Anomalous Peaklike Structure in the Fission Fragment Anisotropies at Sub-barrier Energies in ^{11}B, ^{12}C, ^{16}O, ^{19}F + ^{232}Th Reactions

N. Majumdar and P. Bhattacharya
Saha Institute of Nuclear Physics, 1/AF, Bidhannagar Calcutta 700 064, India

D. C. Biswas, R. K. Choudhury, D. M. Nadkarni, and A. Saxena
Bhabha Atomic Research Centre, Bombay 400 085, India
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Fission fragment angular distributions have been measured for fission following full momentum transfer in ^{11}B, ^{12}C, ^{16}O, and ^{19}F + ^{232}Th systems from above barrier to below sub-barrier energies. The fragment anisotropies $[W(0°)/W(90°)]$ are found to exhibit an anomalous peaklike structure below the fusion barrier in all the systems. This structure has a universal behavior independent of the entrance channel mass asymmetry. With some refinement in the quasifission hypothesis it is possible to explain qualitatively the experimental results reasonably well. [S0031-9007(96)01887-X]

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In recent years, there has been renewed interest in the study of the fragment angular distributions in heavy ion fusion-fission reactions at near and below barrier energies, following the observation that, in a number of systems, the fragment anisotropies are anomalously large [1,2] compared to that expected on the basis of the statistical saddle point model (SSPM) [3] calculations. In some earlier works of inclusive measurements using track detectors, the fragment anisotropies for ^{19}F + ^{232}Th and ^{16}O + ^{232}Th systems were found to have a peaklike structure in the sub-barrier energies [4–6]. However, in later measurements, after taking into account the contributions from incomplete fusion events, the fragment anisotropies for compound nuclear fission (CNF) reactions were found to show only a rising trend with decreasing energy at sub-barrier energies [7–9]. Such a rising behavior in the fragment anisotropy was also reported in more recent measurements for the ^{16}O + ^{238}U [10], ^{19}F + ^{232}Th [11,12], and ^{12}C + ^{232}Th [13] systems.

The increasing trend in anisotropy for CNF at sub-barrier energies was sought to be explained by the quasifission model [10] and pre-equilibrium fission model [9,14]. In the quasifission model, for certain relative orientations of the axes of the deformed target and the projectile, quasifission reactions were postulated to take place. In the pre-equilibrium fission model [9], an angular momentum dependent nonequilibrated K distribution was proposed to explain the rise in anisotropies at sub-barrier energies. In both models, nonequilibrium fission is assumed to dominate at lower energies, and fragment anisotropies are predicted to saturate at the lowest energies. A departure from the predicted trend was reported by us in the ^{12}C + ^{232}Th system where the anisotropy was found to again fall close to SSPM value at deep sub-barrier energies [12]. It may be emphasized that this was the first indication for a clear peaklike structure in fragment anisotropies for CNF reactions, where angular distributions of fragments from the full momentum transfer events were measured. For the ^{12}C + ^{232}Th reaction, the entrance channel mass asymmetry $[\alpha = (M_H - M_L)/(M_H + M_L)]$ is larger than static critical Businaro-Gallone (BG) mass asymmetry $\alpha_{\rm BG}^{\rm crit}$. The quasifission reaction is favorable for systems with entrance channel mass asymmetry smaller than $\alpha_{\rm BG}^{\rm crit}$ [10], and a pre-equilibrium fission model was applied to systems with $\alpha < \alpha_{\rm BG}^{\rm crit}$. In order to examine the behavior of the fragment anisotropies at the sub-barrier energies, we have now carried out extensive measurements of fragment anisotropy and an excitation function for CNF events in a number of systems with entrance channel asymmetries smaller and larger than $\alpha_{\rm BG}^{\rm crit}$. It is seen that the anomalous peaklike structure in the fission fragment anisotropies at sub-barrier energies is a universal feature for all the systems with the projectiles of ^{11}B, ^{12}C, ^{16}O, and ^{19}F on the ^{232}Th target.

The experiments were performed with heavy ions from the Bhabha Atomic Research Centre-Tata Institute of Fundamental Research 14 UD Pelletron at Bombay. A 1.8 mg/cm^2 thick self-supporting ^{232}Th target was used. The energy loss of different beams in the half thickness of the target varied from 0.5 to 1.7 MeV and has been corrected for while analyzing the present data. Coincident fission fragments were detected with two X-Y position sensitive, large area (15.0 cm × 3.5 cm), low pressure (2 to 3 torr) Breskin detectors. The detectors had excellent timing and position resolution, and were transparent to low Z ($Z \leq 20$) ions [15]. One detector was placed at 16.0 cm from the target subtending an angle of 50° at the target. It was moved in three overlapping steps to cover 10° to 110° in the reaction plane, improving the normalization of data and counting statistics compared to our earlier measurements [11,12]. The other detector, placed at a distance of 12.0 cm from the target and subtending 65° angle at it, was moved in the range −70°

to $-170°$ to detect the complementary fragments. The transformations from (X, Y) positions to (θ, ϕ) angles of the coincident fragments were carried out accurately by using calibrations from the positions of the "images" of the support wires of gas windows of detectors. The folding angle distributions of coincident fragments were obtained for typically 5° bins in the forward detector. The fragment yields for CNF events were determined from the folding angle distributions following a suitable kinematic analysis, details of which were reported earlier [11,16].

In Fig. 1, we have shown typical angular distributions of fragments for kinematically separated compound nuclear events at some of the lowest energies, where no measurements have been reported so far. At these energies, there is a large admixture of contributions from noncompound channels to the CNF events. This can be seen from the folding angle distributions (insets in Fig. 1) for 10° bins in the forward detector for 25° (top) and 75° (bottom) fragment emission angles. The positions of the CNF peak, as expected from kinematics, are indicated by arrow marks. Gaussians (solid lines) are fitted to the CNF events and targetlike fission events (at smaller folding angles). At forward angles, targetlike fragment fission events show a long tail to higher folding angles [16]. At very low energies, an extra peak is noticed in all systems, with folding angles about 180° corresponding to very small momentum transfer events, which might be due to the fission of Coulomb excited states of the target. At very low energies and at forward angles, the admixture of other noncompound fission channels was less than 40% and could be corrected for as shown in the figure. The CNF yields were thus determined with ±20%, or better, accuracy.

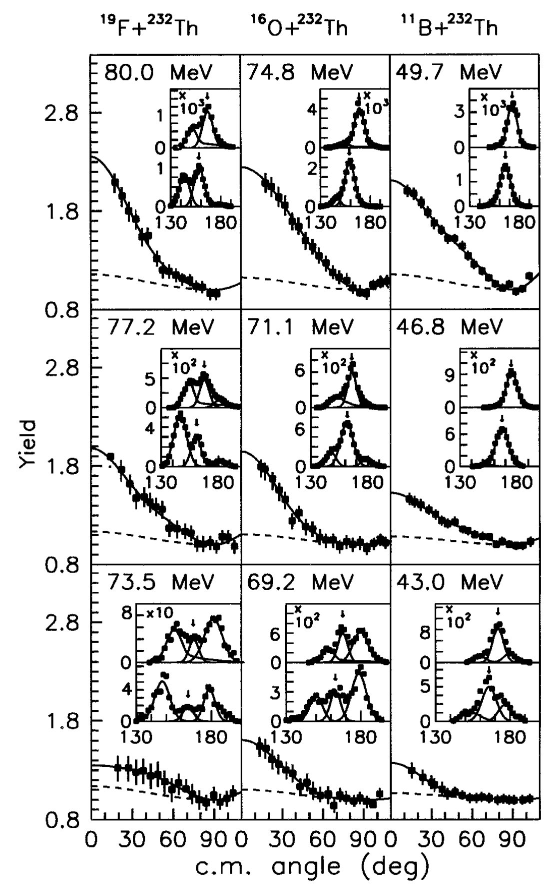

FIG. 1. Typical experimental fission fragment angular distributions (solid squares), Legendre polynomial fits (solid lines), and SSPM calculations (dashed lines) for CNF reactions at subbarrier energies for various systems. The folding angle distributions (counts vs θ_{FF} in degrees) are shown in insets, where the peaks for CNF are marked by arrows.

The experimental angular distributions (solid squares) were fitted by a Legendre polynomial up to P_6 terms (solid lines) to determine the fission fragment angular anisotropy $W(0°)/W(90°)$ for CNF events. The SSPM [3] predictions are shown in Fig. 1 by the dashed lines. The anomalous enhancement of anisotropies are clearly evident from the figures. It may be noted that, even at the lowest energies, reliable fragment angular anisotropies with an accuracy of ±15% could be obtained.

The fission fragment angular anisotropies are shown in Fig. 2 for various systems at all the energies measured in the present work, along with our earlier results for the $^{12}C + ^{232}Th$ system [12]. As can be seen, the fission fragment anisotropies for CNF events are reported for the first time extending to deep sub-barrier energies (about 18% below the Coulomb barrier) for systems with entrance channel mass asymmetries lying on both sides of the α_{BG}^{crit} values. It is seen in Fig. 2 that, for all the systems, the fragment angular anisotropy first decreases as the projectile energy decreases, but, at a certain energy around the barrier, it rises and reaches maximum and then decreases to almost the SSPM value at the lowest energies. The results of SSPM calculations are shown by the full lines in Fig. 2.

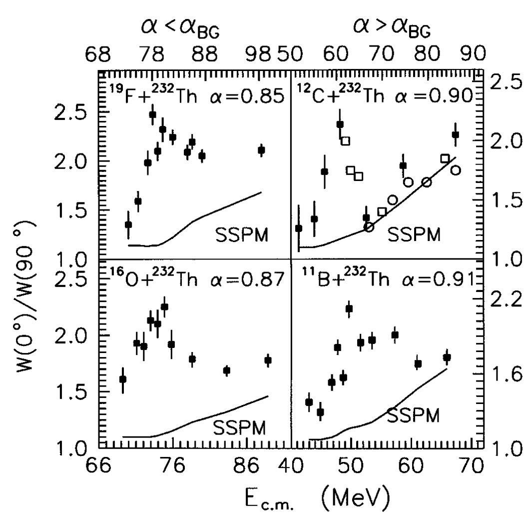

FIG. 2. Variation of fission fragment anisotropies with c.m. energy of projectile for systems with different entrance channel mass asymmetries. The solid lines are theoretical (SSPM) predictions with neutron corrections.

Figure 3 shows the experimental results on the excitation functions, barrier distributions and the second moment of spin distributions [determined using the relation $W(0°)/W(90°) = 1 + \langle l^2\rangle/4K_0^2$] for F, O, and B + Th systems. We have included the relevant results of the earlier work (open symbols) reported by Zhang *et al.* [8]. Because of low statistical error (1%–10%) in cross sections, the barrier distributions are determined with fair accuracy despite the effect of target thickness. The excitation functions and barrier distributions could be fitted very well by coupled channel calculations (solid lines). Typically, the ground state β_2 and β_4 deformation parameters of the target, the 3^- state of ^{232}Th, and the spherical ground state of projectile were included in the calculations. The transmission coefficients (T_l) obtained from these fits were used in subsequent calculations of the SSPM and quasifission analysis. The experimental $\langle l^2\rangle$ values have been compared with $\langle l^2\rangle$ values calculated from coupled channel calculations in the lower part of Fig. 3. In all the systems, the experimental $\langle l^2\rangle$ deviate strongly from the calculated behavior. One interesting observation is that, for the B + Th (and C + Th [12]) system, the peak in the $\langle l^2\rangle$ values occurs at an energy very close to the peak in the barrier distribution, whereas, for the O and F + Th systems, the peak is at an energy 8–10 MeV lower than the peak in barrier distribution. It may be pointed out that this difference is beyond the experimental uncertainty in the barrier distribution function due to target thickness effect, statistics, etc.

The present results have shown that the variations of the fragment anisotropy with projectile energy near and well below the Coulomb barrier energy have a universal behavior for target-projectile combinations having different entrance channel mass asymmetries. In Fig. 4, the results are plotted in a different way to bring out the universal behavior more clearly. We show in Fig. 4 the values of $(A_{\rm exp} - A_{\rm SSPM})/A_{\rm SSPM}$ as a function of beam energy in the form $(E_{\rm c.m.} - V_C)/V_C$, where V_C is the static Coulomb barrier height. This figure brings out the required features that need to be explained by any theoretical model for the calculations of the fission fragment anisotropies in these reactions. The model should explain the rise and fall of the anisotropy irrespective of the entrance channel mass asymmetry and the relative shift in energy at which the peaks occur for systems with $\alpha < \alpha_{\rm BG}^{\rm crit}$ and $\alpha > \alpha_{\rm BG}^{\rm crit}$.

In Fig. 4 we have also shown the theoretical calculations based on the quasifission hypothesis of Hinde *et al.* [10] for ^{19}F and ^{16}O by solid lines. The rise in anisotropy can be explained for projectiles ^{19}F and ^{16}O, but this model cannot predict the fall in anisotropy and only produces a saturation of anisotropy at lower energies. For ^{12}C and ^{11}B, even the rise in anisotropy could not be predicted well. The pre-equilibrium fission model of Liu *et al.* [9], which assumes an exponential dependence of the variance of K distributions (σ_K^2) on the compound nuclear spin, may also explain the rise in anisotropy, but again does not lead to the peaklike structures. For systems with mass asymmetries greater than static critical BG mass asymmetries, it is known that mass relaxes to still higher asymmetries, and any divergence of the system towards saddle before equilibration of shape (quasifission) or tilting angle of the nuclear symmetry axis (pre-equilibrium fission) would produce binary fragments of higher mass asymmetry not recognized experimentally as fission fragments. However, this picture changes due to the shift of the Businaro-Gallone point itself to higher mass asymmetry for higher spins. In a simple theoretical calculation of total energies, including shell effects, the critical mass asymmetry for the ^{12}C + ^{232}Th system is found to shift from the static value of about

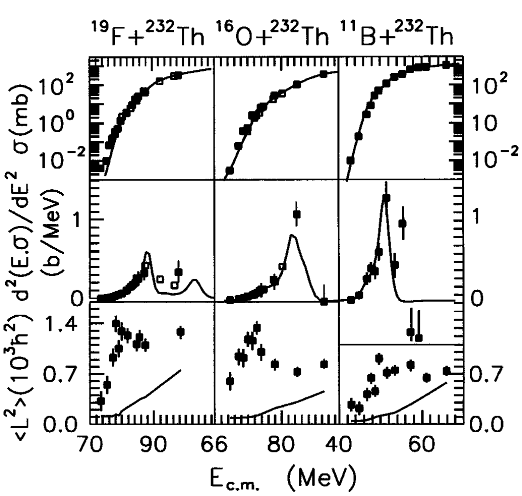

FIG. 3. Variations of experimental cross sections, barrier distributions, and $\langle l^2\rangle$ (solid squares) with c.m. energy. Reported data are shown by open squares [8]. Coupled channel and SSPM calculations are shown by solid lines.

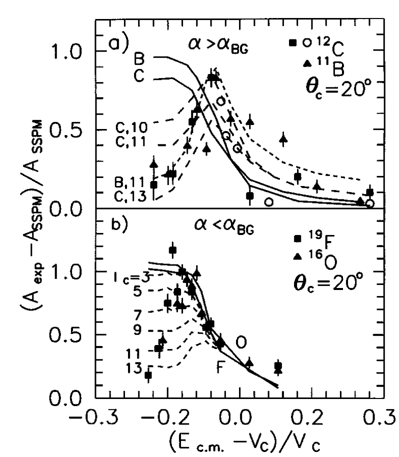

FIG. 4. Universal plot of $(A_{\rm exp} - A_{\rm SSPM})/A_{\rm SSPM}$ vs $(E_{\rm c.m.} - V_C)/V_C$. The solid curves marked C and B in (a), F and O in (b), are fits to the data using quasifission formalism. The dotted curves are fits with cuts in l values in units of $\hbar$.

0.83–0.87 to 0.87–0.91 for a spin of $(15-20)\hbar$, so that, beyond these spins, the mass flow may reverse towards lower asymmetry. Realistic calculation including deformation, etc., is expected to lower the spins at which mass flow reverses in these systems. We can therefore assume that, for spins above some critical value, depending upon the c.m. energy, the mass flow pattern may reverse and be similar to that of the cases with $\alpha < \alpha_{\mathrm{BG}}^{\mathrm{crit}}$. Simple calculation of anisotropy, introducing a cut-off spin above which quasifission mechanism is expected in ^{12}C and ^{11}B + ^{232}Th systems, shows improvement in the fit to anisotropies. At a cut-off spin of $11\hbar$, as shown by the dashed lines in Fig. 4(a), even a peaklike structure in anisotropy may be reproduced. Since there is no experimental evidence or firm theoretical guidelines available on the values of spin at which the reversal of mass flow may take place for these systems, the above picture can be considered only as a plausible mechanism for the boosting of fragment anisotropy in these systems.

On the basis of the existing fission models, the rise and fall in anisotropy at very low energies, observed for ^{19}F and ^{16}O on ^{232}Th, cannot be fully explained. One point that is not considered in the above models is the possible variation of the anisotropy for quasifission reaction events with energy. Below the fusion barrier, the relatively large initial separation of the coalescing heavy ions may give rise to a significant increase in the transition time to saddle shape to the extent that the entrance channel memory may be considerably diluted, thereby increasing the effective variance of the K distribution (K_0^2) even in quasifission reactions, which will give rise to a reduction in the fragment anisotropy. In Fig. 4(b), we have shown by dashed lines the effect of a cut at different values in partial waves, below which the quasifission is assumed to be ineffective in boosting the anisotropy. One may point out that the simple calculations simulate the reduction in anisotropy quite effectively. The present set of data calls for the modification of the existing theoretical models. The effect of spin and excitation energy on the relaxation time of the mass and shape asymmetry should be investigated both theoretically and experimentally. The forward-backward asymmetry in the mass distribution should also be investigated to test the intuitive hypotheses of quasifission mechanism more thoroughly, and such experiments are under way.

In summary, we have reported the measurements of the cross sections and anisotropies of fission fragments following full momentum transfer in systems with entrance channel mass asymmetries smaller and larger than the Businaro-Gallone critical mass asymmetry from above barrier to below sub-barrier energies. In all systems, anisotropies show a peaklike structure at deep sub-barrier energies. The cross sections can be explained by coupled channel calculations, including the deformations and the first few excited states of the target and projectile in all the systems. In a refinement of the nuclear orientation dependent quasifission reaction hypothesis, the peaklike structures in fragment anisotropies can be qualitatively accounted for. More rigorous theoretical calculations are called for to explain the present experimental observation.

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[1] L. C. Vaz and J. M. Alexander, Phys. Rep. **97**, 1 (1983).
[2] R. Vandenbosch *et al.*, Phys. Rev. Lett. **56**, 1234 (1986).
[3] I. Halpern and V. M. Strutinsky, *Proceedings of the 2nd United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva* (United Nations Publications, Geneva, 1958), Vol. 15, p. 408.
[4] H. Zhang *et al.*, Phys. Lett. B **218**, 133 (1989).
[5] H. Zhang *et al.*, Phys. Rev. C **42**, 1086 (1990).
[6] H. Zhang *et al.*, Nucl. Phys. **A538**, 229c (1992).
[7] H. Zhang *et al.*, Phys. Rev. C **47**, 1309 (1993).
[8] H. Zhang *et al.*, Phys. Rev. C **49**, 926 (1994).
[9] Z. Liu *et al.*, Phys. Lett. B **353**, 173 (1995).
[10] D. J. Hinde *et al.*, Phys. Rev. Lett. **74**, 1295 (1995).
[11] N. Majumdar *et al.*, Phys. Rev. C **51**, 3109 (1995).
[12] N. Majumdar *et al.*, Phys. Rev. C **53**, R544 (1996).
[13] A. Karnik *et al.*, Z. Phys. **351**, 195 (1995).
[14] V. S. Ramamurthy and S. S. Kapoor, Phys. Rev. Lett. **54**, 178 (1985).
[15] P. Bhattacharya *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **276**, 585 (1989).
[16] P. Bhattacharya *et al.*, Nuovo Cimento A **108**, 819 (1995).