Fission fragment mass distribution has been measured from the decay of $^{246}$Bk nucleus populating via two entrance channels with slight difference in mass asymmetries but belonging on either side of the Coulomb barrier, at similar excitation energies the width of the fission fragment mass distribution was found to be drastically different for the $^{14}$N + $^{232}$Th reaction compared to the $^{11}$B + $^{235}$U reaction. The entrance channel mass asymmetry was found to affect the fusion process sharply.

PACS numbers: 25.70.Jj
distribution were measured. In an earlier measurement \[10\] of fragment angular distribution for these two systems, deviations from statistical model predictions were observed only for the $^{14}\text{N} + ^{232}\text{Th}$ system, contrary to the claim of a very recent dynamical cluster-decay model calculation \[11\]. The model calculation predicts that contribution from the non-compound fission channel should be higher for the $^{11}\text{B} + ^{235}\text{U}$ compared to the reaction $^{14}\text{N} + ^{232}\text{Th}$.

It is to be noted that both the $^{235}\text{U}$ and $^{232}\text{Th}$ targets chosen in our experiment to produce $^{246}\text{Bk}$ nucleus were deformed. However, the entrance channel mass asymmetries in two reactions were on either side of the Businaro Gallone mass asymmetry parameter value ($\alpha_{BG} = 0.893$) \[12\]. It is of interest to note that in the entrance channel, for a nominal change in the entrance channel mass-asymmetry, the initial mass flow is from the lighter to heavier mass in the system $^{11}\text{B} + ^{235}\text{U}$ ($\alpha = 0.911$), while it is in the reverse direction, i.e., from the heavier to lighter mass in the $^{14}\text{N} + ^{232}\text{Th}$ ($\alpha = 0.886$) system. Any inequality of the widths of the mass distribution in the decay of the $^{246}\text{Bk}$ for the systems with matched excitation and angular momentum in the entrance channel would be a confirmation of the effect of non-compound fusion-fission paths in the multi-dimensional potential energy surfaces. We have also used the reaction of $^{14}\text{N} + ^{197}\text{Au}$ as a reference reaction, which is expected to be almost pure fusion-fission reaction at the excitation energies covered in the experiment.

We have in previous communications \[3,13\] established that measurement of the width of the mass distribution is a powerful tool to probe the reaction mechanism in fusion-fission process. We employed a double armed time of flight spectrometer to simultaneously detect the complimentary fission fragments, rejected those events which showed incomplete fusion and determined the mass distribution for the purely fusion-fission process. The experimental arrangements and the data analysis procedure were described in detail in earlier reports \[14\]. The experiments were carried out using pulsed $^{14}\text{N}$ and $^{11}\text{B}$ beam of width about 1.1 ns, with a pulse separation of 250 ns, from the 15UD Pelletron at the Inter University Accelerator Centre (IUAC), New Delhi. Targets of $^{197}\text{Au}$ (self-supporting), $^{232}\text{Th}$ (on $200 \mu\text{g/cm}^2$ Al backing) and $^{235}\text{U}$ (on $300 \mu\text{g/cm}^2$ Ni backing) of thickness 500 $\mu\text{g/cm}^2$ were used. Targets were placed at an angle of 45$^\circ$ to the beam. The fission fragments were well separated from elastic and quasi-elastic reaction channels, both from the event-time and energy loss spectra in the detectors. The fission fragments from complete fusion events followed by fission were exclusively selected from the correlation of the velocities of the fissioning system in the beam direction ($V_{par}$) relative to the recoil of the fused system and the velocity perpendicular to the reaction plane ($V_{perp}$), as well as the correlation of the polar and azimuthal angles of the fragments ($\theta, \phi$) with respect to the beam axis. A typical measured distributions of the complementary fission events for the system $^{14}\text{N} + ^{232}\text{Th}$ at $E_{cm.} = 77.3$ MeV are shown in Fig. 1. To classify the events which solely come from fission following full momentum transfer with more than 99% certainty, a cut was used as shown in the figure by (red) rectangle in the spectra of velocity distributions of the fissioning nucleus. The masses were determined from the angles, momentum and the recoil velocities for each event.

Representative mass distributions, near and above the Coulomb barrier energies are shown in Fig. 2 for $^{14}\text{N} + ^{197}\text{Au}, ^{11}\text{B} + ^{235}\text{U}$ and $^{14}\text{N} + ^{232}\text{Th}$ systems. It can be observed that measured mass distributions are well fitted with single Gaussian distributions at all energies. The variation of the standard deviation ($\sigma_m$) of the fitted Gaussian to the experimental masses as a function of $E_{c.m.}/V_0$, where the $E_{c.m.}$ is the beam energy in center of mass system and $V_0$ is the Coulomb barrier, are shown in Fig 3 for all three measured systems. It is seen that for $^{14}\text{N} + ^{197}\text{Au}$ and $^{11}\text{B} + ^{235}\text{U}$ reactions the variation of...
\( \sigma_m \) is smooth across the Coulomb barrier. However a significant difference in the trend of the variation of \( \sigma_m \) is observed for the \( ^{14}N + ^{232}Th \) system, it shows a sudden increasing trend around the Coulomb barrier energies. Without delving into the reason for different behaviour for the \( ^{14}N + ^{232}Th \) system, it was also noticed that for this system, events following the incomplete-fusion followed by fission is also significant compared to that for other two systems. Since admixture of transfer induced fission events, which increase with lowered beam energy, may give rise to a wider mass distribution, extra care was taken while analysing the data of \( ^{14}N + ^{232}Th \) system at energies where we observed a sudden increase in the width of the mass distributions as shown in Fig. 3. In Fig. 4 we show the folding angle distribution of all the fragments for \( ^{14}N + ^{232}Th \) at \( E_{cm}/V_b = 1 \). The gate on the velocity correlations for fragments as shown in Fig. 1 reduces the possible contribution of the transfer induced events to below 1%. To quantitatively evaluate the change in the width of the mass distribution of even this possible small admixture of transfer fission events, an additional conditionality was introduced through the imposition of a gate \((163^\circ \text{ to } 174^\circ)\) around the peak at \(165.4^\circ\) which corresponds to that expected for the full momentum transfer symmetric fission events. This action changed the width of mass distribution which was smaller than the statistical error in \( \sigma_m \). This clearly establishes that the sudden increase in \( \sigma_m \) is not due to admixture of transfer induced events.

The variation of standard deviation of the mass distributions with excitation energy for two reactions \( ^{14}N + ^{232}Th \) and \( ^{11}B + ^{235}U \) forming the same composite system \( ^{246}Bk \) is shown in Fig. 5. Solid (red) line in the figure shows the calculated variation from statistical theory \(^{15}\) following the relation \( \sigma_m^* = \frac{a}{E^1} \), where \( E^1 \) is the excitation energy at the scission point, \( a \) is the nuclear level density parameter. A value of the stiffness parameter \( k = 0.0033 \text{ MeV/amu}^2 \) fitted the \( ^{11}B + ^{235}U \) data well \(^{10}\). It is interesting to note that for the \( ^{14}N + ^{232}Th \) reactions, not only there is a sudden jump of mass widths (\( \sigma_m \)) near the Coulomb barrier but also the magnitude is higher than the \( ^{11}B + ^{235}U \) reactions over the entire range of excitation energies.

The width of fission fragment mass distribution mainly depends on the excitation energy. However, it has weaker linear dependence on the mean square angular momentum \(< I^2 > \) brought in by the projectile \(^{11}B \). In Fig. 6 we show the measured \(^{10}\) variation of \(< I^2 > \) with excitation energy for the two systems forming the same composite system \( ^{246}Bk \). It can be seen that average mean square angular momentum value for the system \( ^{11}B + ^{235}U \) is always higher than those for \( ^{14}N + ^{232}Th \) in the range of our measured excitation energies. So, even if we correct the predicted widths of the mass distribution for the possible contribution for \(< I^2 > \), the correction for the \( ^{14}N + ^{232}Th \) system would be smaller compared to that for \( ^{11}B + ^{235}U \) and would not explain the observed sharp increase of the mass width for \( ^{14}N + ^{232}Th \) around the Coulomb barrier as shown in Fig. 6.

We have observed that for the fusion of two heavy nu-

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**FIG. 3:** (Color online) Variation of the standard deviation \( \sigma_m \) to the fitted Gaussian of the fission fragments mass distribution as a function of \( E_{cm}/V_b \)

**FIG. 4:** (Color online) Measured fragment folding angle distribution for the system \( ^{14}N + ^{232}Th \) at projectile energy \( E_{cm} = 73.5 \text{ MeV} \)

**FIG. 5:** (Color online) Measured variation of \( \sigma_m \) with excitation energy for the two reaction forming the same composite system \( ^{246}Bk \). Calculated variation is shown by solid (red) line.
nuclei forming the compound nucleus $^{246}$Bk through the reactions $^{11}$B+$^{235}$U and $^{14}$N+$^{232}$Th at the similar excitation energy the fused system behaves differently and the reactions paths followed by the two systems, particularly around the Coulomb barrier, are significantly different. The targets in both cases are prolate deformed in the ground state while the projectiles are spherical; yet, the reaction paths followed by the two systems are quite different. In the case of $^{11}$B, the composite $^{246}$Bk shows a behaviour according to the predicted course following statistical equilibration of the composite to a compound nucleus followed by binary fission. This reaction mechanism holds true at near and below the Coulomb barrier and the variation of the width of the mass distribution closely follows that predicted from the statistical laws as shown by the solid (red) line in Fig. 6. On the contrary, this expected reaction mechanism does not hold true for the $^{14}$N+$^{232}$Th system, as the mass widths at all the measured energies are larger than those predicted by the statistical theory and show a sharply increasing trend as the energy is lowered than about 1.05 times the Coulomb barrier.

We have earlier reported anomalous behaviour of the mass width, increasing with the decrease in energy, for the reacting systems of $^{12}$C, $^{16}$O and $^{19}$F on $^{232}$Th. Although these three reactions did not produce the same composite system, we could explain the increase in the mass widths in terms of a orientation dependent quasi-fission reaction mechanism. For the $^{14}$N+$^{232}$Th system, in the measured energy region, the reactions proceed mostly through the impact of the projectile on the polar region of the target nucleus and it drives the non-compact entrance channel shape to an almost mass symmetric saddle shape leading to increased mass widths, rather than a compact equilibrated fused system, which undergoes fission through shape oscillations. We can explain the observed increase of the mass widths with decrease in energy, in the case of $^{14}$N+$^{232}$Th system, as a quasi-fission phenomenon, however, in case of the $^{11}$B+$^{235}$U system, the initial separation in the entrance channel may not be sufficient to drive the system to a non-compact entrance channel to a mass asymmetric saddle shape. We also point out that, although the entrance channel mass asymmetries for the two systems do not differ much, in the two cases the flow of mass is completely different as the two nuclei fuse together. In the system $^{14}$N+$^{232}$Th, the entry point to the multidimensional potential surface is such that the system is driven to lower mass asymmetry leading to greater probability to diverge to a mass asymmetric saddle rather than a compact fused system, while the picture is just the reverse in the case of $^{11}$B+$^{235}$U, whereby the system is driven to higher mass asymmetry and thus is more probable to reach a compact fused system and undergo statistical fission after equilibration.

We conclude that in the fusion of the $^{246}$Bk, in addition to the effect of deformation, where the reaction proceeds mostly through impact through the polar region of the prolate thorium or uranium targets, the entrance channel mass asymmetry plays a crucial role in the reaction mechanism, particularly in the energy close to the Coulomb barrier. Even a small change in the entrance channel mass asymmetry, which effectively reverses the flow of mass in fusing the target and projectile, results in completely different reaction mechanism - a re-separation of the composite in $^{14}$N+$^{232}$Th over a mass asymmetric saddle, or the statistical equilibration followed by fission in the case of $^{11}$B+$^{235}$U. The entrance channel sharply affects the fusion process in the production of the nucleus $^{246}$Bk.

We are thankful to Dr. A. Saxena of BARC, Mumbai and Dr S. K. Das of VECC for providing help of making few of the targets used in the experiment. Thanks are due to the staff members of the IUAC Pelletron for providing good quality pulsed beam required for the experiment.

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