

Presence of quasifission in the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction populating the compound nucleus ^{206}Po

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Fission fragment mass distribution has been studied for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ populating the compound nucleus ^{206}Po at near-barrier energies to understand the effects of entrance channel mass asymmetry and deformation in the preactinide region. No appreciable deviation from a single Gaussian fit to the experimental mass distribution shows a nearly symmetric mass split for the composite system at the present experimental energy range. The experimentally measured fission fragments mass variance for $^{30}\text{Si} + ^{176}\text{Yb}$ has been compared with the more asymmetric reaction $^{12}\text{C} + ^{194}\text{Pt}$ having mass asymmetry lying on either side of the α_{BG} value. The statistical saddle point model (SSPM) calculations based on compound nucleus fission for the two reactions indicate the presence of quasifission in the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction. Moreover, the higher variance of mass distribution near and below barrier energies shows the effect of deformation of the projectile and target on quasifission. The experimental data are also compared with the fission of nearby systems. The present result is consistent with the earlier findings of evaporation residue (ER) cross section for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$, where suppression in the ER cross section is attributed to noncompound nucleus fission and its dependence on entrance channel properties.

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I. INTRODUCTION

The systematic study of the fusion-fission process is very important to understand the complex dynamical evolution of the composite system formed via heavy-ion-induced reactions at energies near the Coulomb barrier. For the synthesis of superheavy elements (SHEs), the excitation energy of the composite system is required to be just above the fusion threshold, where the formation and survival probability of the heavy (or superheavy) evaporation residues (ERs) are maximum [1–3]. However, in some cases, it is evident experimentally that many collision trajectories lead to fusion hindrance not only by the compound nucleus (CN) fission but also due to the noncompound nucleus (NCN) fission processes like fast fission [4–6], preequilibrium fission [7], and quasi-fission (QF) [8,9], which competes with the ER formation at different angular momentum and excitation energies. In CN fission, the composite system after fusion achieves the

equilibration of all degrees of freedom (compound nucleus configuration) and ends up in fission via the mass symmetric unconditional saddle point in the potential energy surface (PES), while in QF the dinuclear system [10] reaches the mass conditional asymmetric saddle leading to the incomplete equilibration of mass and shape degrees of freedom [11–13].

The properties of the entrance channel of the colliding nuclei are crucial for studying the onset and presence of quasi-fission, and they have significantly aided in the theoretical and experimental understanding of the reaction dynamics over the last few decades. The charge product of the projectile and the target nuclei (Z_p, Z_T) [11,14–16], mass asymmetry (α) [$\alpha = (A_T - A_p)/(A_T + A_p)$] (where A_T and A_p are the target and projectile mass, respectively) with respect to the Businaro-Gallone [17] critical mass asymmetry α_{BG} [18–21], shell effects [22–25], deformation of the colliding partners [15,26–28], CN fissility [29,30], neutron-to-proton ratio of the CN [31,32], etc. are the key factors that heavily influence the heavy-ion-induced reaction mechanism. To disentangle the CN fission from NCN fission processes, researchers have extensively used various experimental probes, utilizing one or

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TABLE I. Entrance channel parameters calculated for the systems considered under this study. V_B is the average capture barrier in the center-of-mass frame; χ_{CN} , χ_{eff} , χ_m are the fissility of the CN, entrance channel fissility, and mean fissility, respectively, calculated using the prescription given in Ref. [30]. Quadrupole deformation (β_2) values are taken from Ref. [65]. The meaning of the remaining notations are described in the text.

Reaction	V_B (MeV)	χ_{CN}	χ_{eff}	χ_m	α	α_{BG}	$\beta_2(\text{projectile})$	$\beta_2(\text{target})$	$Z_P Z_T$
$^{30}\text{Si} + ^{176}\text{Yb}$	112.7	0.7165	0.5406	0.6579	0.7087	0.8469	-0.315	0.289	980
$^{12}\text{C} + ^{194}\text{Pt}$	56.60	0.7165	0.3657	0.5996	0.8834	0.8469	-0.40 [72]	0.130	468
$^{24}\text{Mg} + ^{186}\text{W}$	103.46	0.7350	0.5239	0.6646	0.7714	0.8570	0.605	0.225	888
$^{30}\text{Si} + ^{180}\text{Hf}$	115.65	0.7350	0.5479	0.6726	0.7142	0.8570	-0.315	0.267	1008
$^{48}\text{Ti} + ^{154}\text{Sm}$	154.16	0.7229	0.6445	0.6968	0.5247	0.8505	0.011	0.270	1364
$^{34}\text{S} + ^{168}\text{Er}$	125.10	0.7229	0.5753	0.6737	0.6637	0.8505	0.252	0.297	1088
$^{24}\text{Mg} + ^{178}\text{Hf}$	101.46	0.7229	0.5180	0.6546	0.7623	0.8505	0.605	0.278	864
$^{16}\text{O} + ^{186}\text{Os}$	72.88	0.7229	0.4252	0.6237	0.84158	0.8505	-0.010	0.209	608
$^{30}\text{Si} + ^{186}\text{W}$	118.25	0.7504	0.5547	0.6851	0.7222	0.8648	-0.315	0.225	1036

more entrance channel parameters. These probes include the study of fission fragments' (FFs) mass-angle correlation and the width of the fragments mass distribution [20,21,33,34], anomalies in the angular distribution of the fission fragments [35–37], measurement of evaporation residue cross section [14,16,38], and neutron multiplicity [39,40].

R. Rafiei *et al.*, measured the fission fragment mass distribution for the systems $^{16}\text{O} + ^{186}\text{Os}$, $^{24}\text{Mg} + ^{178}\text{Hf}$, $^{34}\text{S} + ^{168}\text{Er}$, and $^{48}\text{Ti} + ^{154}\text{Sm}$ populating the compound nucleus ^{202}Po with different entrance channel properties (see Table I). The observed broadening in the fragment mass ratio distribution for the systems $^{34}\text{S} + ^{168}\text{Er}$ and $^{48}\text{Ti} + ^{154}\text{Sm}$ was attributed to quasifission [15]. Mass angle and mass ratio distributions of the fission fragments were studied in the fission of ^{210}Rn formed through different entrance channels: $^{16}\text{O} + ^{194}\text{Pt}$, $^{24}\text{Mg} + ^{186}\text{W}$ [20], and $^{30}\text{Si} + ^{180}\text{Hf}$ [21] at near-barrier energies. The presence of quasifission was concluded for the latter two systems based on higher mass ratio variance than theoretical statistical model calculations, although no mass-angle correlation was found for all three reactions. For the system $^{27}\text{Al} + ^{186}\text{W}$ [41], no broader fragment mass distribution was observed, despite having similar entrance channel properties. Berriman *et al.* [14] conducted an experiment to measure fission fragment mass distribution and evaporation residue cross-section for the reactions $^{12}\text{C} + ^{204}\text{Pb}$, $^{19}\text{F} + ^{197}\text{Au}$, and $^{30}\text{Si} + ^{186}\text{W}$, where broader fragment mass distribution and hindrance in ER cross sections for the ^{19}F and ^{30}Si induced reactions compared to the ^{12}C induced reaction were attributed to the presence of quasifission in $^{19}\text{F} + ^{197}\text{Au}$ and $^{30}\text{Si} + ^{186}\text{W}$ reactions. Tripathi *et al.* measured the fission fragments angular distributions for the systems $^{19}\text{F} + ^{197}\text{Au}$ [42], $^{24}\text{Mg} + ^{192}\text{Os}$, $^{16}\text{O} + ^{188}\text{Os}$ [43], and $^{28}\text{Si} + ^{176}\text{Yb}$ [36] forming compound nuclei in the pre-actinide region, and found that the experimental data can be reproduced with the help of statistical saddle-point model (SSPM) [44,45] calculations, thereby negating the presence of any NCN processes. This observation is contrary to the earlier findings of Berriman *et al.* for the system $^{19}\text{F} + ^{197}\text{Au}$. Moreover, the ER cross section for the $^{28}\text{Si} + ^{176}\text{Yb}$ reaction at near-barrier energies was found to be suppressed compared to the calculated statistical model code CCFUS + PACE2 values [16]. Recently, Hajara *et al.* measured the ER cross section for

$^{30}\text{Si} + ^{176}\text{Yb}$ reaction over the excitation energy range from 47.68 to 113.73 MeV and found significant suppression of ER cross section due to NCN fission [38]. A similar study for the reaction $^{19}\text{F} + ^{187}\text{Re}$ with different entrance channel properties shows no evidence of quasifission in the fission of ^{206}Po [46]. To study the effect of shell closure, Chaudhuri *et al.* [25] measured the fission fragments mass distribution for the reactions $^{12}\text{C} + ^{194,198}\text{Pt}$ populating $^{206,210}\text{Po}$ in the excitation energy range of $\approx 40\text{--}57$ MeV and no signature of shell effect in the mass distribution was observed. This result is contrary to the findings of Shrivastava *et al.* [37] and Golda *et al.* [39] for the same CN, where fission fragment anisotropy and neutron multiplicity were measured, respectively, to understand the shell effect.

In this present work, we have measured the fission fragment mass distribution of the compound system ^{206}Po populated through $^{30}\text{Si} + ^{176}\text{Yb}$ in the energy range of $0.93 \leq E_{c.m.}/V_B \leq 1.04$ to study the entrance channel mass asymmetry and deformation effect on the fission dynamics. The asymmetric mass distribution in spontaneous and low energy fission of the actinides, unlike the prediction of the liquid drop model [47–51] and unexpected observations of mass-asymmetric fission in ^{180}Hg [31,32,52] and other sublead nuclei [53,54], continues the interest of researchers to understand the role of shell effects and influence of the entrance channel in fission. Po ($Z = 84$) lies midway between the mercury and the actinide group elements, therefore it is very interesting to unfold the dynamical evolution of the system induced by heavy ions. The present experimental findings are compared with the available data for the same CN produced via the more asymmetric reaction $^{12}\text{C} + ^{194}\text{Pt}$ [25] and also with the mass distributions of the nearby systems. In the reaction $^{12}\text{C} + ^{194}\text{Pt}$, entrance channel mass asymmetry is greater than the critical α_{BG} value and CN fission was reported [25]. Therefore, the variance of the mass distribution for $^{30}\text{Si} + ^{176}\text{Yb}$ at different energies is explicitly used to understand the onset or presence of quasifission in the light of SSPM calculation for the CN fission. The relevant entrance channel parameters of the reactions under consideration are shown in Table I. Detailed discussions regarding the experimental setup, data analysis, results, and conclusions are reported in the subsequent sections.

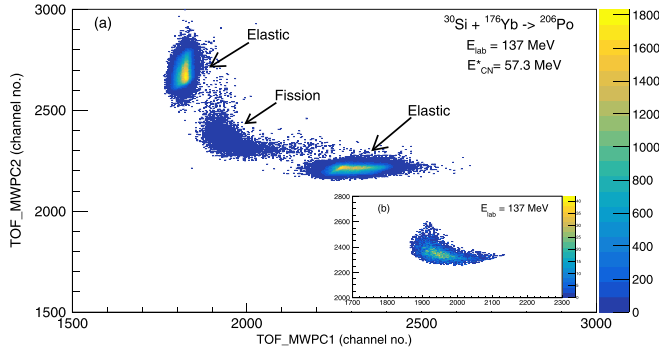


FIG. 1. Plot of time-of-flight (TOF) spectra for the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction at $E_{\text{lab}} = 137$ MeV of the two MWPCs. (a) The spectra of all collected events. (b) Gated fission events.

II. EXPERIMENTAL DETAILS

The experiment was performed at Inter University Accelerator Centre (IUAC), New Delhi, with the 15 UD pelletron accelerator. A pulsed beam of ^{30}Si with pulse separation of 250 ns and pulse width of ≈ 1 ns having laboratory energy (E_{lab}) of 124 to 137 MeV was bombarded on a ^{176}Yb target foil of $\approx 130 \mu\text{g}/\text{cm}^2$ thickness. The target was prepared at the target laboratory of IUAC with carbon backing of thickness $\approx 25 \mu\text{g}/\text{cm}^2$ [55]. To collect the fission fragments, two multiwire proportional counters (MWPCs) [56] of active area $20 \times 10 \text{ cm}^2$ [57] were kept at the two movable arms of the scattering chamber. The MWPCs were mounted at the folding angle calculated from the reaction kinematics. For coincidence measurement of the fission products, MWPC1 and MWPC2 were placed in symmetric angles of $\pm 70^\circ$ with respect to the beam direction, corresponding to the angle of 90° in the center-of-mass (c.m.) frame of reference. The target was mounted in the target ladder and kept perpendicular to the beam. The distance between the target and the detectors was fixed at 25 cm. For beam monitoring and focusing the beam at the center of the target, two silicon surface barrier detectors (SSBDs) were placed at $\pm 12^\circ$ with respect to the beam axis. The MWPCs have very good position and timing resolution and they were operated with isobutane gas at low pressure (≈ 4 mbar), so that the elastic particles were transparent to the detectors. The position signals of the particles were obtained

from the wire planes of the detectors with the help of the delay line readout technique with a resolution better than 1.5 mm, while the timing information was given by the central foil of the MWPCs. The times of flight and the position signals were recorded in list mode using the root [58] based data acquisition system NiasMARS. The details of the data acquisition setup and related electronics are discussed in Refs. [56,57].

III. EXPERIMENTAL DATA ANALYSIS

The fission events were separated from elastic events using the timing correlation of the MWPCs by putting a gate as shown in Fig. 1. The list-mode data stored in the data acquisition system from the two MWPCs provided time of flight (TOF) and X and Y position information. For analysis of the data, the calibration of all time-to-digital converters (TDCs) was performed using an ORTEC time calibrator module which gives pulses of fixed time intervals. The position calibration was performed using the known active area of the detectors. The calibrated positions were then converted to the spherical polar coordinates θ ($\theta_{1,\text{lab}}$, $\theta_{2,\text{lab}}$) and ϕ ($\phi_{1,\text{lab}}$, $\phi_{2,\text{lab}}$) with the help of experimental geometry [56,59] in the laboratory frame of reference for the binary fission fragments (FF1, FF2). The folding angle distribution of the fission fragments was constructed and it was found that the peaks of the distribution matched well with the calculated values for full momentum transfer (FMT) from the projectile to the target. Figure 2 shows the correlation spectra of the folding angle and azimuthal angle of the binary fragments at energies ranging from below to above the Coulomb barrier. To avoid any kind of contamination from background and incomplete momentum transfer events, we put a gate around the intense region of the correlation spectra (corresponding to the calculated values) and only the gated events were considered for the reconstruction of the velocities of the fission fragments.

The velocity vectors of the FFs ($\vec{v}_{1,\text{lab}}$, $\vec{v}_{2,\text{lab}}$) are determined following the absolute time method (AMT) [60] using TOF and angles (θ , ϕ). The velocity of the fissioning system in the laboratory frame ($\vec{V}_{\text{lab}}$) was decomposed into parallel $\vec{V}_{\parallel}$ and perpendicular $\vec{V}_{\perp}$ components to the beam axis according to Eqs. (1) and (2), following the kinematic coincidence geometry described in Ref. [27]:

$$V_{\parallel} = \frac{v_{1,\text{lab}} v_{2,\text{lab}} \sin(\theta_{1,\text{lab}} + \theta_{2,\text{lab}})}{v_{1,\text{lab}} \sin \theta_{1,\text{lab}} + v_{2,\text{lab}} \sin \theta_{2,\text{lab}}}, \quad (1)$$

$$V_{\perp} = \frac{v_{1,\text{lab}} v_{2,\text{lab}} \sin \theta_{1,\text{lab}} \sin \theta_{2,\text{lab}} \sin \phi_{12}}{\sqrt{(v_{1,\text{lab}}^2 \sin^2 \theta_{1,\text{lab}} + v_{2,\text{lab}}^2 \sin^2 \theta_{2,\text{lab}} - 2v_{1,\text{lab}} v_{2,\text{lab}} \sin \theta_{1,\text{lab}} \sin \theta_{2,\text{lab}} \cos \phi_{12})}}. \quad (2)$$

For FMT events leading to complete fusion, the $\vec{V}_{\parallel}$ component of the fissioning nucleus is expected to be equal to the compound nucleus velocity $\vec{V}_{\text{CN}}$ while $\vec{V}_{\perp}$ should be zero. A correlation plot between $\vec{V}_{\parallel}$ and $\vec{V}_{\perp}$ components is helpful to determine the events originating from fusion-fission from incomplete or transfer induced events, if any. The components

of the velocity of the fission fragments at $E_{\text{lab}} = 128$ MeV for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ is shown in Fig. 3. The FMT events corresponds to the intense band around the velocity coordinates $(V_{\parallel}/V_{\text{CN}}, V_{\perp}) = (1, 0)$ were extracted to obtain the fragments' mass. The energy loss of the FFs inside the target material was calculated using SRIM software [61] and

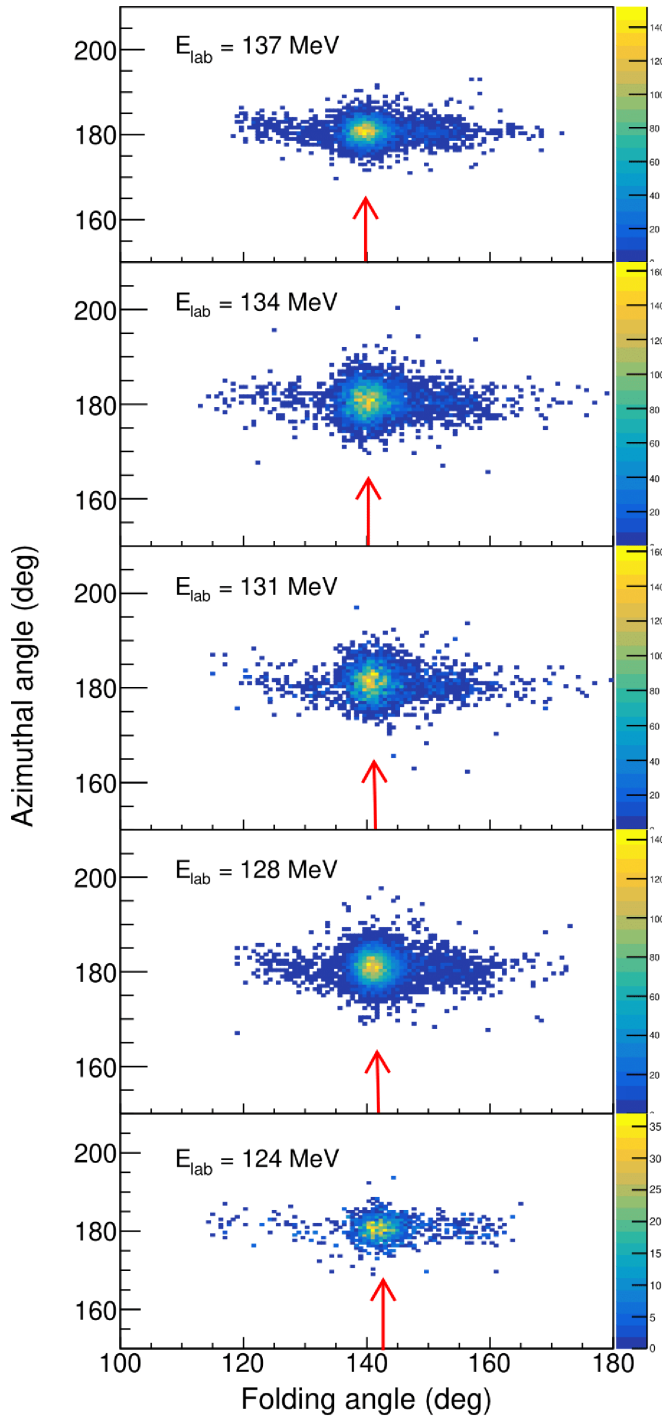


FIG. 2. Distribution of polar (θ) and azimuthal (ϕ) angles of the fission fragments at different energies for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. The red arrow corresponds to the calculated folding angle from reaction kinematics.

incorporated in the analysis, considering that the reaction takes place at the center of the target. The corrected laboratory velocities were then converted to the c.m. frame velocities $\bar{v}_{1,\text{c.m.}}$ and $\bar{v}_{2,\text{c.m.}}$ by kinematic transformations. From the conservation of linear momentum ($m_1 \bar{v}_{1,\text{c.m.}} = m_2 \bar{v}_{2,\text{c.m.}}$), the experimental fission fragments' mass ratio was obtained with

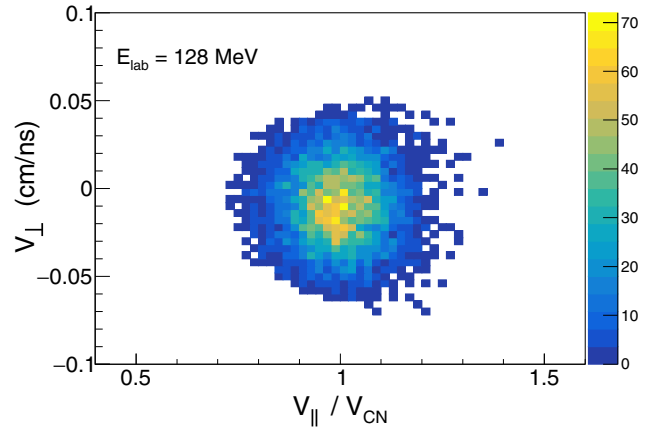


FIG. 3. Velocity distribution of the fission fragments at $E_{\text{lab}} = 128$ MeV for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. The full momentum transfer events corresponds to the intense band around the velocity coordinates $(V_{\parallel}/V_{\text{CN}}, V_{\perp}) = (1, 0)$.

the help of Eq. (3). Further masses of the FFs were calculated assuming that the sum of the projectile and target masses is equal to the compound nuclear mass according to Eq. (4):

$$M_R = \frac{m_2}{m_1 + m_2} = \frac{v_{1,\text{c.m.}}}{v_{1,\text{c.m.}} + v_{2,\text{c.m.}}}, \quad (3)$$

$$M_1 = (1.0 - M_R) \times M_{\text{CN}}, \quad (4)$$

where, M_R , M_1 , and M_{CN} are the fragments' mass ratio, mass of FF1 (detected in MWPC1) and mass of the compound nucleus, respectively.

IV. RESULTS AND DISCUSSION

The mass-angle correlation and mass distribution of the fission fragments provide an important insight into the heavy-ion-induced reaction mechanism and are very useful to differentiate fusion-fission and quasifission processes, especially when the energy is close to or below the barrier. The mass-angle correlation of the fission fragments for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ at $E_{\text{lab}} = 128$ MeV is shown in Fig. 4, where mass of FFs is plotted against center-of-mass angle ($\theta_{\text{c.m.}}$). An isotropic distribution between fragments' mass and c.m. angle has been observed within the angular coverage of the MWPCs and the studied energy range ($E^* = 46.2$ – 57.3 MeV). The reported mass-angle correlation for the less asymmetric reactions $^{24}\text{Mg} + ^{178}\text{Hf}$, $^{34}\text{S} + ^{168}\text{Er}$ [15], $^{24}\text{Mg} + ^{186}\text{W}$ [20], and $^{30}\text{Si} + ^{180}\text{Hf}$ [21] in the literature, having similar entrance channel mass asymmetry (α) values, support the findings of the present measurement. The FF mass distributions for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ at different CN excitation energies are displayed in Fig. 5. It can be observed that the gross behavior of the FF mass distribution is nearly symmetric (centered at $M_R = 0.5$ or $M = M_{\text{CN}}/2$) and the experimental data can be represented well by a single Gaussian function. The goodness of fit (χ^2 values) for the single Gaussian fitting are given in the Fig. 5. This finding supports the earlier results on the fission of $^{206,210}\text{Po}$ [25] and nearby CNs [15,21] at excitation

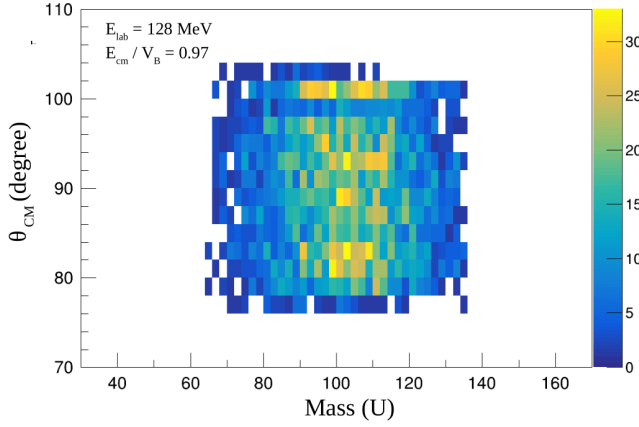


FIG. 4. Plot of fission fragment mass vs center-of mass angle ($\theta_{\text{c.m.}}$) for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ at $E_{\text{lab}} = 128$ MeV.

energies above ≈ 40 MeV. To understand the mass distribution at different excitation energies, the variation of the mass width (σ_m) at all E^* is extracted from the standard deviation of the fitted Gaussian function. In the present work, we are interested in studying the dependence of σ_m with entrance channel mass asymmetry and deformation, therefore σ_m values obtained from the single Gaussian function are considered as discussed in the Refs. [15,53,62,63]. The experimental σ_m as a function of CN excitation energy for the systems $^{30}\text{Si} + ^{176}\text{Yb}$ and $^{12}\text{C} + ^{194}\text{Pt}$, populating the same compound nucleus ^{206}Po but having different entrance channel properties, is shown in Fig. 6. It shows that the experimental σ_m increases with increasing excitation energy for both systems however, the magnitude of σ_m for the more symmetric system is higher than that of the asymmetric system at similar E^* . Therefore, to explore the effect of mean square angular momentum ($\langle l^2 \rangle$) on σ_m , we have calculated fusion $\langle l^2 \rangle$ for the two systems using the coupled channel code CCFULL [64], considering rotational couplings of the projectile and the target. The variation of $\langle l^2 \rangle$ with E^* is shown in Fig. 7. The Woods-Saxon potential parameters for the systems [38] and static deformation (β_2 , β_4) values of the projectiles and the targets [65] were provided as an input in the CCFULL calculation. As shown in Fig. 7, $\langle l^2 \rangle$ values are lower for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ than for $^{12}\text{C} + ^{194}\text{Pt}$ for the whole range of excitation energy, which confirms that $\langle l^2 \rangle$ is not responsible for the higher magnitude of σ_m for this reaction.

According to the statistical saddle point model (SSPM), for an equilibrated CN, the mass variance (σ_m^2) depends linearly on saddle point temperature (T_{saddle}), and mean square angular momentum ($\langle l^2 \rangle$) [66] and can be expressed as

$$\sigma_m^2 = \lambda T + \beta \langle l^2 \rangle, \quad (5)$$

where λ and β are fitting constants. The T_{saddle} can be calculated from Eq. 6 as given

$$T_{\text{saddle}} = \sqrt{\frac{E_{\text{c.m.}} + Q - B_f(l) - E_{\text{rot}} - E_{\text{pre}}^{\text{sad}}}{a}}, \quad (6)$$

where $E_{\text{c.m.}}$ and Q are the center-of-mass energy and the Q-value, respectively. $B_f(l)$ and E_{rot} are the fission barrier

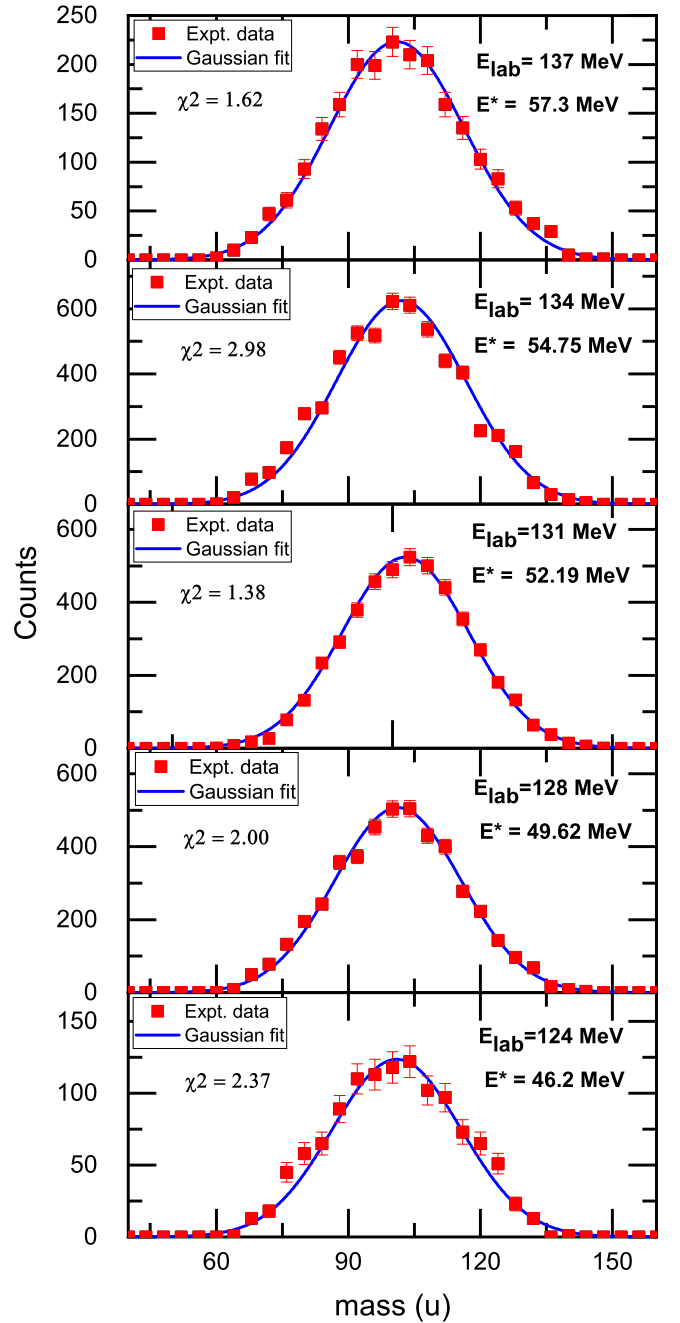


FIG. 5. Fission fragments mass distribution at different excitation energies for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ with single fit Gaussian function (blue solid line).

at particular angular momentum (l) and rotational energy at saddle [67]. $E_{\text{pre}}^{\text{sad}}$ is the energy carried by the prefission neutrons [68] and a is the nuclear level density parameter, whose value is taken as $a = M_{\text{CN}}/10$. On the other hand, fission $\langle l^2 \rangle$ values were calculated with the help of CCFULL and the statistical model code PACE4 [69]. The constants λ and β were determined by best fitting the experimental σ_m values for the reaction $^{12}\text{C} + ^{194}\text{Pt}$, where complete CN fission was reported [25]. The resulting best-fit values were $\lambda = 98$ and $\beta = 0.06$, which are consistent with values found for nearby

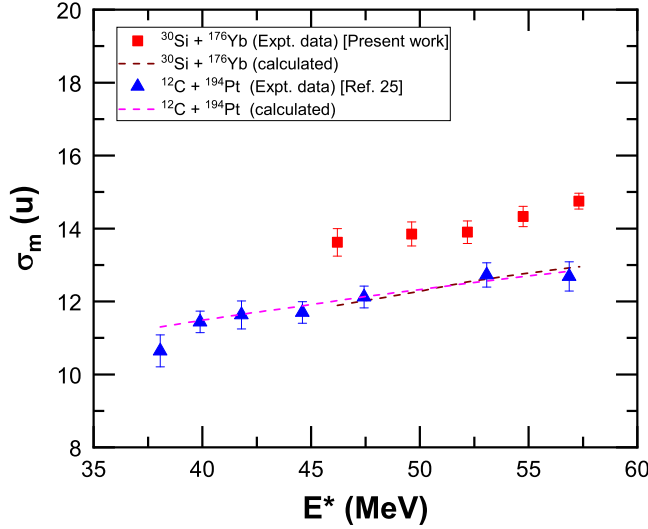


FIG. 6. Dependence of variation of the mass width σ_m of the symmetric mass distribution as a function of excitation energy (E^*) for two different entrance channels forming ^{206}Po . The dashed line is for the calculated σ_m values according to Eq. (5).

nuclei [33,70]. A detailed discussion of these constants can be found in the literature given in the Refs. [66,70]. The SSPM calculated σ_m values for both the reactions $^{12}\text{C} + ^{194}\text{Pt}$ and $^{30}\text{Si} + ^{176}\text{Yb}$, using the same set of λ and β , are shown in the Fig. 6 (dashed lines). From Fig. 6, it is evident that the calculated and experimental σ_m values differ significantly for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. If the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction also favors complete CN fission, then the same values of λ and β should ideally represent the experimental mass width. Therefore, the higher values of experimental σ_m values for the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction compared to the SSPM calculations may be attributed to the presence of NCN fission. The fast fission contribution is insignificant in the energy range of the present measurement, as angular momentum values are much lower than

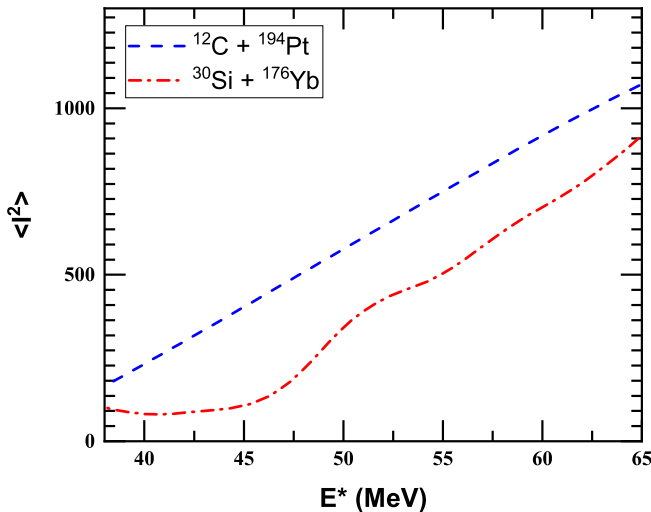


FIG. 7. Variation of fusion $\langle I^2 \rangle$ with CN excitation energy (E^*) for the systems $^{30}\text{Si} + ^{176}\text{Yb}$ and $^{12}\text{C} + ^{194}\text{Pt}$.

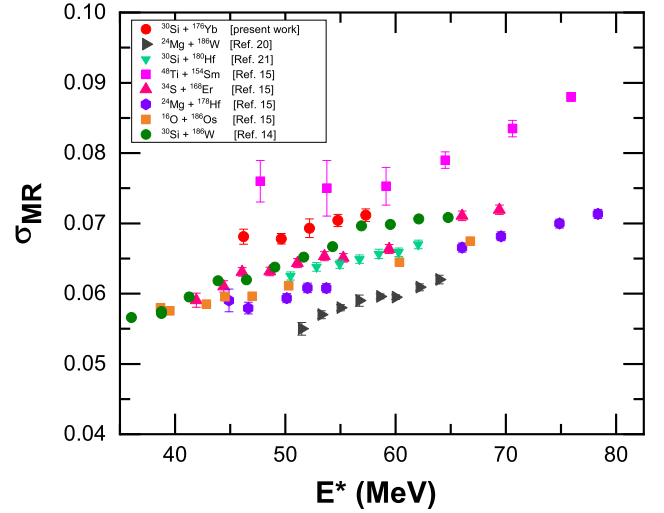


FIG. 8. The experimental width of the mass ratio distribution (σ_{MR}) for the system $^{30}\text{Si} + ^{176}\text{Yb}$ compared with the available experimental data of the nearby systems as a function of E^* .

the critical angular momentum ($l_c = 77 \hbar$), where liquid drop model fission barrier $B_f(l_c)$ vanishes. Moreover, the presence of preequilibrium fission (PEF) does not change the mass distribution as it is related to the shape degree of freedom and it is expected that mass equilibration takes place earlier than the shape equilibration [8]. The percentage contribution of PEF calculated [71] is also negligible (only $\approx 3.55\%$) at the highest energy of $E^* = 57.3 \text{ MeV}$. Thus, anomalous increase in the width of FF mass distribution compared to the theoretical prediction may be due to the presence of quasifission in the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. This result also supports the recent measurement of ER cross section for the same reaction, where suppression of ER cross section was observed [38], and the suppression of experimental ER cross section compared to the theoretical model calculation was attributed to NCN fission.

In Fig. 8, a comparison of the experimental width of the mass ratio distribution (σ_{MR}) for the system $^{30}\text{Si} + ^{176}\text{Yb}$ as a function of E^* is shown with the available experimental data from the literature. The systems considered for comparison have different entrance channel properties in terms of mass asymmetry, deformation, $Z_p Z_T$, mean fissility (χ_m), etc. (see Table I), and they populate CN in the preactinide region, more particularly near ^{206}Po . From Fig. 8, it is evident that σ_{MR} for $^{30}\text{Si} + ^{176}\text{Yb}$ are consistent with the earlier data of the nearby systems within a similar range of excitation energy.

To understand the deviation from CN fission in the present measurement, in Fig. 9, the ratio of the experimental ($\sigma_{m,\text{expt.}}^2$) to the calculated ($\sigma_{m,\text{cal.}}^2$) variances of the fission fragments mass distribution is displayed as a function of $E_{\text{c.m.}}/V_B$ for the reactions $^{30}\text{Si} + ^{176}\text{Yb}$ and $^{12}\text{C} + ^{194}\text{Pt}$. The blue dashed line at $\frac{\sigma_{m,\text{expt.}}^2}{\sigma_{m,\text{cal.}}^2} = 1$ represents the pure CN formation. A significant deviation from expected CN formation is observed for the system $^{30}\text{Si} + ^{176}\text{Yb}$, while $\sigma_{m,\text{expt.}}^2/\sigma_{m,\text{cal.}}^2$ values are scattered around the dashed line for the reaction $^{12}\text{C} + ^{194}\text{Pt}$, which populates the same CN. From this analysis, the role of entrance channel mass asymmetry can be seen in the

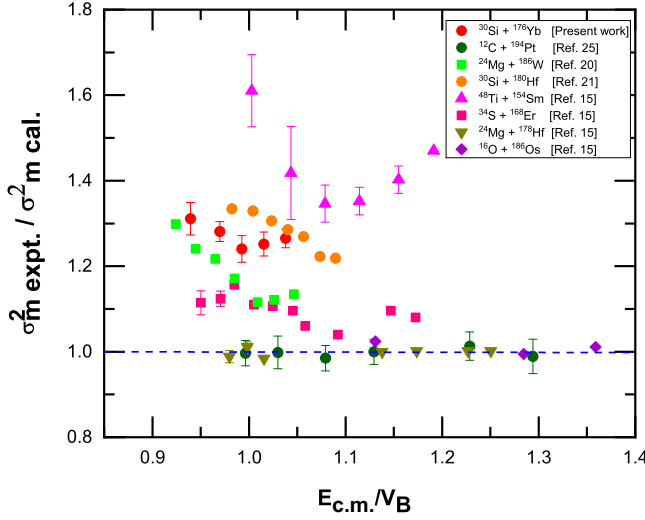


FIG. 9. Ratio between the experimental and calculated variance of the mass distribution as a function of $E_{c.m.}/V_B$ for the reactions forming CN in the preactinide region.

dynamical evolution of the composite system as α values lie on the either side of α_{BG} for these two reactions as mentioned in Table I. A reversal in the direction of the mass flow from projectile to target ($\alpha > \alpha_{BG}$) or from target to projectile ($\alpha < \alpha_{BG}$) may lead to different reaction mechanisms [73]. In Fig. 9, the observed increasing trend of $\sigma_{m,\text{expt.}}^2 / \sigma_{m,\text{cal.}}^2$ values from the expected CN formation for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ at below-barrier energies may be attributed to the deformation alignment effect on QF. For deformed nuclei, shape alignment of the projectile and the target at their contact configuration influences the trajectory of the multidimensional potential energy surface [11,15,26,74,75] and leads to QF when the elongated contact configuration exceeds the unconditional saddle-point configuration. As the projectile ^{30}Si and the target ^{176}Yb have higher static quadrupole deformation (β_2) values -0.315 (oblate) and 0.289 (prolate), respectively [65], the orientation dependent QF probability increases drastically at below-barrier energies. To give a better insight into the σ_m distributions at below-barrier energies, $^{30}\text{Si} + ^{176}\text{Yb}$ reaction data are also compared with the literature, as shown in Fig. 9. A similar increasing trend of $\sigma_{m,\text{expt.}}^2 / \sigma_{m,\text{cal.}}^2$ values at near- to below-barrier energies for the reactions $^{30}\text{Si} + ^{180}\text{Hf}$, $^{34}\text{S} + ^{168}\text{Er}$, $^{48}\text{Ti} + ^{154}\text{Sm}$, and $^{24}\text{Mg} + ^{186}\text{W}$ are observed, where static quadrupole deformation of the projectile or the target or both are higher. In an earlier measurement [76] for $^{19}\text{F} + ^{232}\text{Th}$, $^{16}\text{O} + ^{232}\text{Th}$, $^{12}\text{C} + ^{232}\text{Th}$, $^{16}\text{O} + ^{209}\text{Bi}$, and $^{19}\text{F} + ^{209}\text{Bi}$ reactions with deformed and spherical targets, Ghosh *et al.* discussed the influence of deformation in the FFs' mass distribution as all the reactions have $\alpha < \alpha_{BG}$. The width of the mass distribution for the reactions with deformed targets has a remarkable increase at near- to below-barrier energies, while for the reactions with spherical targets a smooth variation of σ_m values with E^* have been observed. There-

fore, it may be concluded that, along with mass asymmetry, deformation and its alignment at below-barrier energies play a significant role in the enhancement of QF probability in heavy-ion-induced reactions.

V. CONCLUSION

Fission fragments' mass distribution has been measured for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$ forming the CN ^{206}Po . The width of the mass distribution (σ_m) in the energy range of $0.93 < \frac{E_{c.m.}}{V_B} < 1.04$ is exclusively used to understand the fission dynamics. The FF mass distributions are fitted with a single Gaussian function. The σ_m values at different CN excitation energies for the system $^{30}\text{Si} + ^{176}\text{Yb}$ are compared with the available experimental data for the reaction $^{12}\text{C} + ^{194}\text{Pt}$, which favors CN fission. The higher magnitude of the experimental σ_m values compared to the SSPM calculations can be ascribed to the presence of QF in the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. The $\sigma_{m,\text{expt.}}^2 / \sigma_{m,\text{cal.}}^2$ plot for the two reactions forming the same CN, with different entrance channel mass asymmetry (α) values that lie on the either side of the α_{BG} value, represents the deviation from the CN behavior for the more symmetric system. $^{30}\text{Si} + ^{176}\text{Yb}$ has α less than α_{BG} , which governed the mass flow from the target to the projectile, resulting in the formation of a dinucleus that leads to QF, in contrast to the other system. Moreover, the significant increase in $\sigma_{m,\text{expt.}}^2 / \sigma_{m,\text{cal.}}^2$ value at below-barrier energies suggests the role of deformation and its alignment effect on QF for the reaction $^{30}\text{Si} + ^{176}\text{Yb}$. The results obtained in this work are consistent with the measured evaporation residue (ER) cross section for the same system, where hindrance in the measured ER cross section was attributed to the presence of noncompound nucleus processes. Further, these experimental results suggest the incorporation of the mass asymmetry, deformation of the colliding partners, and $Z_p Z_T$ in the formulation of any theoretical model that attempts to explain the fission process. The relative contribution and importance of different entrance channel parameters in the dynamical evolution of the composite system need to be understood for the synthesis of SHEs. Moreover, it will be interesting to investigate the influence of the single-particle shell model for CN excitation energies below 40 MeV or for the sub-barrier region on fission fragment mass distribution for ^{206}Po and its nearby preactinide nuclei induced by heavy ions.

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- [1] S. Bjørnholm and W. J. Swiatecki, Dynamical aspects of nucleus-nucleus collisions, *Nucl. Phys. A* **391**, 471 (1982).
- [2] J. P. Blocki, H. Feldmeier, and W. J. Swiatecki, Dynamical hindrance to compound-nucleus formation in heavy-ion reactions, *Nucl. Phys. A* **459**, 145 (1986).
- [3] Z.-Q. Feng, G.-M. Jin, J.-Q. Li, and W. Scheid, Production of heavy and superheavy nuclei in massive fusion reactions, *Nucl. Phys. A* **816**, 33 (2009).
- [4] C. Ngô, Fusion dynamics in heavy ion collisions, *Prog. Part. Nucl. Phys.* **16**, 139 (1986).
- [5] C. Lebrun, F. Hanappe, J. F. Lecomte, F. Lefebvres, C. Ngô, J. Peter, and B. Tamain, Influence of angular momentum on the mass distribution width of heavy ion induced fission: What is the frontier between fission and quasi-fission? *Nucl. Phys. A* **321**, 207 (1979).
- [6] B. Borderie, M. Berlinger, D. Gardès, F. Hanappe, L. Nowicki, J. Péter, B. Tamain, S. Agarwal, J. Girard, C. Grégoire *et al.*, A possible mechanism in heavy ion induced reactions: “fast fission process”, *Z. Phys. A* **299**, 263 (1981).
- [7] V. S. Ramamurthy and S. S. Kapoor, Interpretation of fission-fragment angular distributions in heavy-ion fusion reactions, *Phys. Rev. Lett.* **54**, 178 (1985).
- [8] B. B. Back, Complete fusion and quasifission in reactions between heavy ions, *Phys. Rev. C* **31**, 2104 (1985).
- [9] J. Töke, R. Bock, G. X. Dai, A. Gobbi, S. Gralla, K. D. Hildenbrand, J. Kuzminski, W. Müller, A. Olmi, H. Stelzer *et al.*, Quasi-fission—the mass-drift mode in heavy-ion reactions, *Nucl. Phys. A* **440**, 327 (1985).
- [10] A. Nasirov, K. Kim, G. Mandaglio, G. Giardina, A. Muminov, and Y. Kim, Main restrictions in the synthesis of new super-heavy elements: Quasifission and/or fusion fission, *Eur. Phys. J. A* **49**, 147 (2013).
- [11] W. J. Swiatecki, The dynamics of nuclear coalescence or reseparation, *Phys. Scr.* **24**, 113 (1981).
- [12] P. Möller and A. J. Sierk, Into the fission valley, *Nature (London)* **422**, 485 (2003).
- [13] A. Diaz-Torres, Competition between fusion and quasifission in a heavy fusing system: Diffusion of nuclear shapes through a dynamical collective potential energy landscape, *Phys. Rev. C* **74**, 064601 (2006).
- [14] A. C. Berriman, D. J. Hinde, M. Dasgupta, C. R. Morton, R. D. Butt, and J. O. Newton, Unexpected inhibition of fusion in nucleus–nucleus collisions, *Nature (London)* **413**, 144 (2001).
- [15] R. Rafiei, R. G. Thomas, D. J. Hinde, M. Dasgupta, C. R. Morton, L. R. Gasques, M. L. Brown, and M. D. Rodriguez, Strong evidence for quasifission in asymmetric reactions forming ^{202}Po , *Phys. Rev. C* **77**, 024606 (2008).
- [16] K. Sudarshan, R. Tripathi, S. Sodaye, S. K. Sharma, P. K. Pujari, J. Gehlot, N. Madhavan, S. Nath, G. Mohanto, I. Mukul, A. Jhingan, and I. Mazumdar, Spin distributions and cross sections of evaporation residues in the $^{28}\text{Si} + ^{176}\text{Yb}$ reaction, *Phys. Rev. C* **95**, 024604 (2017).
- [17] M. Abe, KEK Report No. 86-26, KEK TH-28, 1986 (unpublished).
- [18] S. Kailas, Heavy-ion induced fission at near-barrier energies, *Phys. Rep.* **284**, 381 (1997).
- [19] S. Kailas, K. Mahata, R. G. Thomas, and S. S. Kapoor, Nuclear structure and dynamics from heavy-ion induced fission reactions, *Nucl. Phys. A* **787**, 259 (2007).
- [20] E. Prasad, K. M. Varier, R. G. Thomas, P. Sugathan, A. Jhingan, N. Madhavan, B. R. S. Babu, R. Sandal, S. Kalkal, S. Appannababu *et al.*, Conclusive evidence of quasifission in reactions forming the ^{210}Rn compound nucleus, *Phys. Rev. C* **81**, 054608 (2010).
- [21] A. Shamlath, M. Shareef, E. Prasad, P. Sugathan, R. Thomas, A. Jhingan, S. Appannababu, A. K. Nasirov, A. M. Vinodkumar, K. M. Varier *et al.*, Fission fragment mass distribution studies in $^{30}\text{Si} + ^{180}\text{Hf}$ reaction, *Nucl. Phys. A* **945**, 67 (2016).
- [22] A. Y. Chizhov, M. G. Itkis, I. M. Itkis, G. N. Kniajeva, E. M. Kozulin, N. A. Kondratiev, I. V. Pokrovsky, R. N. Sagaidak, V. M. Voskressensky, A. V. Yerein *et al.*, Unexpected entrance-channel effect in the fission of ^{216}Ra , *Phys. Rev. C* **67**, 011603(R) (2003).
- [23] A. Wakhle, C. Simenel, D. J. Hinde, M. Dasgupta, M. Evers, D. H. Luong, R. du Rietz, and E. Williams, Interplay between quantum shells and orientation in quasifission, *Phys. Rev. Lett.* **113**, 182502 (2014).
- [24] A. Sen, T. K. Ghosh, S. Bhattacharya, K. Banerjee, C. Bhattacharya, S. Kundu, G. Mukherjee, A. Asgar, A. Dey, A. Dhal *et al.*, Fission fragment mass distributions from ^{210}Po and ^{213}At , *Phys. Rev. C* **96**, 064609 (2017).
- [25] A. Chaudhuri, T. K. Ghosh, K. Banerjee, S. Bhattacharya, J. Sadhukhan, S. Kundu, C. Bhattacharya, J. K. Meena, G. Mukherjee, A. K. Saha *et al.*, No influence of a $n=126$ neutron-shell closure in fission-fragment mass distributions, *Phys. Rev. C* **92**, 041601(R) (2015).
- [26] D. J. Hinde, M. Dasgupta, J. R. Leigh, J. P. Lestone, J. C. Mein, C. R. Morton, J. O. Newton, and H. Timmers, Fusion-fission versus quasifission: Effect of nuclear orientation, *Phys. Rev. Lett.* **74**, 1295 (1995).
- [27] D. J. Hinde, M. Dasgupta, J. R. Leigh, J. C. Mein, C. R. Morton, J. O. Newton, and H. Timmers, Conclusive evidence for the influence of nuclear orientation on quasifission, *Phys. Rev. C* **53**, 1290 (1996).
- [28] J. C. Mein, D. J. Hinde, M. Dasgupta, J. R. Leigh, J. O. Newton, and H. Timmers, Precise fission fragment anisotropies for the $^{232}\text{C} + ^{232}\text{Th}$ reaction: Supporting the nuclear orientation dependence of quasifission, *Phys. Rev. C* **55**, R995 (1997).
- [29] R. K. Choudhury and R. G. Thomas, Non-equilibrium processes in heavy-ion induced fission reactions, *J. Phys. Conf. Ser.* **282**, 012004 (2011).
- [30] R. G. Thomas, Fission fragment mass and angular distributions: Probes to study non-equilibrium fission, *Pramana* **85**, 303 (2015).
- [31] E. Prasad, D. J. Hinde, K. Ramachandran, E. Williams, M. Dasgupta, I. P. Carter, K. J. Cook, D. Y. Jeung, D. H. Luong, S. McNeil *et al.*, Observation of mass-asymmetric fission of mercury nuclei in heavy ion fusion, *Phys. Rev. C* **91**, 064605 (2015).
- [32] K. Nishio, A. Andreyev, R. Chapman, X. Derckx, C. E. Ilmann, L. Ghys, F. Berger, K. Hirose, H. Ikezoe, J. Khuyagbaatar *et al.*, Excitation energy dependence of fragment-mass distributions from fission of $^{180,190}\text{Hg}$ formed in fusion reactions of $^{36}\text{Ar} + ^{144,154}\text{Sm}$, *Phys. Lett. B* **748**, 89 (2015).
- [33] Kavita, K. S. Golda, T. K. Ghosh, A. Jhingan, P. Sugathan, A. Chatterjee, B. R. Behera, A. Kumar, R. Kumar, N. Saneesh *et al.*, Fusion-fission dynamics of $^{188,190}\text{Pt}$ through fission fragment mass distribution measurements, *Phys. Rev. C* **100**, 024626 (2019).
- [34] S. R. Reddy, A. Pal, S. K. Duggi, T. Santhosh, P. Shah, T. Singh, K. Prameela, V. V. Parkar, N. N. Deshmukh, P. K. Rath *et al.*,

- Fission modes in ^{223}Ac and ^{227}Pa compound nuclei, *Phys. Rev. C* **110**, 014622 (2024).
- [35] T. Banerjee, S. Nath, A. Jhingan, G. Kaur, R. Dubey, A. Yadav, P. V. Laveen, A. Shamlath, M. Shareef, J. Gehlot *et al.*, Fission fragment angular distributions in pre-actinide nuclei, *Phys. Rev. C* **94**, 044607 (2016).
- [36] R. Tripathi, K. Sudarshan, S. K. Sharma, K. Ramachandran, A. V. R. Reddy, P. K. Pujari, and A. Goswami, Fission fragment angular distributions in the reactions $^{16}\text{O} + ^{188}\text{Os}$ and $^{28}\text{Si} + ^{176}\text{Yb}$, *Phys. Rev. C* **79**, 064607 (2009).
- [37] A. Shrivastava, S. Kailas, A. Chatterjee, A. M. Samant, A. Navin, P. Singh, and B. S. Tomar, Shell effects in fission fragment anisotropies for $^{12}\text{C} + ^{194,198}\text{Pt}$ systems, *Phys. Rev. Lett.* **82**, 699 (1999).
- [38] K. Hajara, M. M. Musthafa, C. V. Midhun, S. Akbar, P. T. M. Shan, N. Madhavan, S. Nath, J. Gehlot, Gonika, R. Biswas *et al.*, Evaporation residue cross section measurements for the $^{30}\text{Si} + ^{176}\text{Yb}$ reaction, *Phys. Rev. C* **105**, 044619 (2022).
- [39] K. Golda, A. Saxena, V. Mittal, K. Mahata, P. Sugathan, A. Jhingan, V. Singh, R. Sandal, S. Goyal, J. Gehlot *et al.*, Determination of shell correction energies at saddle point using pre-scission neutron multiplicities, *Nucl. Phys. A* **913**, 157 (2013).
- [40] C. Sharma, B. R. Behera, Shruti, Amit, B. Rohila, A. Kaur, Subodh, N. Dhand, A. Kumar, P. Sugathan *et al.*, Fission dynamics and entrance-channel study in the ^{210}Po compound nucleus via light-particle multiplicities, *Phys. Rev. C* **107**, 064615 (2023).
- [41] S. Appannababu, S. Mukherjee, B. K. Nayak, R. G. Thomas, P. Sugathan, A. Jhingan, E. Prasad, D. Negi, N. N. Deshmukh, P. K. Rath *et al.*, Fission fragment mass distributions in reactions forming the ^{213}Fr compound nucleus, *Phys. Rev. C* **83**, 034605 (2011).
- [42] R. Tripathi, K. Sudarshan, S. Sodaye, A. V. R. Reddy, K. Mahata, and A. Goswami, Fission fragment angular distribution for the $^{19}\text{F} + ^{197}\text{Au}$ fusion-fission reaction at near-barrier energies, *Phys. Rev. C* **71**, 044616 (2005).
- [43] R. Tripathi, K. Sudarshan, S. Sodaye, A. Goswami, A. Reddy, and K. Mahata, Fission fragment angular distribution in ^{24}Mg induced reactions on ^{192}Os and ^{197}Au , *Int. J. Mod. Phys. E* **17**, 419 (2008).
- [44] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).
- [45] I. Halpern and V. M. Strutinsky, in *Proceedings of the Second United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958*, edited by J. H. Martens *et al.* (United Nations, Switzerland, 1958), Vol. 15, p. 408.
- [46] K. Hajara, M. Musthafa, N. Madhavan, S. Nath, J. Gehlot, C. Midhun, S. Akbar, F. S. Shana, A. Parihari, R. Biswas *et al.*, Entrance channel dependence of quasi fission in reactions leading to ^{206}Po compound nucleus, *Nucl. Phys. A* **1042**, 122789 (2024).
- [47] N. Bohr and J. A. Wheeler, The mechanism of nuclear fission, *Phys. Rev.* **56**, 426 (1939).
- [48] L. Meitner, Fission and nuclear shell model, *Nature (London)* **165**, 561 (1950).
- [49] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).
- [50] C. Straede, C. Budtz-Jørgensen, and H.-H. Knitter, $^{235}\text{U}(n, f)$ fragment mass-, kinetic energy-and angular distributions for incident neutron energies between thermal and 6 MeV, *Nucl. Phys. A* **462**, 85 (1987).
- [51] V. M. Strutinsky, Shell effects in nuclear masses and deformation energies, *Nucl. Phys. A* **95**, 420 (1967).
- [52] A. N. Andreyev, J. Elseviers, M. Huyse, P. Van Duppen, S. Antalic, A. Barzakh, N. Bree, T. E. Cocolios, V. F. Comas, J. Diriken *et al.*, New type of asymmetric fission in proton-rich nuclei, *Phys. Rev. Lett.* **105**, 252502 (2010).
- [53] R. Tripathi, S. Sodaye, K. Sudarshan, B. K. Nayak, A. Jhingan, P. K. Pujari, K. Mahata, S. Santra, A. Saxena, E. T. Mirgule, and R. G. Thomas, Fission fragment mass distributions in $^{35}\text{Cl} + ^{144,154}\text{Sm}$ reactions, *Phys. Rev. C* **92**, 024610 (2015).
- [54] E. Prasad, D. J. Hinde, M. Dasgupta, D. Y. Jeung, A. C. Berriman, B. M. A. Swinton-Bland, C. Simenel, E. C. Simpson, R. Bernard, E. Williams *et al.*, Systematics of the mass-asymmetric fission of excited nuclei from ^{176}Os to ^{206}Pb , *Phys. Lett. B* **811**, 135941 (2020).
- [55] L. Sarma, K. Kalita, H. Al Rashid, A. Das, N. K. Deb, M. Bhuyan, M. Khan, S. Abhilash, and D. Kabiraj, Fabrication and characterization of highly enriched thin ^{176}Yb targets for the reaction dynamic studies on fission mass distribution, *Vacuum* **224**, 113131 (2024).
- [56] T. K. Ghosh, S. Pal, T. Sinha, S. Chattopadhyay, K. S. Golda, and P. Bhattacharya, Time of flight (TOF) spectrometer for accurate measurement of mass and angular distribution of fission fragments in heavy ion induced fission reactions, *Nucl. Instrum. Methods Phys. Res., Sect. A* **540**, 285 (2005).
- [57] A. Jhingan, P. Sugathan, K. Golda, R. Singh, T. Varughese, H. Singh, B. Behera, and S. Mandal, Compact multiwire proportional counters for the detection of fission fragments, *Rev. Sci. Instrum.* **80**, 123502 (2009).
- [58] R. Brun and F. Rademakers, ROOT—an object oriented data analysis framework, *Nucl. Instrum. Methods Phys. Res., Sect. A* **389**, 81 (1997).
- [59] T. K. Ghosh, Study of heavy ion induced fission fragment angular and mass distribution at near and sub-coulomb barrier energies, Ph.D. thesis, Jadavpur University, Kolkata, India, arXiv:nucl-ex/0508009.
- [60] I. Mukul, S. Nath, K. S. Golda, A. Jhingan, J. Gehlot, E. Prasad, S. Kalkal, M. B. Naik, T. Banerjee, T. Varughese *et al.*, Probing fusion-fission dynamics in ^{203}Bi , *Phys. Rev. C* **92**, 054606 (2015).
- [61] J. Ziegler and J. Biersack, computer code SRIM, 2011.
- [62] Vikas, Kavita, K. S. Golda, T. K. Ghosh, A. Jhingan, P. Sugathan, N. Saneesh, Mohit, B. R. Behera, R. Kumar, and H. Singh, Reply to “Comment on ‘Fusion-fission dynamics of $^{188,190}\text{Pt}$ through fission fragment mass distribution measurements’”, *Phys. Rev. C* **109**, 069802 (2024).
- [63] S. Gupta, C. Schmitt, K. Mahata, A. Shrivastava, P. Sugathan, A. Jhingan, K. S. Golda, N. Saneesh, M. Kumar, G. Kaur *et al.*, Asymmetric fission around lead: The case of ^{198}Po , *Phys. Rev. C* **100**, 064608 (2019).
- [64] K. Hagino, N. Rowley, and A. Kruppa, A program for coupled-channel calculations with all order couplings for heavy-ion fusion reactions, *Comput. Phys. Commun.* **123**, 143 (1999).
- [65] P. Möller, A. J. Sierk, T. Ichikawa, and H. Sagawa, Nuclear ground-state masses and deformations: FRDM(2012), *At. Data Nucl. Data Tables* **109-110**, 1 (2016).
- [66] M. G. Itkis and A. Y. Rusanov, The fission of heated nuclei in reactions involving heavy ions: static and dynamical aspects, *Phys. Part. Nucl.* **29**, 160 (1998).

- [67] A. J. Sierk, Macroscopic model of rotating nuclei, *Phys. Rev. C* **33**, 2039 (1986).
- [68] S. Soheyli and M. K. Khalili, Pre-saddle neutron multiplicity for fission reactions induced by heavy ions and light particles, *Phys. Rev. C* **87**, 034610 (2013).
- [69] A. Gavron, Statistical model calculations in heavy ion reactions, *Phys. Rev. C* **21**, 230 (1980).
- [70] M. G. Itkis, S. M. Luk'yanov, V. N. Okolovich, Y. E. Penionzhkevich, A. Y. Rusanov, V. S. Salamatov, G. N. Smirenkin, and G. G. Chubaryan, Experimental study of the mass and energy distributions of fragments from fission, *Ya. Fiz.* **52**, 23 (1990).
- [71] E. Prasad, K. Varier, R. Thomas, A. Vinodkumar, K. Mahata, S. Appannababu, P. Sugathan, K. Golda, B. Babu, A. Saxena *et al.*, Fission fragment angular distribution measurements for $^{16}\text{O}+^{194}\text{Pt}$ reaction at energies near the Coulomb barrier, *Nucl. Phys. A* **882**, 62 (2012).
- [72] M. Yasue, T. Tanabe, F. Soga, J. Kokame, F. Shimokoshi, J. Kasagi, Y. Toba, Y. Kadota, T. Ohsawa, and K. Furuno, Deformation parameter of ^{12}C via $^{12}\text{C}(\alpha, \alpha')$ and $^{12}\text{C}(\alpha, \alpha'\alpha)$ reactions, *Nucl. Phys. A* **394**, 29 (1983).
- [73] T. K. Ghosh, K. Banerjee, C. Bhattacharya, S. Bhattacharya, S. Kundu, P. Mali, J. K. Meena, G. Mukherjee, S. Mukhopadhyay, T. K. Rana *et al.*, Sharp change-over from compound nuclear fission to quasifission, *Phys. Rev. C* **79**, 054607 (2009).
- [74] V. Y. Denisov and W. Norenberg, Entrance channel potentials in the synthesis of the heaviest nuclei, *Eur. Phys. J. A* **15**, 375 (2002).
- [75] D. J. Hinde, M. Dasgupta, and A. Mukherjee, Severe inhibition of fusion by quasifission in reactions forming ^{220}Th , *Phys. Rev. Lett.* **89**, 282701 (2002).
- [76] T. K. Ghosh, S. Pal, K. S. Golda, and P. Bhattacharya, Evidence of microscopic effects in fragment mass distribution in heavy ion induced fusion–fission reactions, *Phys. Lett. B* **627**, 26 (2005).