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Anomalous increase in width of fission-fragment mass distribution as a probe for onset of quasifission reactions in deformed target-projectile system at near and sub-barrier energies

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Fission-fragment mass distribution has been studied for the $^{16}O+^{232}Th,^{209}Bi$ systems over an energy range of 102.8–78.6 MeV and 81.6–72.6 MeV, respectively, in a laboratory frame. The variance of the mass distribution (σ_m^2) for the $^{16}O+^{209}Bi$ system varies linearly with center of mass energy, while a significant anomalous behavior is found for the system $^{16}O+^{232}Th$. Coupled with our earlier observation for the system $^{19}F+^{232}Th$ [T. K. Ghosh *et al.*, Phys. Rev. C **69**, 031603(R) (2004)], we propose that the accurate measurement of mass distribution is a powerful tool to look for the onset of a nonstatistical reaction mechanism in heavy-ion-induced fission of deformed heavy nuclei.

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In heavy-ion-induced fission reactions on deformed targets at near and below Coulomb barrier energies, anomalous enhancements of the fragment angular anisotropy, with respect to the statistical saddle-point model (SSPM) [1] predictions, have been observed [2–4]. However, with spherical targets, the angular distributions follow the SSPM predictions. As an example, in reaction $^{16}O+^{232}Th$ (deformed target), an anomalous increase in fragment anisotropy was observed [4–7], but in $^{16}O+^{209}Bi$ (spherical target), no such anomalous increase in fragment angular anisotropy was observed [8]. Hinde *et al.* [9] postulated a nuclear orientation-dependent quasifission reaction to explain the enhancement in fragment anisotropy. It was assumed that, up to a critical angle between the projectile trajectory and the symmetry axis of the deformed target, the dinuclear system preferentially moves over a mass asymmetric conditional saddle point, leading to a narrower K distribution. Thus, a larger fragment anisotropy can be obtained, compared to that predicted by SSPM [1]. With a decrease in energy, the quasifission increasingly dominates in near and below barrier energies. In the above model, no quasifission mechanism was expected for a spherical projectile-target combination.

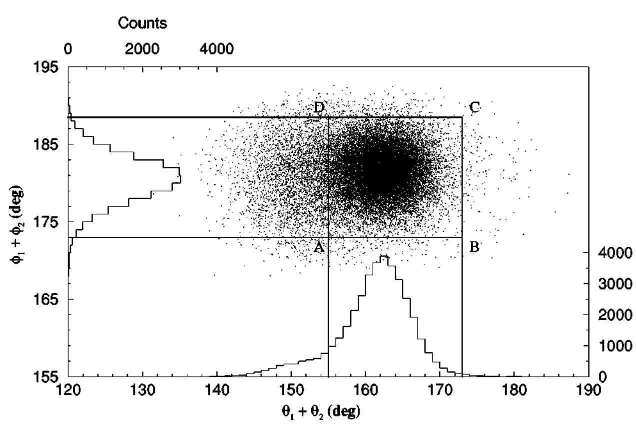

FIG. 1. Distributions of complimentary fission fragments in (θ,ϕ) for the system $^{16}O+^{232}Th$ at $E_{c.m.}=77.3$ MeV. Rectangle ABCD indicates the gate used to select the FF events for mass determination.

Apart from the enhancement of fragment angular anisotropy, the probable effects of the assumed quasifission would be asymmetry or a significant increase in the width of the fission-fragment mass distributions [10,11]. Strong support for this assumption came from our recent observation of a sudden increase of the variance of the mass distribution (σ_m^2) of fission fragments at near and below barrier energies in the $^{19}F+^{232}Th$ system [12]. The variance, σ_m^2, of the mass distribution was found to be a strong signal for the onset of a completely different mechanism other than statistical fusion fission (FF).

It is well established that in $^{16}O+^{232}Th$, anomalous behavior of the fragment anisotropy at near and below Coulomb

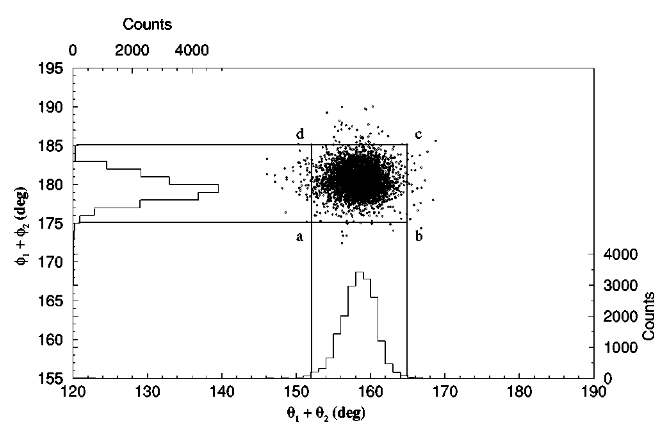

FIG. 2. Distributions of complimentary fission fragments in (θ,ϕ) for the system $^{16}O+^{209}Bi$ at $E_{c.m.}=76.2$ MeV.

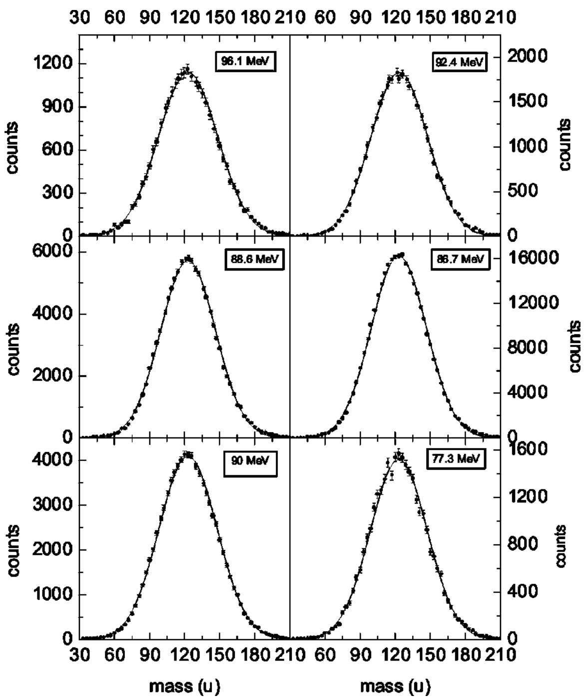

FIG. 3. Mass distributions for the system $^{16}O+^{232}Th$ at different projectile energies (c.m.). The Gaussian fits are shown by solid lines.

barrier energies follows the trend, as observed in $^{19}F+^{232}Th$ [5]. In contrast, the fragment anisotropy in $^{16}O+^{209}Bi$ follows the SSPM predictions quite well [8,13]. In this communication, we report the result of the measurement of the

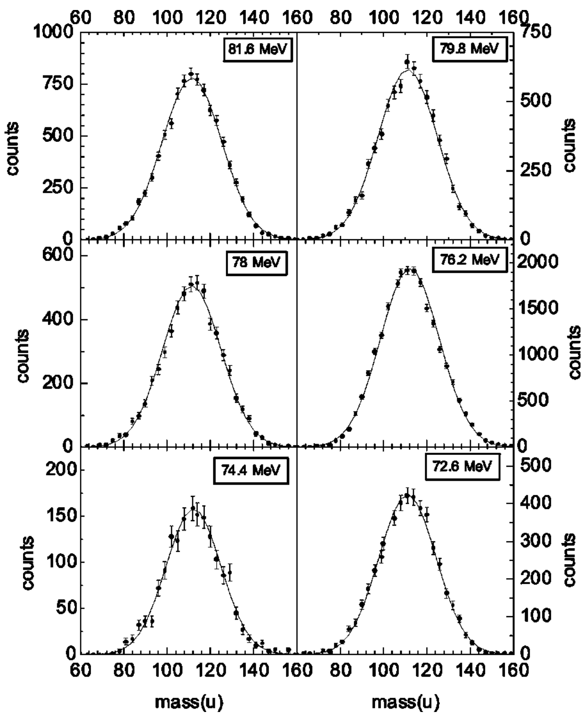

FIG. 4. Mass distributions for the system $^{16}O+^{209}Bi$ at different projectile energies (c.m.). The Gaussian fits are shown by solid lines.

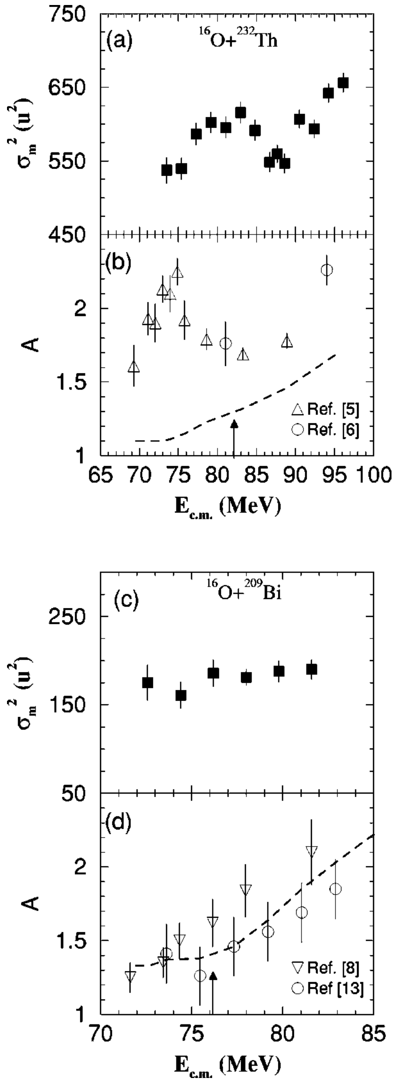

FIG. 5. (a) Mass variance σ_m^2 and (b) anisotropy A, as a function of $E_{\text{c.m.}}$ for the system $^{16}O+^{232}Th$. (c) Mass variance σ_m^2 and (d) anisotropy A, as a function of $E_{\text{c.m.}}$ for the system $^{16}O+^{209}Bi$. In (b) and (d) the dashed line represents the SSPM calculation with correction for prescission neutron emission [6,13]. The Coulomb barrier is indicated by an arrow.

widths of the mass distributions in $^{16}O+^{232}Th$, compared with those from $^{16}O+^{209}Bi$, to examine if the variance of the mass distribution can be used as a reliable probe for the onset of a nonstatistical equilibrium in deformed targets and projectile systems in near and below Coulomb barrier energies.

The experiment was carried out using a pulsed beam of ^{16}O from the 15UD Pelletron at the Nuclear Science Centre (NSC), in New Delhi, India. The pulse width was about 0.9 ns, with a pulse separation of 250 ns. The targets were self-supporting ^{232}Th foil of thickness $1.8\ \text{mg/cm}^2$ and $500\ \mu\text{g/cm}^2$ thick self-supported ^{209}Bi. The target was aligned at an angle of 30° to the beam. Complimentary fission fragments were detected with large area X-Y position-sensitive multiwire proportional counters [14,15]. The fission fragments were separated from elastic and quasielastic channels using time of flight of particles and the energy-loss signal in the detectors. Folding angle technique [16] was used to differentiate between FF and transfer-fission (TF) events. The experimental arrangements, data acquisition, and data analysis techniques were identical to those in Refs. [12,15].

Fission fragments were separated from elastics and quasielastics particles by correlations of arrival times and energy loss of particles in two detectors. Following the method as adopted in Ref. [12], we could reduce the contamination of elastic and quasielastic to fission channels below 1%. It is to be noted that ^{16}O+^{232}Th reaction also had considerable cross sections for TF events similar to those observed in ^{19}F+^{232}Th reaction [12]. The fission fragments for fusion-fission events were determined from the distribution of polar and azimuthal angles. The events within the rectangle "ABCD," as shown in Fig. 1, were due to FF in the polar (θ) and azimuthal (ϕ) correlations. However, in ^{16}O+^{209}Bi, the TF channel contributes less than 1%, as could be observed in Fig. 2, where very few events lie outside of the rectangle marked abcd in correlated θ-ϕ distributions of fragments.

Masses of the fragments were determined from precise measurements of flight paths and flight time difference of the complementary fission fragments event wise [12]. The mass distributions at different center-of-mass (c.m.) energies are shown in Fig. 3 for ^{16}O+^{232}Th, and in Fig. 4 for ^{16}O+^{209}Bi. It can be observed that mass distributions are well fitted with Gaussian, even at the lowest energies. As in the case of ^{19}F+^{232}Th [12], we failed to observe any significant departure from a single Gaussian fit in either of the reactions, and possible admixture of asymmetric mass distributions were ruled out.

Figure 5(a) shows the variation of the square of the variances of the fitted Gaussian, σ_m^2, to the experimental masses as a function of the c.m. energy in ^{16}O+^{232}Th. We observed a very similar trend of the variation of σ_m^2 with decreasing energy, as was observed for the ^{19}F+^{232}Th system. In ^{16}O+^{232}Th, above the fusion barrier, σ_m^2 decreases smoothly with the energy, but near the barrier at about 87 MeV, σ_m^2 starts to rise and reaches a peak around 81 MeV. At still lower energies, it again starts to fall smoothly with a decrease in energy. However, the rise in the σ_m^2 is about 15%, compared to as almost 50% rise observed in ^{19}F+^{232}Th [12]. It is noted that the rise in σ_m^2 occurs exactly at the energy in which an anomalous rise in fragment anisotropy had been observed [5], as shown in Fig. 5(b). The dashed curve in Fig. 5(b) is the prediction from SSPM.

The variation of σ_m^2 in ^{16}O+^{209}Bi reaction is shown in Fig. 5(c). The width of the mass distribution is much smaller, compared to the ^{16}O+^{232}Th system, and varies slowly with energy. Figure 5(d) shows that in ^{16}O+^{209}Bi, the variation of fragment angular anisotropy with energy did not show any large, anomalous behavior, compared to the SSPM predictions (dashed line).

Observance of the sudden and significant increase in the width of the mass distribution in ^{16}O+^{232}Th and in ^{19}F+^{232}Th, coupled with the absence of such an effect in ^{16}O+^{209}Bi, clearly establishes that the accurate measurement of mass distribution is also a powerful tool to look for the onset of a nonstatistical reaction mechanism in heavy-ion-induced fission of deformed heavy nuclei. The anomalous increase in the width of fragment mass distribution and fragment anisotropy in both the ^{16}O and ^{19}F+^{232}Th systems strongly support the postulated orientation-dependent quasifission mechanism in heavy deformed target-projectile systems in near and sub-barrier energies.

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