Fission fragment angular distributions in the ^{9}Be + ^{232}Th reaction

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Fission fragment angular distributions have been measured for a ^{9}Be + ^{232}Th system at four different beam energies around the Coulomb barrier. The experimental results on fission fragment anisotropies have been compared with predictions of the standard statistical saddle-point model (SSPM) and the preequilibrium fission (PEQ) model including projectile ground-state spin. It is observed that both SSPM and the PEQ model fail to reproduce the experimental results, indicating that projectile breakup may affect the fission fragment anisotropies.

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It has been well established that the study of fission fragment angular distributions provides a good source of information about the fusion-fission dynamics [1]. The fission fragment anisotropies obtained from heavy-ion reactions involving actinide targets when compared with standard statistical saddle-point model (SSPM) predictions show differences for both below and above the Coulomb barrier energies for many target-projectile systems. This has been explained as being due to the entrance channel characteristics of the interacting nuclei, such as large deformation of the target nuclei and the ground-state spin alignment of the target or projectile with the nuclear deformation axis [2–5], which can be attributed to the presence of preequilibrium fission, which occurs when the system undergoes fission before the projection of total angular momentum on the symmetry axis (K) degree of freedom is completely equilibrated. As the system does not reach the compound nuclear shape, it retains the memory of the entrance channel, resulting in larger anisotropies [3]. The interaction of projectiles at points perpendicular to the symmetry axis of the deformed target is favored in the fission through a compact compound nuclear shape, which leads to a fusion-fission reaction where the observed anisotropies are expected to be consistent with SSPM predictions [4]. It is also reported that the ground-state spin of the projectile or target influences the fission anisotropies by aligning the nuclear spin with the nuclear deformation axis [5,6]. The sub-barrier fission anisotropies have been very well explained by the preequilibrium (PEQ) model of Thomas *et al.* [2]. The recent experimental results on reactions involving loosely bound projectiles with low breakup threshold energies have shown that either there is enhancement of the fusion cross sections due to the coupling of the breakup channels to fusion or there is fusion hindrance due to the loss of incident flux because of breakup [7,8]. It is also reported that with heavier targets, the incomplete fusion channels are favored at energies around the Coulomb barrier due to the projectile breakup effects [9,10]. The small breakup threshold energy of ^{9}Be into ^{8}Be + ^{1}n (1.67 MeV) or into ^{5}He + ^{4}He (2.55 MeV) makes it interesting to study the effect of breakup on fission fragment angular distributions. The objective of the present Brief Report is to study the effect of breakup on the fission fragment angular distributions for the system ^{9}Be + ^{232}Th around the Coulomb barrier. As the entrance channel mass asymmetry α of the present system is greater than the Bussinaro-Gallone mass asymmetry α_{BG}, it will be interesting to study the effects of target deformation, projectile spin, and channel couplings on the fission fragment angular distributions.

The experiment was performed at the 14 UD BARC-TIFR Pelletron accelerator facility in Mumbai, India. The ^{9}Be beam was bombarded on a self-supporting ^{232}Th target thickness of 1.9 mg/cm^{2} at four different beam energies of 39, 41, 44, and 50 MeV. Two silicon surface barrier detectors (SSBD's) with a thickness of 15 μm were used to detect the fission fragments. These two SSBD's were placed at a distance of 13.5 cm from the target on a rotatable arm inside the scattering chamber. A collimator with a 5 mm diameter was placed in front of each of the two SSBD's. Another SSBD with a thickness of 300 μm was placed at a distance of 42.0 cm from the target, at an angle of 25° with respect to the beam direction. This detector, with a collimator of 1.0 mm, was used to measure Rutherford scattering events to monitor the beam on the target and for normalization of the fission yields at different angles. The SSBD's were rotated from 80° to 170° in steps of 5°–10° to measure the fission yields at different energies. Data at overlapping angles were taken for normalization of the solid angles for the two SSBD's. The fission events were clearly separated from the elastic events in all bombarding energies. The measured fission fragment angular distributions at different energies were transformed to the center-of-mass system assuming Viola's systematic for the fragment kinetic energies [11]. The fission fragment angular distributions measured at four different bombarding energies are shown in Fig. 1.

The experimentally measured fission fragment angular distributions at various beam energies were fitted with Legendre polynomials to extract the fragment anisotropies. It is assumed that the fusion channel completely decays through the fission channel because of the high fissility of the present system. The total fission cross sections at different bombarding energies were obtained by integrating the experimentally measured angular distributions. The experimental fission excitation function along with theoretical predictions of coupled channel

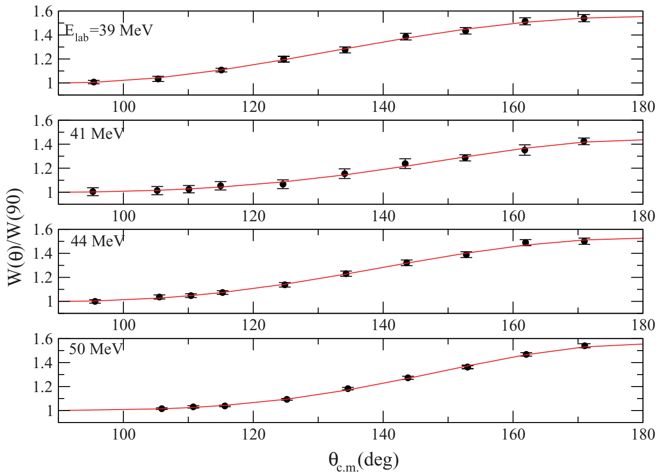

FIG. 1. (Color online) The fission fragment angular distributions for the system ^{9}Be + ^{232}Th along with Legendre polynomial fits at different bombarding energies.

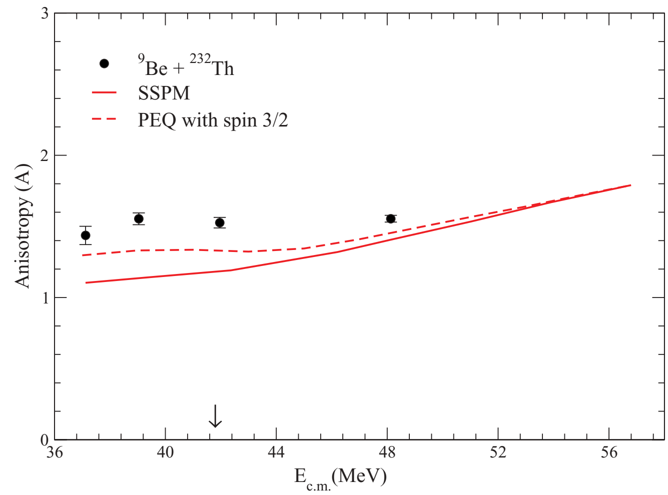

FIG. 3. (Color online) The fission anisotropies for ^{9}Be + ^{232}Th along with SSPM and PEQ model predictions.

code for fusion (CCFUS) [12] is shown in Fig. 2 for the present system. According to SSPM, fission fragment anisotropy is given by the relation

$$A = 1 + \langle l^2 \rangle / 4K_0^2, \tag{1}$$

where

$$K_0^2 = T I_{\mathrm{eff}} / h^2$$

and T, I_{eff}, and $\langle l^2 \rangle$ are the temperature, the effective moment of inertia at the saddle point, and the mean-square angular momentum of the fissioning system, respectively. E^* is the excitation energy, and $T = \sqrt{E^*/a}$ is the temperature of the fissioning system. Here a is taken as $A_{CN}/8$, where A_{CN} is the mass of the compound nucleus. The values of I_{eff}, the angular-momentum-dependent fission barrier B_f, and the rotational energy E_{rot} of the fissioning nucleus are calculated by using a rotating finite-range model [13]. The PEQ model calculations have been carried out by taking into account the projectile ground-state spin value of 3/2. The experimental anisotropies at different bombarding energies have been compared with the SSPM and PEQ model predictions, as shown in Fig. 3. It is observed that both SSPM and the PEQ model reproduce the experimental results above the barrier energies. For energies below the barrier, the SSPM grossly underpredicts the fission fragment anisotropies. The PEQ model predicts higher anisotropies in comparison to SSPM, but the values still remain somewhat lower than the experimental data at sub-barrier energies.

In order to understand the reaction mechanism, we have compared results for measured fission anisotropies for various systems with different projectiles on the ^{232}Th target [14]. It can be seen that fission anisotropies increase with the projectile mass number except for ^{9}Be, as shown in Fig. 4. From Fig. 4, it may be inferred that, due to the possible breakup of loosely bound ^{9}Be projectile nucleus, in addition to the full

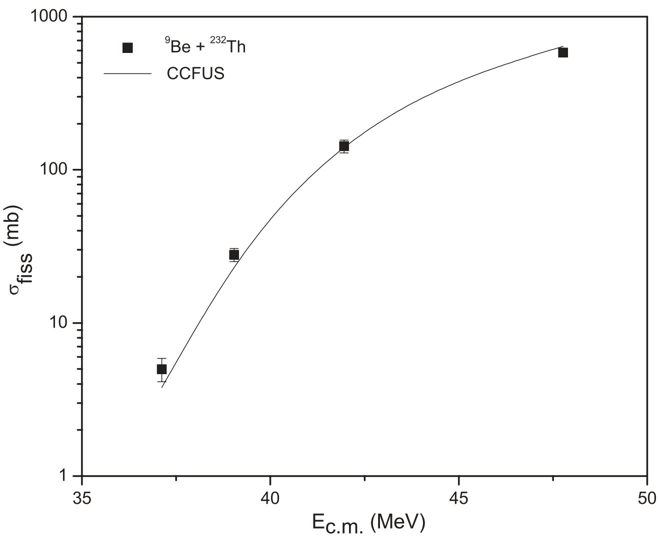

FIG. 2. The fission excitation function for the reaction ^{9}Be + ^{232}Th along with the coupled-channel code CCFUS predictions.

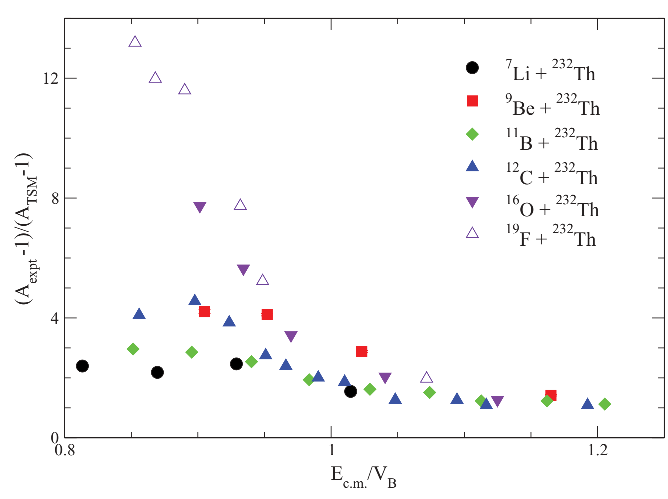

FIG. 4. (Color online) The comparison of fission anisotropies for different projectiles on the ^{232}Th target [14] with the present experimental results.

momentum-transfer events from the complete fusion of the projectile, there may be significant contribution from breakup fusion events at sub-barrier energies. Due to the incomplete transfer of momentum the final anisotropies of the measured reaction may be different from the full momentum-transfer anisotropies. If the projectile breaks and a part of it fuses with the target, the temperature of the compound nucleus that is formed by incomplete fusion (ICF) at the saddle point will be less than the temperature of the compound nucleus formed by complete fusion. This will lead to a narrow K_0^2 distribution, and as a result, the anisotropy of the fission fragments will increase.

In conclusion, we have measured fission fragment angular distributions for a ^{9}Be + ^{232}Th system at four different beam energies around the Coulomb barrier. The fission fragment anisotropy results have been compared with the SSPM and PEQ model predictions, which fail to reproduce the experimental data. It may be inferred that, in addition to complete fusion events, there is some contribution from incomplete fusion events that leads to higher fission anisotropy. It will be interesting to study the fusion-fission dynamics with a ^{9}Be projectile by separating complete and incomplete fusion events.

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