PHYSICAL REVIEW C **77**, 021601(R) (2008)

Fission fragment anisotropies for the ^{13}C+^{235}U system at near-Coulomb barrier energies

B. P. Ajitkumar,[1] K. M. Varier,[2] B. V. John,[3] A. Saxena,[3] B. K. Nayak,[3] D. C. Biswas,[3] R. G. Thomas,[3] and S. Kailas[3]
[1]*Inter University Accelerator Centre, New Delhi-110067, India*
[2]*Department of Physics, University of Calicut, Calicut -673635, India*
[3]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai-400 085, India*

(Received 11 October 2007; published 28 February 2008)

The fission fragment angular distribution measurements for the ^{13}C+^{235}U system have been carried out to study the entrance channel dependence and spin dependent effects in the fission fragment anisotropies. This particular combination of target and projectile leads to ^{248}Cf compound nucleus that has been studied earlier using three other entrance channels viz. ^{11}B+^{237}Np, ^{12}C+^{236}U, and ^{16}O+^{232}Th. A comparison of the measured anisotropy data for all the four systems, with the statistical saddle-point model and pre-equilibrium fission (PEF) model, brings out a clear signature of entrance channel dependence in fission anisotropy values, characteristic of the PEF model.

DOI: 10.1103/PhysRevC.77.021601 PACS number(s): 25.70.Jj

The fission fragment angular distribution is a rich source of information of the fission process in general and fission dynamics in particular. From a number of detailed studies of heavy-ion induced fission reactions at near Coulomb barrier energies, it emerges that the fission fragment anisotropy values depend on the entrance channel properties of the colliding nuclei, mass asymmetry, bombarding energy with respect to the fusion barrier, and the compound nucleus shell structure [1–12]. It was noticed that at below Coulomb barrier energies, the fission anisotropies for essentially all target-projectile combinations involving an actinide target were significantly higher than those expected from the statistical saddle-point model (SSPM) [13]. However, at energies above the Coulomb barrier, the measured anisotropies displayed dependence on the entrance channel mass-asymmetry. For many systems, the anisotropies were anomalously large compared to the SSPM predictions. A majority of the existing models attribute the observation of anomalous fission anisotropies to the presence of noncompound nucleus fission mechanisms such as quasifission, fast-fission, and preequilibrium fission, rather than to the breakdown of the SSPM. Almost 20 years ago, Ramamurthy and Kapoor [14] proposed the pre-equilibrium fission (PEF) model to explain the anomalous anisotropies in several heavy-ion induced fission reaction at above barrier energies. In a series of experiments, Ramamurthy *et al.* [1] provided the experimental signature for the presence of PEF in addition to compound nuclear fission. The entrance channel dynamics (related to entrance channel mass-asymmetry value α with respect to Businaro-Gallone critical value α_{BG}) which is the key element of PEF has been brought out in a number of measurements involving ^{232}Th, ^{235,236,238}U, and ^{237}Np as targets and ^{9}Be, ^{10,11}B, ^{12,13}C, ^{16}O, and ^{19}F as projectiles [1–5]. It was clear that the role of deformation, spin and orientation of interacting nuclei had to be integrated with the PEF model to describe the fragment anisotropy data over the entire energy range. Thomas *et al.* [15] have incorporated these features in a prescription and using this approach, the fission fragment anisotropy data for the various actinide targets could be described from below to above barrier energies. Further, it was shown by Thomas *et al.* [15] that at sub-barrier energies, all the systems exhibited anomalous anisotropies irrespective of the entrance channel mass asymmetry due to channel coupling and consequent shift of critical mass asymmetry parameter α_{BG} towards higher asymmetries.

It is important to further elucidate the dynamics of the noncompound nucleus fission mechanisms in heavy-ion reactions in the backdrop of the rigorous research being done for super heavy nuclei production. A precision test for the PEF model had been carried out in the present work by measuring fragment anisotropies in ^{13}C+^{235}U reaction at near Coulomb barrier energies. This particular combination of target and projectile leads to ^{248}Cf ($\alpha_{\mathrm{BG}} = 0.897$) compound nucleus that has already been studied using three other entrance channels viz. ^{11}B+^{237}Np ($\alpha = 0.911$), ^{12}C+^{236}U ($\alpha = 0.903$), and ^{16}O+^{232}Th ($\alpha = 0.871$) [1,4]. The α value for ^{13}C+^{235}U system is 0.895 and this is lower than but very close to α_{BG}. The addition of this system, also offered the possibility to investigate whether the expected transition from 'normal' [due to compound nucleus (CN) fission] to 'anomalous' (due to PEF+CN fission) values of fission anisotropies across α_{BG}, is gradual or sudden. The prediction of the PEF model was put to test simultaneously in these four systems where some of the systematic uncertainties of compound nuclear fission analysis were removed. Another interest behind the present investigation is that the target ^{235}U has a large spin value ($7/2^-$) which has been shown to strongly influence fission anisotropy values at sub-Coulomb energies for ^{12}C+^{235}U system [7]. This interesting observation is now cross checked with the data from ^{13}C ($1/2^-$) beam.

The experiment was performed using ^{13}C beam from the BARC-TIFR Pelletron accelerator. The ^{235}U target of thickness 200–300 μgm/cm^2 deposited on thin aluminium backing was placed at the center of the general purpose scattering chamber. The fission fragments were detected by two ΔE(10–15 microns) -E(300–500 microns) surface barrier detector telescopes each of solid angle 0.7 msr. The measurements were carried out from $\theta_{\mathrm{lab}} = 80^\circ$ to 170° at 10° intervals. One monitor detector of solid angle 0.03 msr was placed at $\theta_{\mathrm{lab}} = 40^\circ$ for normalization with Rutherford scattering cross sections. Typical beam intensities used in the measurements

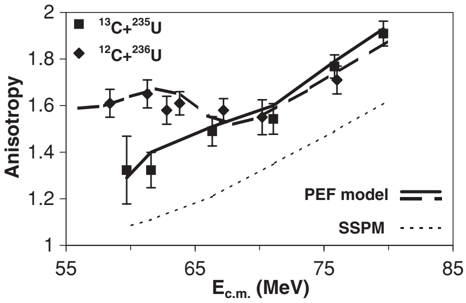

FIG. 1. Measured fission fragment anisotropies (A) for ^{13}C+^{235}U system (present work, squares) along with the calculated values from SSPM (dotted line) and PEF (continuous line) models. A comparison is also made with the data for ^{12}C+^{236}U system (diamonds) from Ref. [4,19] and corresponding PEF model calculations (dashed line).

were of the order of 10 pnA. Counting times were substantially larger at lower energies, for instance at the lowest energy for each angle we measured the data for nearly 8 h to build sufficient statistics. The fission yields in the telescopes at various lab angles were transformed to fragment angular distributions in the center of mass system by assuming symmetric mass division and using the Viola systematics of fragment kinetic energies [16]. This is a reasonable assumption even for events having admixture of PEF for the following reason: The PEF events are hypothesized to take place after crossing the unconditional saddle unlike fast-fission and quasifission. The main difference between CN fission and PEF is that in the latter case the K degree of freedom is not equilibrated but other degrees such as energy and mass-asymmetry are fully equilibrated. Therefore the assumption of symmetric mass division is justified in case of PEF. The anisotropy values (A) defined as the yield ratio $W(180^\circ)/W(90^\circ)$ were determined in the $E_{\mathrm{c.m.}}$range from 60 to 80 MeV and these are shown in Fig. 1 as squares. The error bars include both statistical and least squares fit errors. The total fission cross sections (assumed to be the same as fusion cross section for this high fissility system as the evaporation residue cross sections are negligible [17]) at various bombarding energies were obtained by integrating the measured angular distributions. The fusion excitation function thus obtained for the present reaction has been compared with the predictions of the coupled-channels code CCDEF [18] using $V_B = 63.3$ MeV, $R_B = 11.84$ fm, $\hbar\omega = 4.8$ MeV and $\beta_2 = 0.26$ in Fig. 2. It is seen that the experimental data are well reproduced by the CCDEF calculations.

The anisotropy values for the present system, ^{13}C+^{235}U, are similar to the ones for ^{12}C+^{235}U system reported by Lestone *et al.* [7]. The change of projectile from ^{12}C(0^+) to ^{13}C$(1/2^-)$ keeping same target nucleus (^{235}U) did not bring significant changes in anisotropy values and this observation is consistent with the expectation of the model of Thomas *et al.* [15].

The present system populates the same compound nucleus as ^{12}C+^{236}U for which anisotropy data in the near and sub-barrier range are available in Refs. [4,19]. Anisotropy data for the present system (squares) and ^{12}C+^{236}U system (diamonds) are compared in Fig. 1. The dramatic effect due to spin of ^{235}U$(I = 7/2^-)$ is clearly seen from the data at sub-barrier energies and both the data are accounted well by the prescription of Thomas *et al.* (continuous and dashed lines in Fig. 1).

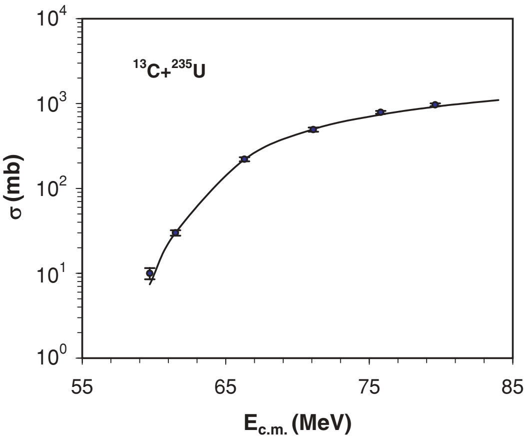

FIG. 2. The fusion (fission) excitation function for ^{13}C+^{235}U along with the prediction of the coupled-channels code CCDEF [18].

Before proceeding with the detailed calculations, it is desirable to compare the data with the predictions of the statistical saddle-point model (SSPM) [13]. The fission fragment anisotropy A is defined as

$$A = 1 + \langle l^2 \rangle / \left[4K_0^2 \right]$$

where $\langle l^2 \rangle$ is the mean squared value of the compound nucleus l distribution and K_0^2 is the variance of the K distribution given as $K_0^2 = I_{\mathrm{eff}} T / \hbar^2$. Here, T is the temperature at the saddle point and I_{eff} is the effective value of the moment of inertia. The fission barrier (B_f) and the I_{eff} values have been taken from the diffuse surface liquid drop model of Sierk [20]. The variation of the fission barrier and the moment of inertia with angular momentum was taken into account. The temperature T was calculated using the level density parameter $a = A_{\mathrm{CN}}/9$ MeV^{-1} (here A_{CN} is the mass number of the compound nucleus). The correction to excitation energy arising due to pre-scission neutrons [21] is taken into account using the systematics of Saxena *et al.* [22]. The neutrons for the pre-saddle phase were deduced using the systematics of Ref. [22]. The $\langle l^2 \rangle$ values have been calculated from the fit to the fission (fusion) excitation function. The SSPM predictions are shown in Fig. 1 as a dotted line. The calculated values are typically 20% lower than the experimental values.

In order to investigate the role of entrance channel mass asymmetry in influencing the measured anisotropy values, we have carried out a comparison of ratios of experimental to SSPM anisotropy values $(A_{\mathrm{exp}}/A_{\mathrm{cal}})$ for the four systems ^{11}B+^{237}Np, ^{12}C+^{236}U, ^{13}C+^{235}U, and ^{16}O+^{232}Th. In the comparison, we have limited the data set to above barrier energies $(E/V_B > 1.1)$ to reduce the barrier dependent effects. The upper energy is limited to E/V_B values close to 1.3 to 1.4 [4] so that the fast-fission contributions (corresponding to $B_f = 0$) are not significant. The effective fissility χ_{eff} values as defined in [23,24] for the above systems are below the critical value $\chi_{\mathrm{eff}} = 0.72$ implying that the quasifission contributions are also insignificant. In Fig. 3, we have plotted $A_{\mathrm{exp}}/A_{\mathrm{cal}}$ values against the entrance channel mass asymmetry

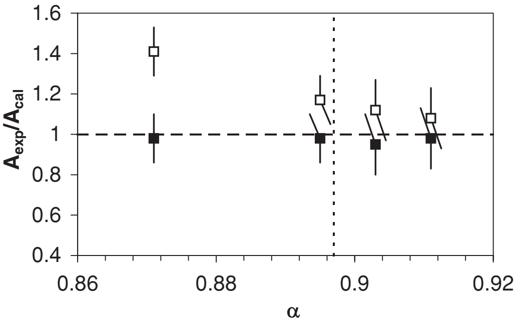

FIG. 3. Ratio of experimental and calculated anisotropy ($A_{\rm exp}/A_{\rm cal}$) versus entrance channel mass asymmetry α. The open squares are the results when $A_{\rm exp}$ are compared with $A_{\rm cal}$ obtained using the SSPM (only CN fission). The filled squares are obtained when $A_{\rm exp}$ are compared with $A_{\rm cal}$ obtained using the prescription of Thomas *et al.* [15] (both CN fission and PEF). The vertical dotted line represents the $\alpha_{\rm BG}$ boundary.

α (open squares). It can be seen that the ratios are close to one within errors for ^{11}B and ^{12}C projectiles and follow the SSPM trend. While a slight deviation from one is seen for ^{13}C projectile, a significantly stronger departure from the SSPM trend is observed for ^{16}O projectile. It is interesting to note that while the systems with $\alpha > \alpha_{\rm BG}$ display anisotropy values which are consistent with the SSPM predictions, the ones with $\alpha < \alpha_{\rm BG}$exhibit increasingly larger deviations when compared to the SSPM calculations. This behavior of anisotropy values changing from ‘normal’ to ‘anomalous’ across $\alpha_{\rm BG}$ is consistent with expectation of PEF model. To elucidate this point further, we have also carried out a detailed analysis taking into account both compound and PEF components along with the effects due to orientation dependence, entrance channel dependence with respect to the Businaro-Gallone (BG) critical mass asymmetry, static properties of the target and projectile following Thomas *et al.* [15] for the same data set. The results are given in Fig. 3 as ratio of experimental to PEF model anisotropies ($A_{\rm exp}/A_{\rm cal}$, filled squares) and the ratios are nearly one indicating that the calculations reproduce the data very well. As we have treated different systems but all forming the same compound nucleus, the above comparison can be taken as a signature of entrance channel dependence in fission anisotropy values which is a characteristic of PEF model. It is not *a priori* clear whether the onset of PEF process across $\alpha_{\rm BG}$ should be sudden or gradual. The shape of the potential energy surface determined as a function of the mass asymmetry values is expected to influence the dynamics of PEF process. The present results suggest that the onset of PEF across $\alpha_{\rm BG}$ is rather gradual. It may be added here that in addition to the present work, the presence of PEF has been clearly brought in our earlier study [5] related to ^{11}B+^{235}U and ^{14}N+^{232}Th, both forming the same compound nucleus ^{246}Bk.

To conclude, the fragment angular anisotropies have been measured for the ^{13}C+^{235}U system at near Coulomb barrier energies. This particular combination of target and projectile leads to ^{248}Cf compound nucleus that has been studied earlier using three other entrance channels. From a systematic analysis of anisotropies in these four fissioning systems, we have provided a clear evidence for entrance channel dependence in fission anisotropy values across the $\alpha_{\rm BG}$, consistent with the expectations of PEF model. Further, the transition from ‘normal’ to ‘anomalous’ across the $\alpha_{\rm BG}$ has been found to be gradual rather than abrupt.

We gratefully acknowledge Dr. S. S. Kapoor for useful suggestions and his keen interest in this work. We also thank the staff of Pelletron Accelerator for smooth running of the machine during the run.

[1] V. S. Ramamurthy *et al.*, Phys. Rev. Lett. **65**, 25 (1990).
[2] A. Karnik *et al.*, Phys. Rev. C **52**, 3189 (1995).
[3] S. Kailas, Phys. Rep. **284**, 381 (1997); Pramana J. Phys. **53**, 485 (1999).
[4] R. Vandenbosch *et al.*, Phys. Rev. C **54**, R977 (1996); S. Kailas *et al.*, *ibid.* **59**, 2580 (1999).
[5] B. R. Behera *et al.*, Phys. Rev. C **69**, 064603 (2004).
[6] S. Kailas, K. Mahata, R. G. Thomas, and S. S. Kapoor, Nucl. Phys. **A787**, 259c (2007).
[7] J. P. Lestone, A. A. Sonzogni, M. P. Kelly, and R. Vandenbosch, Phys. Rev. C **56**, R2907 (1997).
[8] D. J. Hinde *et al.*, Phys. Rev. Lett. **74**, 1295 (1995); M. Dasgupta and D. J. Hinde, Nucl. Phys. **A734**, 148 (2004).
[9] B. K. Nayak, R. G. Thomas, R. K. Choudhury, A. Saxena, P. K. Sahu, S. S. Kapoor, Raghav Varma, and D. Umakanth, Phys. Rev. C **62**, 031601(R) (2000).
[10] N. Majumdar, P. Bhattacharya, D. C. Biswas, R. K. Choudhury, D. M. Nadkarni, and A. Saxena, Phys. Rev. Lett. **77**, 5027 (1996).
[11] A. Shrivastava, S. Kailas, A. Chatterjee, A. M. Samant, A. Navin, P. Singh, and B. S. Tomar, Phys. Rev. Lett. **82**, 699 (1999).
[12] K. Mahata, S. Kailas, and S. S. Kapoor, Phys. Rev. C **74**, 041301(R) (2006).
[13] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).
[14] V. S. Ramamurthy and S. S. Kapoor, Phys. Rev. Lett. **54**, 178 (1985).
[15] R. G. Thomas, R. K. Choudhury, A. K. Mohanty, A. Saxena, and S. S. Kapoor, Phys. Rev. C **67**, 041601(R) (2003).
[16] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).
[17] T. Sikkeland, A. E. Larsh, and G. E. Gordon, Phys. Rev. **123**, 2112 (1961).
[18] J. Fernandez-Niello, C. H. Dasso, and S. Landowne, Comput. Phys. Commun. **54**, 409 (1989).
[19] T. Murakami, C. C. Sahm, R. Vandenbosch, D. D. Leach, A. Ray, and M. J. Murphy, Phys. Rev. C **34**, 1353 (1986).
[20] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[21] A. Saxena, S. Kailas, A. Karnik, and S. S. Kapoor, Phys. Rev. C **47**, 403 (1993).
[22] A. Saxena, A. Chatterjee, R. K. Choudhury, S. S. Kapoor, and D. M. Nadkarni, Phys. Rev. C **49**, 932 (1994).
[23] J. P. Blocki, H. Feldmeier, and W. J. Swiatecki, Nucl. Phys. **A459**, 145 (1986).
[24] P. Armbruster, C. R. Phys. **4**, 571 (2003).