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Sub-barrier fission fragment angular distributions for the system $^{19}F + ^{232}Th$

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Abstract. The measurements of fission fragment angular distributions for the system $^{19}F + ^{232}Th$ have been extended to the sub-barrier energies of 89·3, 91·5 and 93·6 MeV. The measured anisotropies, within errors are nearly the same over this energy region. However, the deviation of the experimental values of anisotropies from that of standard statistical model predictions increases as the bombarding energy is lowered.

Keywords. Fission reactions at sub-barrier energies; $^{19}F + ^{232}Th$ system.

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1. Introduction

The observation of anomalous fission fragment anisotropies [1,2] as compared to the predictions of the standard saddle point statistical model (SSPSM) has led to a revival of interest in the study of fission fragment anisotropies in heavy ion-induced fission. The deviation from SSPSM behaviour has been observed over a wide range of energies, from below to above barrier energies and for different target-projectile combinations. In an earlier work at energies mostly above the barrier, for projectiles like ^{16}O and ^{19}F it has been suggested [3,4] that the deviation from SSPSM can be explained if one assumes that for cases where fission barriers and the temperatures are comparable, in addition to the normal statistical compound nucleus fission process a new process of pre-equilibrium fission (unequilibrated in K-degree of freedom) also contributes to the observed fissions. However, at near- and sub-barrier energies the deviation from SSPSM could also arise at least in part due to increase in $\langle I^2 \rangle$ (as compared to that expected from one-dimensional barrier penetration model) due to coupling to other degrees of freedom [2]. Recent data of fission fragment anisotropies for several systems measured at sub-barrier energies [5,6] are significantly higher as compared to SSPSM predictions irrespective of the entrance channel asymmetry of the interacting system. The reasons for this observed anomalous behaviour are yet to be understood.

From a measurement of fission fragments using mica track detectors, Zhang *et al* [7,8] have reported not only abnormally large values of anisotropies but also a peak-like structure in the anisotropy versus energy plot for the system $^{19}F + ^{232}Th$ at a sub-barrier energy of $E(\text{Lab}) = 91·4$ MeV. There is also the unpublished preliminary results of fission fragment angular distribution measurements of Fujiwara *et al* [9] for this system at $E(\text{Lab}) = 90$, 92 and 94 MeV employing single window ionization chamber as a fission detector. Their results do not indicate the presence of a peak-like structure. From other detailed investigations [10, 11] it is clear that such a peak-like behaviour in anisotropy versus energy plot cannot arise due to possible small admixture of transfer induced fissions (involving particle transfers). This peak-like structure, if confirmed, would imply the presence of a new reaction mechanism in the sub-barrier region which is not incorporated in the present models. To verify the presence of this peak-like structure in the anisotropy versus energy plot, we have extended our earlier measurements [4] of fission fragment angular distributions for this system to the sub-barrier energies using silicon/gas detectors.

2. Experimental procedure and results

The present experiment was performed using the ^{19}F beam available from the BARC–TIFR 14 UD Pelletron accelerator at Bombay. The fission fragment angular distributions were measured at laboratory, bombarding energies of 89·3, 91·5 and 93·6 MeV, utilizing a natural thorium target of thickness $200\,\mu$g/cm^2 (thickness estimated from alpha counting) deposited on a $10\,\mu$m thick aluminium backing. The above-mentioned effective bombarding energies have been obtained after correcting for Th target thickness and small carbon build up present in the target [12]. The fission fragments were detected using two thin silicon detectors of $20\,\mu$m thickness. The elastic and the inelastic scattering events of ^{19}F from the ^{232}Th target were rejected using 'veto' detectors placed behind the thin Si detectors. The fission fragment angular distribution measurements were carried out in the angular range of $\theta = 85°$ to 170°. The fission spectra measured at 90° and 170° (at E(Lab) = 93·6 MeV) are shown in figure 1. On the low energy side of the spectrum there is an interference from alpha particles probably emitted in reactions with the backing and having energies too low to reach the veto detector. (The source of contamination has been checked in a separate measurement using gas-Si telescope and identifying the particle groups). This leads to uncertainty of less than 5% in fission yield extraction in the worst case. The overall uncertainty on the measured anisotropy varied from 8 to 10%. At E(Lab) = 93·6 MeV, a gas (ΔE)-Si(E) telescope [13] was also used and the anisotropy value obtained agreed with that from using the former set-up. As the data measured with the latter set up were of lower statistics due to smaller solid angle, they are not shown in figure. A monitor detector was placed at 50° to detect the elastically scattered F from Th. Fission cross-sections were obtained by normalizing the fission yield to the monitor yield, assuming the latter to arise from Rutherford scattering. The measured fission fragment angular distributions were transformed to the centre-of-mass system assuming symmetric mass division and Viola systematics [14] for the total fragment kinetic energy. The angular distributions were fitted using the relation $W(\theta) = a + b\cos^2\theta + c\cos^4\theta$ with a, b and c as adjustable parameters. In figure 2 the angular distributions normalized to W (90°) values evaluated from the above fits are shown. The experimental anisotropy values $A = W(180°)/W(90°)$ deduced from the fits to the data are shown in figure 3 along with the results of earlier measurements of Zhang *et al* [7] and Fujiwara *et al* [9]. In the inset of figure 3 the anisotropy values measured in the entire energy range of 80 to 100 MeV by our group [4] and by Zhang *et al* [7] are shown. The main conclusion of the present work (seen from figure 3) is that not only the anisotropy values measured here are significantly smaller than the ones reported by Zhang *et al* [7] but also do not show the appearance of a peak-like structure in the anisotropy versus energy plot.

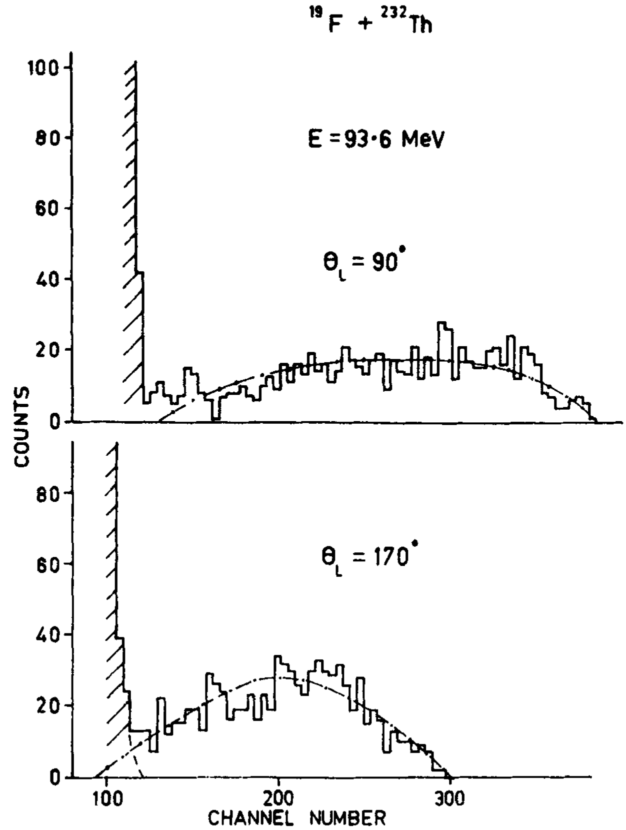

Figure 1. Fission fragment spectra measured using thin Si detector (plus a veto detector) at $\theta = 90°$ and 170° at E(Lab) = 93·6 MeV. The low energy contaminant is shown by a shaded area (see text for details). The dash-dot line is drawn to guide the eye.

Table 1. Summary of the experimental and the theoretical results $^{19}F + ^{232}Th$.

E (MeV) (Lab)	σ_F (mb) (expt)	σ_F (mb) (cal)	$\langle l^2 \rangle$	K_0	A (cal)	A (expt)
89·3	4·5 ± 0·5	4·1	122	16·2	1·12	1·75 ± 0·20
91·5	13·4 ± 1·4	14·4	189	16·5	1·19	1·85 ± 0·20
93·6	28·0 ± 3·0	31·6	258	16·6	1·24	1·95 ± 0·15

Note. cal = calculation. expt = experimental value
K_0^2 is the variance of K distribution (refs [3, 4] for more details).

The angular distributions were integrated to obtain the total fission cross-section (σ_F) and the resultant fission excitation function is displayed in figure 4. The other data sets on fission cross-sections in the literature [4, 7, 9, 15] are also shown in figure.

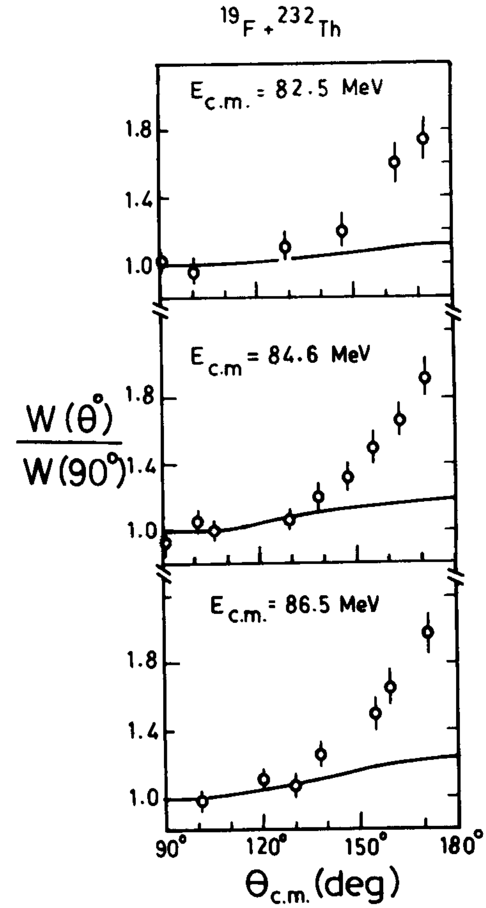

Figure 2. Fission fragment angular distributions for the system $^{19}F + ^{232}Th$ at $E_{cm} = 82{\cdot}5$, $84{\cdot}6$ and $86{\cdot}5$ MeV. The solid lines are the standard saddle point statistical model calculations as discussed in the text.

3. Analysis and discussion

In order to determine the spin distribution values at each energy a Wong model fit to the cross-section data (including the deformation of the target) has been made following the procedure discussed earlier [4] and this is shown as a continuous line in figure 4. While the cross-section values reported by Fujiwara *et al* [9] are consistent with the present measurements, the results of Zhang *et al* [7] are somewhat higher and this may partly be due to their finding larger anisotropies (larger cross-section at backward angles). While the above three groups obtained the total fission cross section by integrating the angular distribution data, Leigh [15] determined the same assuming $W(\theta) \alpha 1/\sin(\theta)$, a procedure which may lead to higher values of σ_F. The somewhat higher values of cross-sections reported by Leigh may be related to this aspect.

The fission fragment angular distributions and the anisotropies have been calculated using the procedure discussed by Ramamurthy *et al* [3] and the $\langle I^2 \rangle$ values determined from Wong model fit to cross-section data. Summary of the results is given in table 1. It may be pointed out that the measurements reported in [7,9] and the present one

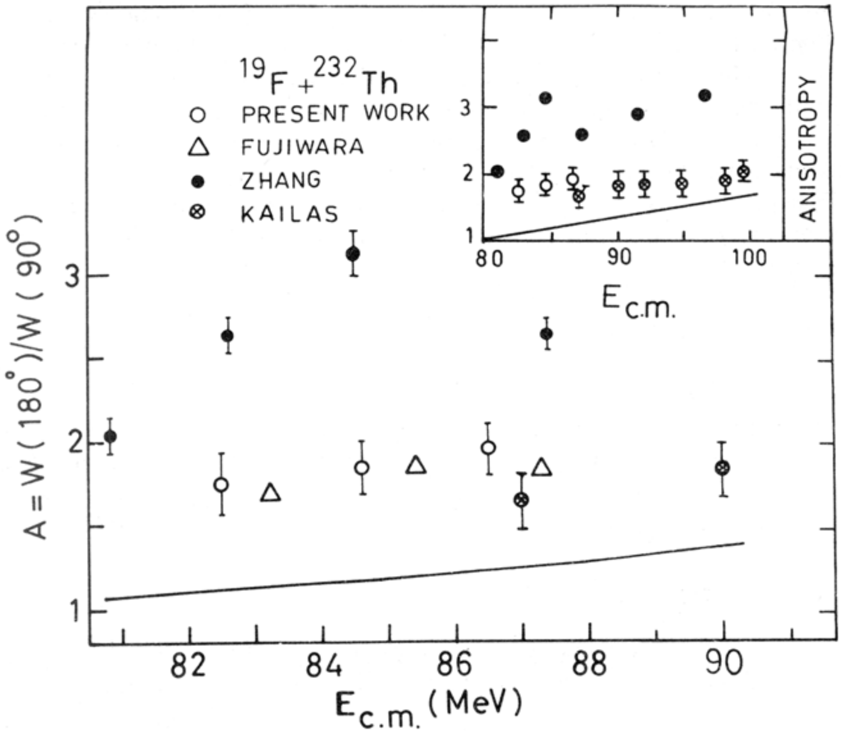

Figure 3. The experimental fission fragment anisotropies for the $^{19}F + ^{232}Th$ system. The anisotropy values measured by Kailas *et al* [4], Zhang *et al* [7] and Fujiwara *et al* [9] are also shown. The solid line represents the SSPSM calculation. The inset shows our data in the energy region 80 to 100 MeV compared with those of Zhang *et al* and the SSPSM calculation.

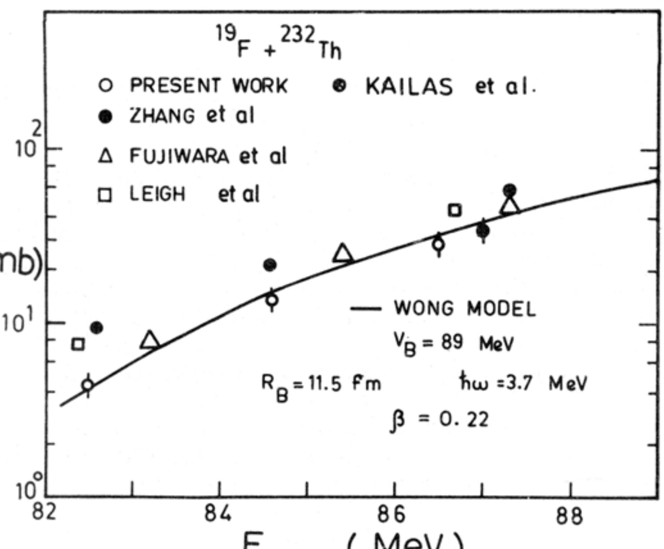

Figure 4. Measured fission excitation function for the system $^{19}F + ^{232}Th$ compared with the Wong model fit. The cross-section values determined by Kailas *et al* [4], Zhang *et al* [7], Leigh [15] and Fujiwara *et al* [9] are also shown.

are inclusive and they contain mainly fusion-fission and small amounts of transfer-fission events. As transfer fission is not separated in these measurements, the $\langle I^2 \rangle$ values obtained assuming the measured fission cross-section is all due to complete momentum transfer and hence the anisotropy values calculated can be considered to be upper limits. In figures 2 and 3 these calculations are shown as continuous lines. It is observed from the present angular distribution data and the measured anisotropies that though the anisotropy values are significantly smaller than the ones of Zhang *et al* [7] they are still higher and anomalous as compared to the SSPSM predictions.

4. Conclusion

In conclusion, the present measurements of fission fragment angular distributions for the system $^{19}F + ^{232}Th$ and the data of Fujiwara *et al* [9] are in strong disagreement with the results of Zhang *et al* [7]. The present results, within errors, do not support the observation of a peak-like structure in the anisotropy versus energy plot at these sub-barrier energies covering the energy region of 89·3 to 93·6 MeV.

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