er}$, all forming the ^{220}Th nucleus at similar excitation energies.

In the present study, we have measured neutron multiplicities for the $^{31}\text{P} + ^{170}\text{Er}$ reaction, leading to the formation of ^{201}Bi within excitation energy range of 62–84 MeV. Dynamical calculations have been conducted to determine the dissipation strength parameter and formation time. These calculations are also extended to the $^{19}\text{F} + ^{184}\text{W}$ reaction, which populates ^{203}Bi at the same excitation energies, to reproduce neutron multiplicities.

Mass-angle distribution and pre-scission neutron multiplicity studies have previously been carried out for the $^{19}\text{F} + ^{184}\text{W}$ reaction to investigate the presence of non fusion-fission [24]. The two reactions studied here, $^{31}\text{P} + ^{170}\text{Er}$ and $^{19}\text{F} + ^{184}\text{W}$, have different entrance channel mass asymmetries (α). As a result, comparing these reactions allows us to examine the impact of entrance channel properties on nuclear dissipation and fusion-fission dynamics.

2. Experimental set up

The experiment was conducted using a pulsed beam of ^{31}P at energies of 150–180 MeV, with a 250 ns pulse separation. The pulsed beam was provided by the 15UD Pelletron + LINAC at the Inter University Accelerator Centre (IUAC), New Delhi, India. A self-supporting target of ^{170}Er of 2.1 mg/cm² thickness was used in this experiment. Two multiwire proportional counters (MWPCs) with an active area of $20 \times 10 \text{ cm}^2$ [29,30] are placed at $\pm 67^\circ$ folding angle with respect to the beam direction. Two silicon detectors (M1 and M2) were positioned at $\pm 12^\circ$ relative to the beam direction in the horizontal plane at 42.0 cm from the target to monitor the beam. The MWPCs were operated with isobutane gas at a pressure of 3.5 mbar. Neutrons were detected in coincidence with fission fragments using the NAND array [31–33], which consists of 50 organic liquid scintillator neutron detectors. The data acquisition system was triggered by a logical OR of the time-of-flight (TOF) signals from both MWPCs, in conjunction with a logical AND operation involving the beam's radio frequency (RF) signal. Fig. 1 illustrates the complete experimental setup, including the BC501A liquid scintillator detectors, each consisting of a $5'' \times 5''$ cylindrical cell coupled to a $5''$ photomultiplier tube (PMT-R4144).

Fig. 2 shows the time-of-flight (TOF) spectra obtained from the two multiwire proportional counters (MWPCs). These MWPCs were used to detect the fission fragments emitted from the target following the heavy-ion induced reaction $^{31}\text{P} + ^{170}\text{Er}$. The TOF signals play a crucial role in discriminating true fission events from other reaction channels such as elastic scattering and transfer reactions. A coincidence condition between the two MWPCs ensures that the detected fragments are complementary and originate from the same fission event. In the figure, the solid black contour represents the fission gate, within which events are considered true fission fragments, while those outside this gate correspond to background or unrelated signals. This gating significantly reduces contamination and enhances the accuracy of the neutron multiplicity measurements.

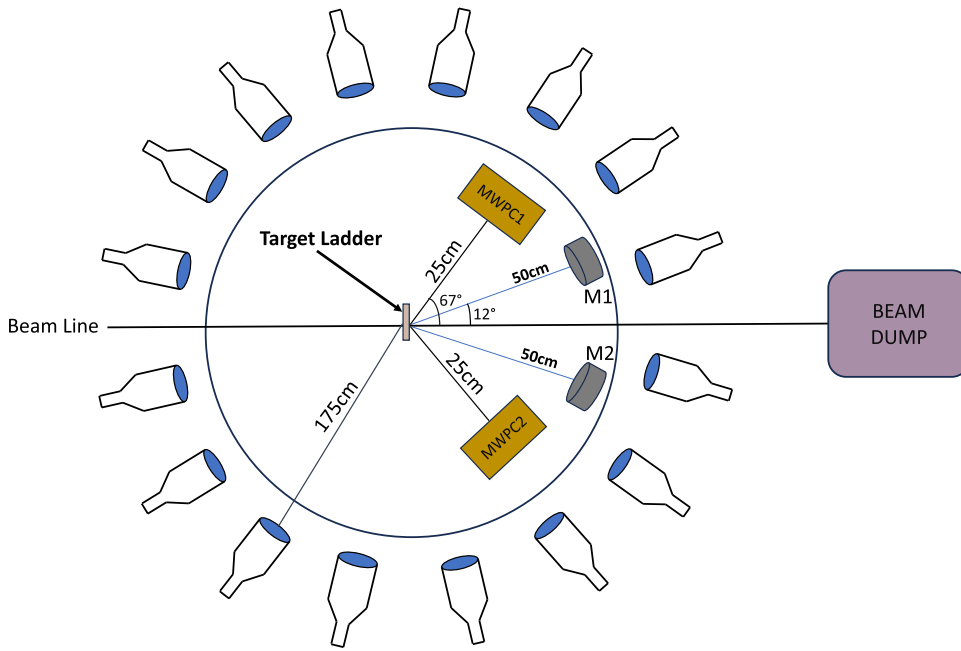


Fig. 1. Experimental configuration for the measurement of neutron multiplicity.

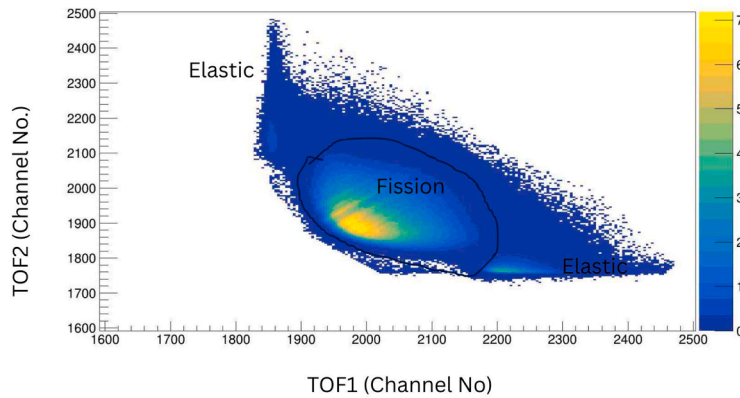


Fig. 2. Time correlations between the MWPC detectors. Solid black contour is the fission gate.

Neutrons were distinguished from gamma rays using the pulse shape discrimination (PSD) method [34], which combines zero-crossing and time-of-flight (TOF) techniques. Fig. 3 presents a Pulse Shape Discrimination (PSD) versus Time-of-Flight (TOF) plot for the BC501A liquid scintillator detectors used in the NAND array. Since the BC501A scintillators detect both neutrons and gamma rays, their signals can overlap. To separate these, a PSD technique is applied, exploiting the fact that neutrons and gamma rays produce scintillation pulses with different decay characteristics. Two distinct bands are clearly visible corresponding to prompt gamma-ray events and neutron events. The clear separation between these bands demonstrates the excellent neutron-gamma discrimination capability of the detection system. This separation is essential for accurately extracting neutron energy spectra and multiplicities.

The neutron TOF spectra were converted into energy spectra using the prompt gamma peak as a reference, using the standard non-relativistic relation.

A ROOT-based data acquisition system was employed to collect event-mode data [35].

3. Data analysis and results

The observed neutron energy spectra were fitted simultaneously using the Watt's equation [36], incorporating three moving sources: CN and two completely accelerated fission fragments in order to derive the pre- and post-scission neutron multiplicities. The total neutron multiplicity is then given by:

$$M_{total} = M_{pre} + 2M_{post} \quad (1)$$

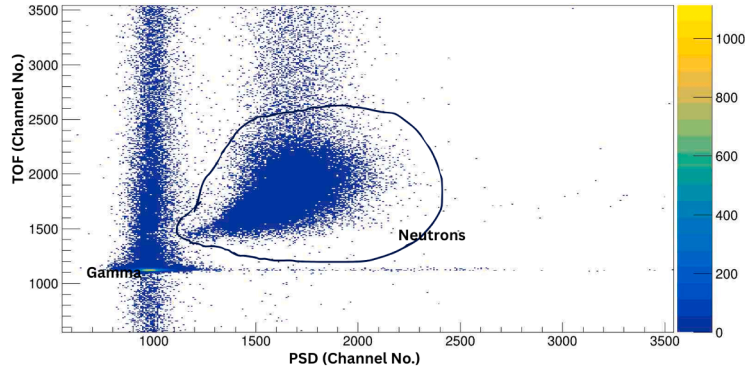


Fig. 3. PSD versus TOF plot showing the excellent discrimination of neutrons from the gamma rays.

Table 1

Extracted values of M_{pre} , $2M_{post}$, T_{pre} , T_{post} and M_{total} .

$E^* (MeV)$	M_{pre}	$2M_{post}$	$T_{pre} (MeV)$	$T_{post} (MeV)$	M_{total}
84.4	3.77 ± 0.12	2.08 ± 0.04	1.35 ± 0.035	1.17 ± 0.03	5.85 ± 0.12
80.2	3.57 ± 0.10	2.22 ± 0.04	1.40 ± 0.03	1.13 ± 0.03	5.79 ± 0.10
75.5	3.16 ± 0.09	2.52 ± 0.03	1.16 ± 0.03	1.24 ± 0.02	5.68 ± 0.09
71.1	3.00 ± 0.09	2.18 ± 0.03	1.26 ± 0.02	1.14 ± 0.02	5.18 ± 0.09
62.0	2.24 ± 0.09	2.00 ± 0.03	1.12 ± 0.03	1.06 ± 0.02	4.24 ± 0.09

It was assumed that neutron emission from these moving sources was isotropic in their respective rest frames. Consequently, the measured double differential neutron multiplicities are expressed as:

$$\frac{d^2 M_n}{dE_n d\Omega_n} = \sum_{i=1}^3 \frac{M_i \sqrt{E_n}}{2(\pi T_i)^{\frac{3}{2}}} \times \exp \left(-\frac{E_n - 2\sqrt{\frac{E_n E_i}{A_i}} \cos \theta_i + \frac{E_i}{A_i}}{T_i} \right) \quad (2)$$

where A_i , E_i , and T_i denote the mass, kinetic energy, and temperature of each source that emits neutrons, and E_n denotes the neutron energy in the laboratory frame. The multiplicity contributing from each source is denoted by M_i . The angle at which a neutron emits relative to its emitting source is represented by θ_i . T_{pre} was determined by using the relation

$$T_{pre} = \sqrt{\frac{E^*}{a}} \quad (3)$$

where 'a' is the level density parameter and E^* is the CN excitation energy. To account for the cascade of successive particle evaporation, the value of 'a' is further scaled down by a factor of 11/12th of the expected value of $A_{CN}/10\text{MeV}^{-1}$. The kinetic energies of fission fragments (E_2 and E_3) are determined by using Viola systematics for symmetric fragmentation [37]. All of the neutron energy spectra were fitted simultaneously keeping the M_{pre} , M_{post} , T_{pre} , and T_{post} free parameters. Table 1 presents the values of these free parameters, obtained after best fitting.

Fig. 4 presents the few fitted neutron spectra. The obtained M_{pre} values are compared with the results of $^{19}\text{F} + ^{184}\text{W}$ reaction [24] to study the entrance channel effect.

4. Theoretical calculations

4.1. Langevin dynamical model calculations (VECLAN)

In order to understand the strength of dissipation parameter in fusion-fission process, dynamical calculations have been performed using VECLAN [38]. VECLAN is a computational code developed by Jhilam Sadhukhan for extracting neutron multiplicity using a Monte Carlo Langevin approach. It is specifically designed for studying nuclear fission dynamics, including neutron evaporation, energy dissipation, and angular momentum effects in heavy ion induced reactions. The heavy-ion-induced reactions can be viewed as three consecutive kinetic evolutions: from the formation of thermalized binuclear composites to their trapping in nuclear potential well, then either evolving to a fully equilibrated CN or decaying via non fusion-fission trajectories. The compound nucleus (CN) formed can either decays to residues after light charged particle emission or undergoes fission. According to the theory of compound nuclear reactions, M_{pre} should be independent of the entrance channel, as neutron evaporation takes place only after a CN with a specific angular momentum (ℓ) and excitation energy (E^*) has been formed [39]. We evaluate M_{pre} by assuming that every captured

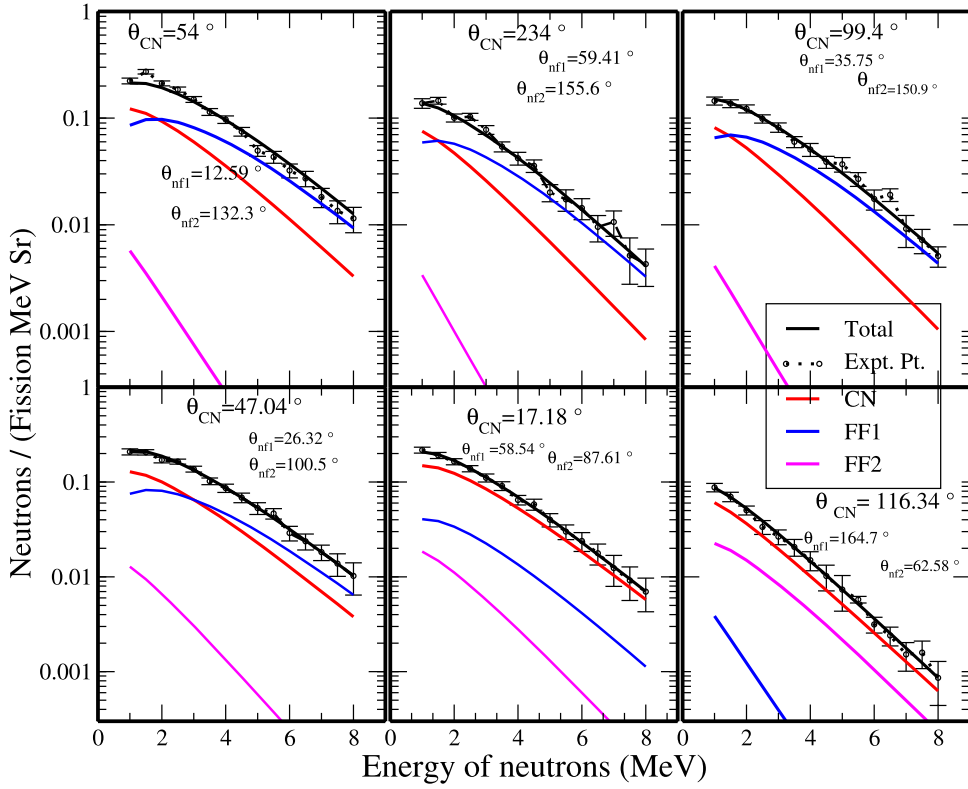


Fig. 4. Neutron spectra for the reaction $^{31}\text{P} + ^{170}\text{Er}$ at an excitation energy of 80.2 MeV. The solid black circles represent experimental data points. The fits for pre-scission (red), post-scission from one fragment (blue), and from the other fragment (magenta) are also displayed. The solid black line indicates the sum of all three contributions. Here, θ_{CN} denotes the angle of the neutron detector relative to the beam axis, while θ_{nf1} and θ_{nf2} represent the angles between the emitted neutrons and the fission fragments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

event emerges into a CN. In order to simulate the time-evolution for compound nucleus, we solve Langevin dynamics for fission. For the Hill-Wheeler elongation coordinate c [40], the Langevin equation is [41]

$$\frac{dp}{dt} = -\frac{p^2}{2} \frac{d}{dc} \left(\frac{1}{m} \right) - \frac{dF(c)}{dc} - \beta p + g\Gamma(t) \quad (4)$$

$$\frac{dc}{dt} = \frac{p}{m} \quad (5)$$

where p is the collective momentum and m is the shape-dependent collective inertia determined using the Werner-Wheeler prescription [42]. Γ represents the random force, with its strength determined by the fluctuation-dissipation theorem ($g = \sqrt{mT\eta}$) [43]. Here, η is the dissipation coefficient. The double-folding Yukawa-plus-exponential potential provides the Helmholtz free energy, $F(c)$ [44], as follows:

$$F(c) = V(c) - [a(c) - a(0)]T^2 \quad (6)$$

where $a(c)$ is the shape dependent level density parameter, $V(c)$ represents the potential energy of the system and T is the Fermi gas temperature. In $V(c)$, pairing and deformation-dependent shell energy corrections are taken into account. In order to derive the microscopic energy corrections, the two-centered shell model [45] is solved and Strutinsky's prescription is employed [46]. At every Langevin time-step, the evaporation of neutrons, protons, α -particles, and GDR γ -rays is taken into account by using Monte Carlo technique. Within the parameters of the usual statistical model prescription, evaporation widths are calculated [47,48]. To reproduce the experimental M_{pre} , the reduced dissipation strength β ($\beta = \eta/m$) is used as a free parameter and β is individually adjusted for each excitation energy as shown in Fig. 5(b). It is observed that the dissipation parameter β increases with excitation energy. Using the corresponding values of β , the calculated pre-scission neutron multiplicities (M_{pre}) are plotted against excitation energy in Fig. 5(a) for both reactions. Both M_{pre} and β show an increasing trend with rising excitation energy.

4.2. HICOL calculations

Dynamical model calculations were performed using the HICOL code for both reactions at the same excitation energy. We employed Feldmeier's model [49], in which the colliding nuclei are treated as two Fermi gases that exchange momentum, particles, and entropy

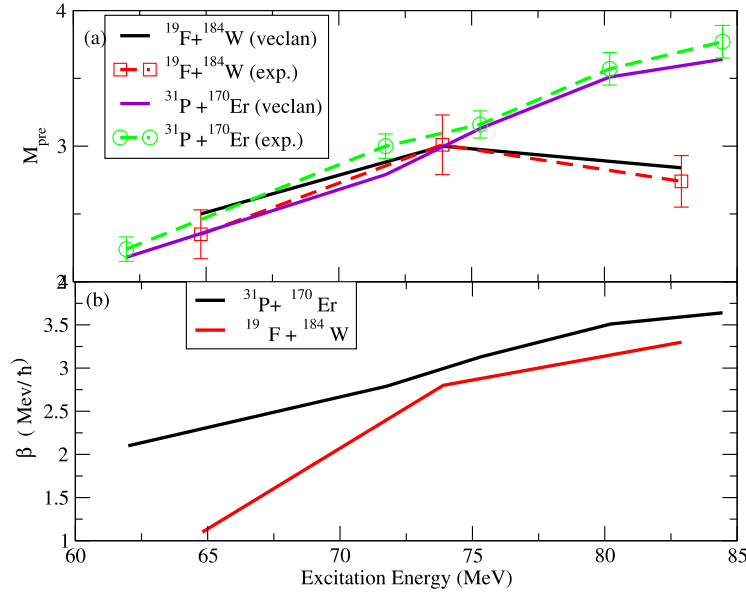


Fig. 5. (a) Experimental and calculated (Veclan) neutron multiplicity for $^{31}\text{P} + ^{170}\text{Er}$ and $^{19}\text{F} + ^{184}\text{W}$ reactions at different excitation energies. M_{pre} values for $^{19}\text{F} + ^{184}\text{W}$ are taken from Ref. [24] (b) β used for the dynamical calculations for both reactions.

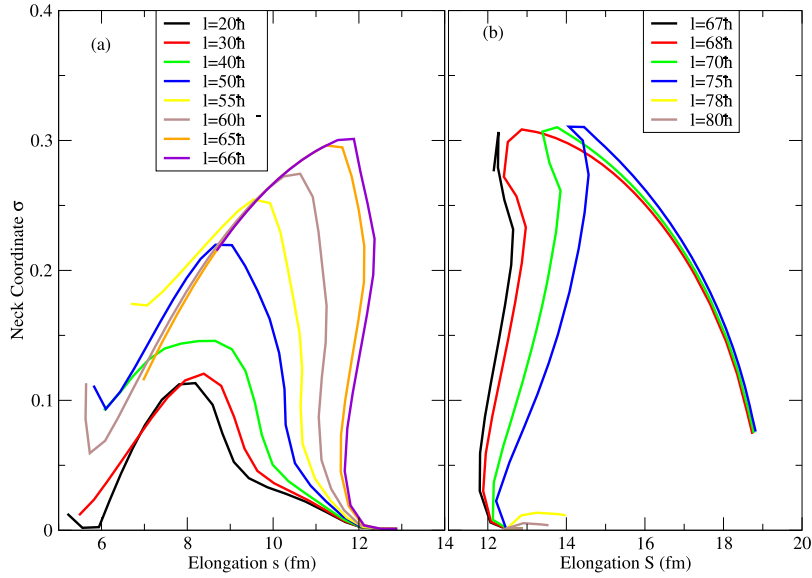


Fig. 6. The neck coordinate versus elongation for fusion and non-fusion trajectories for the $^{31}\text{P} + ^{170}\text{Er}$ reaction at $E^* = 84.4$ MeV are illustrated in (a) and (b) respectively.

through a window in the mean single-particle potential. The temporal evolution of the collision dynamics is obtained by solving the Fokker-Planck equation incorporating a dissipative fluctuating force.

The evolving nuclear configuration is represented by a sequence of shapes resembling two connected spheres, joined by a neck that varies smoothly. The total volume V_o of the composite system is preserved throughout the interaction, ensuring constant mass and charge densities. Each shape is described by three macroscopic collective coordinates: the distance between the centers of the colliding nuclei (s), the neck coordinate (σ), and the mass asymmetry (Δ), defined as follows:

- s - the distance between the centers of the two spheres.
- σ - a dimensionless measure of the neck size, defined as:

$$\sigma = \frac{V_o - \frac{4}{3}\pi R_1^3 - \frac{4}{3}\pi R_2^3}{V_o} \quad (7)$$

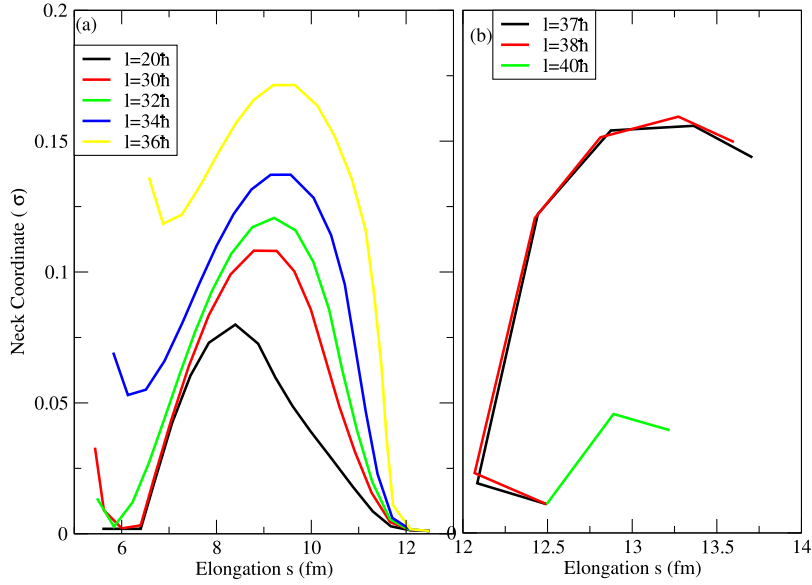


Fig. 7. The neck coordinate versus elongation for fusion and non-fusion trajectories for the $^{19}\text{F} + ^{184}\text{W}$ reaction at $E^* = 85$ MeV are illustrated in (a) and (b) respectively.

where R_1 and R_2 are the radii of the two spherical fragments. The range of σ is $[0, 1]$, where $\sigma = 0$ corresponds to complete separation (i.e., no neck), and $\sigma = 1$ corresponds to the initial mononuclear shape with vanishing fragment volumes.

- Δ - the system mass asymmetry, directly expressed in terms of projectile and target mass numbers:

$$\Delta = \frac{A_T - A_P}{A_T + A_P} = \alpha \quad (8)$$

where A_T and A_P are the mass numbers of the target and projectile, respectively. This parameter is sometimes also denoted by α , particularly in the context of entrance channel mass asymmetry. For clarity, in this work we consistently use Δ to represent both the entrance channel and dynamic asymmetry, depending on context.

The model provides a macroscopic description of nucleus-nucleus collisions, including one-body dissipation effects due to nucleon motion against time-dependent nuclear boundaries [50].

The results of the HICOL simulations are shown in Figs. 6 and 7. Fig. 6 presents the fusion and non-fusion trajectories for the $^{31}\text{P} + ^{170}\text{Er}$ reaction, while Fig. 7 shows those for the $^{19}\text{F} + ^{184}\text{W}$ reaction at the same excitation energy i.e. 84.4 MeV. For the $^{31}\text{P} + ^{170}\text{Er}$ reaction, fusion is observed for angular momenta up to $\ell = 20h$ to $66h$. For $\ell > 66h$, although the composite system develops a thick neck, it does not proceed to complete fusion; instead, it re-separates into two fragments. However, the neck coordinate σ does not approach zero, implying the system does not return to the initial contact configuration but undergoes shape evolution indicative of near-symmetric mass split. While fusion-fission is not achieved, the geometry and symmetry of the neck at scission suggest the emission of nearly symmetric fragments. As shown in figure 7, fusion does not take place for angular momenta up to $\ell > 36h$ for $^{19}\text{F} + ^{184}\text{W}$ reaction.

From the fusion trajectories, we extract the formation time (τ_{fr}) of the compound nucleus (CN) [51]. For the $^{31}\text{P} + ^{170}\text{Er}$ system, $\tau_{fr} \approx 8.6 \times 10^{-21}$ s, whereas for the $^{19}\text{F} + ^{184}\text{W}$ reaction, $\tau_{fr} \approx 0.44 \times 10^{-21}$ s at $\ell = 30h$. The maximum formation time for $^{31}\text{P} + ^{170}\text{Er}$ is $\approx 49.2 \times 10^{-21}$ seconds at $\ell = 66h$ whereas the maximum formation time for $^{19}\text{F} + ^{184}\text{W}$ is $\approx 6.1 \times 10^{-21}$ seconds at $\ell = 36h$. A more symmetric entrance channel configuration leads to an increased formation time for the CN. This results in a longer pre-equilibrium phase and a higher likelihood of neutron evaporation prior to fusion. Consequently, more neutrons are emitted during the formation of the CN in the $^{31}\text{P} + ^{170}\text{Er}$ reaction compared to the $^{19}\text{F} + ^{184}\text{W}$ reaction.

This finding is consistent with existing theoretical expectations and literature. The entrance channel mass asymmetry, quantified by Δ , is 0.691 for the $^{31}\text{P} + ^{170}\text{Er}$ reaction and 0.812 for the $^{19}\text{F} + ^{184}\text{W}$ reaction. The lower Δ (i.e., more symmetric entrance channel) in the former results in longer formation time and increased neutron emission.

5. Summary and conclusion

In this study, we investigated the influence of the entrance channel on fusion-fission dynamics by measuring neutron multiplicities for the $^{31}\text{P} + ^{170}\text{Er}$ reaction across an excitation energy range of 62-84 MeV. Present results were compared with existing data from the $^{19}\text{F} + ^{184}\text{W}$ reaction, providing valuable insights into the role of entrance channel effects.

Our findings show that the collective dynamics involved in fusion processes significantly affect neutron multiplicities. Notably, we observed two distinct behaviors for the two entrance channels. The formation time of the compound nucleus in the $^{31}\text{P} + ^{170}\text{Er}$

reaction is longer compared to the $^{19}\text{F} + ^{184}\text{W}$ reaction, as indicated by HICOL dynamic simulations. These observations highlight the critical role of entrance channel effects in shaping fusion-fission dynamics and provide a deeper understanding of the underlying mechanisms at play.

Additionally, the dissipative nature of both reactions is evident from the increase in the dissipation parameter (β) with excitation energy.

CRedit authorship contribution statement

Neha Dhanda: Writing – original draft, Data curation, Conceptualization, Writing – review & editing, Formal analysis, Methodology; **Ashok Kumar:** Writing – review & editing, Supervision; **Chetan Sharma:** Writing – review & editing, Visualization; **Amninder-jeet Kaur:** Visualization, Writing – review & editing; **Basant Sura:** Visualization, Writing – review & editing; **Komal:** Visualization, Writing – review & editing; **Amit:** Visualization, Writing – review & editing; **Kiran:** Visualization, Writing – review & editing; **B. R. Behera:** Visualization, Writing – review & editing; **P. Sugathan:** Visualization, Writing – review & editing; **Akhil Jhinghan:** Visualization, Writing – review & editing; **N. Saneesh:** Visualization, Writing – review & editing; **K. S. Golda:** Visualization, Writing – review & editing; **Mohit Kumar:** Visualization, Writing – review & editing; **Rishabh Parjapati:** Visualization, Writing – review & editing; **Avitesh Agrawal:** Visualization, Writing – review & editing; **Ishika Sharma:** Visualization, Writing – review & editing; **H. P. Sharma:** Visualization, Writing – review & editing; **S. K. Chamoli:** Visualization, Writing – review & editing; **Swapna Balkrishna:** Visualization, Writing – review & editing; **R. Akhil:** Visualization, Writing – review & editing; **Lakhyajit Sarma:** Visualization, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no competing interests.

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