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Near- and sub-barrier $^{12}C+{}^{232}Th$ fission fragment anisotropies

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Recent measurements of fission fragment anisotropies in the $^{12}C+{}^{232}Th$ reaction by Majumdar *et al.* [Phys. Rev. C **53**, R544 (1996)] show a peaklike structure in the sub-barrier energy region. We present new measurements for this reaction at near- and sub-barrier energies. Our results are in dramatic disagreement with the work of Majumdar *et al.* We see no peaklike structure in the fragment anisotropy as a function of the projectile kinetic energy, but instead find an anomalous plateau in the anisotropy at $W(180°)/W(90°)\sim 1.5$. [S0556-2813(97)50501-2]

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A long-standing problem in the study of heavy ion induced nuclear fission has been the anomalous high values of fission fragment anisotropies at near- and sub-barrier energies. Several recent papers have led to a substantial enhancement of our understanding of heavy ion induced fission reactions at near- and sub-barrier energies. Morton *et al.* [1] have resolved the problem of the anomalous fission fragment anisotropies for the $^{16}O+{}^{208}Pb$ reaction. A combination of new data [1,2] and improved modeling techniques has led to an understanding of the $^{16}O+{}^{208}Pb$ fission fragment anisotropies in terms of the standard transition state model of nuclear fission [3]. The significance of this work is that, for projectiles with mass numbers $\lesssim 20$ at near-barrier energies, we are left with only the actinide targets giving a substantial disagreement between measured fragment anisotropies and the transition state model. This implies that it is some property specifically associated with actinide targets that is responsible for the observed anomalous fission fragment anisotropies.

Zhang *et al.* [4] have measured the angular distribution of fission following complete momentum transfer for the reactions ^{16}O and $^{19}F+{}^{232}Th$, and $^{16}O+{}^{238}U$ at near- and sub-barrier energies. They used the fragment folding angle technique to separate fission following complete fusion and fission following transfer. Their measurements have removed doubts that the anomalous fission fragment anisotropies were possibly due to fission following transfer reactions. Liu *et al.* [5] have obtained a reasonable reproduction of the anomalous fission fragment anisotropies in terms of a K degree of freedom relaxation time which increases with decreasing angular momentum. Hinde *et al.* [6] have studied the $^{238}U(^{16}O,f)$ reaction at near- and sub-barrier energies in great detail, measuring both the fission fragment anisotropies as a function of center-of-mass energy, and the distribution of fusion barriers. They observed a rise in the anisotropy of the fission fragments as the projectile energy drops through the distribution of fusion barriers. The correlation between the energy dependence of the anisotropies and the distribution of fusion barriers is striking. This is very suggestive of a relationship between fission fragment anisotropy and the height of the fusion barrier, and led Hinde *et al.* [6] to conclude that collisions with the tips of deformed target nuclei lead to quasifission. Hinde *et al.* [7] have since measured the fragment mass distribution in the $^{238}U(^{16}O,f)$ reaction. They find a small but significant skewness in the mass distribution, which increases as the beam energy falls through the distribution of fusion barriers, displaying an energy dependence similar to the fission fragment anisotropies. This is strong evidence in support of the interpretation that collisions with the tips of deformed target nuclei can lead to quasifission.

Majumdar *et al.* [8] have recently performed similar measurements to those of [4–6] for the ^{19}F, ^{16}O, and $^{12}C+{}^{232}Th$ reactions. With the ^{19}F and ^{16}O projectiles, Majumdar *et al.* obtain results similar to those of [4–6]. The fission fragment anisotropies rise with decreasing projectile energy as one passes through the distribution of fusion barriers. The $^{19}F+{}^{232}Th$ anisotropies rise as high as ~ 2.5 at the lowest energies, while the ^{16}O data seem to saturate at ~ 2.0. If the conclusions of Hinde *et al.* [6] are correct then one might expect the importance of the quasifission process to decrease smoothly with the mass and/or charge of the projectile, due to both the decreasing size of the projectile and the increasing stability of the composite system formed immediately after the fusion barrier is crossed. One might thus expect the $^{12}C+{}^{232}Th$ anisotropies to behave in a similar fashion to the ^{19}F and ^{16}O data, but with the fission fragment anisotropy saturating at a value less than 2. The ^{12}C data of Majumdar *et al.*, behave differently from the ^{19}F and ^{16}O data. Their $^{12}C+{}^{232}Th$ fission fragment anisotropies rise very sharply as the projectile energy decreases into the region of fusion barriers and reaches a value of more than 2, then decrease quickly to values comparable to the predictions of the transition state model. From this peaklike structure one can conclude that either the quasifission mechanism suggested by Hinde *et al.* is not responsible for the anomalous fragment anisotropies in the ^{19}F, ^{16}O, and $^{12}C+{}^{232}Th$ reactions or that the $^{12}C+{}^{232}Th$ reaction is, for some unknown reason, very different from the ^{19}F and $^{16}O+{}^{232}Th$ reactions. We decided that it was important to confirm or negate the peaklike structure in the $^{12}C+{}^{232}Th$ fragment anisotropy data of Majumdar *et al.*

Majumdar *et al.* [8] show fission fragment folding angle distributions for the $^{16}O+{}^{232}Th$ reaction and state that, for this reaction, fission following transfer reactions (at near-barrier energies) is less than 10% of the total fission yield. They show no such data, nor do they make a similar statement about the $^{12}C+{}^{232}Th$ reaction. In order to estimate the yield associated with fission following transfer reactions,

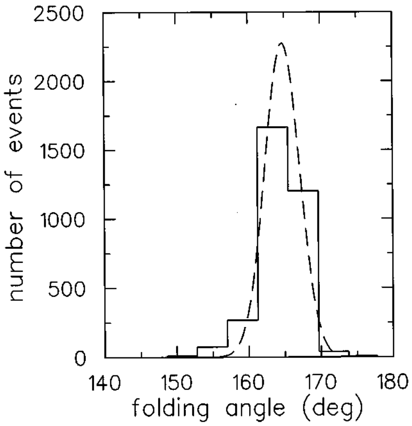

FIG. 1. The histogram shows our measured fragment-fragment folding angle distribution for 60.4 MeV ^{12}C+^{232}Th. The single Gaussian fit shown by the dashed curve has a mean of 164.7° and a standard deviation of 2.4°.

relative to the fission following complete fusion for the ^{12}C+^{232}Th reaction, we measured the fission fragment folding angle distribution for fission events close to 90° in the center-of-mass frame. These measurements were performed with 57.6 MeV to 75.2 MeV ^{12}C beams from the University of Washington Superconducting Booster Linac [9]. A 300 μg/cm^2 ThF$_4$ target on a 100 μg/cm^2 Ni backing was used. The target was oriented at 45° to the beam direction. Twenty 4 cm×2 cm parallel plate avalanche counters were placed in the horizontal plane. Ten of these counters were at angles from $\theta_{\mathrm{lab}}=64°$ to 99° to the beam direction. Each of the detectors was ~30 cm from the target and each was separated from its neighbors by ~4°. The other ten counters were in a similar arrangement but on the other side of the beam axis at angles from $\theta_{\mathrm{lab}}=-55°$ to $-92°$. The ten counters at negative angles were uncollimated and thus each covered an angular range of ±2° in the horizontal direction and ±4° in the vertical direction. The ten counters at positive θ were each collimated by a 1 cm diameter hole in ~0.6 mm thick Ta sheet. Fragment-fragment coincidences between the counters on either side of the beam were observed for ^{12}C+^{232}Th reactions at a number of beam energies from 57.6 MeV to 75.2 MeV. For each coincidence event the folding angle can be deduced with an accuracy of ±2°.

Assuming fission following complete fusion of 60.4 MeV ^{12}C on ^{232}Th, symmetric fission with center-of-mass velocities estimated using Viola systematics [10], and $\theta_{\mathrm{c.m.}}=90°$, we obtain an expected folding angle of 165.5°. The folding angle distribution shown in Fig. 1 is strongly peaked very close to this angle. In this sub-barrier region we would expect any transfer-fission contamination to show as a peak or shoulder in our data at a folding angle significantly smaller than that expected for fission events following complete fusion. The ^{16}O+^{232}Th fission fragment folding angle distributions of Majumdar *et al.* imply a momentum transfer in the sub-barrier transfer reactions that lead to fission of ~1.8 times that associated with complete fusion. Assuming this same factor of 1.8 in the 60.4 MeV ^{12}C+^{232}Th reaction, we obtain an expected folding angle of 154° for the fission events near $\theta_{\mathrm{c.m.}}=90°$, following transfer reactions. The dashed line in Fig. 1 shows a single Gaussian fit to our measured folding angle distribution for 60.4 MeV ^{12}C+^{232}Th. This shows that the transfer-fission component in this reaction is only a small fraction of the total yield. If all the events with folding angles less than 158° are attributed to transfer-fission then the transfer fission at $\theta_{\mathrm{c.m.}}$~90° would still only amount to less than 3% of the total fission yield. We obtain similar results for all other beam energies in our study. We thus see no evidence for a significant transfer-fission yield in the ^{12}C+^{232}Th reaction at near- and sub-barrier energies. Our observation that the transfer-fission component is only a small fraction of the total fission yield in ^{12}C+^{232}Th is consistent with the findings of others [11,12] with *B* and *C* projectiles on various actinide targets. Liu *et al.* [11] find that for the reactions ^{11}B+^{238}U, ^{11}B+^{237}Np, and ^{12}C+^{237}Np, the detected transfer-fission events are less than 2% of the total fission yield and that, within their experimental errors, the fragment anisotropies are not changed by the transfer-fission component. Mein [12] has concluded that in the ^{12}C+^{238}U reaction, the transfer fission comprises less than 5% of the total fission, even at his lowest center-of-mass energy of 56 MeV. With the ^{12}C+^{232}Th transfer-fission yield being so small, it is possible to obtain reliable measurements of the angular distribution for fusion-fission by simply studying the inclusive (i.e., singles) fission fragment yields. To do this we placed twenty 4 cm×2 cm parallel plate avalanche counters at angles from $\theta_{\mathrm{lab}}=90°$ to 170° to the beam direction. Each of the detectors was ~30 cm from the target and each covered an angular range of ±2° in the horizontal

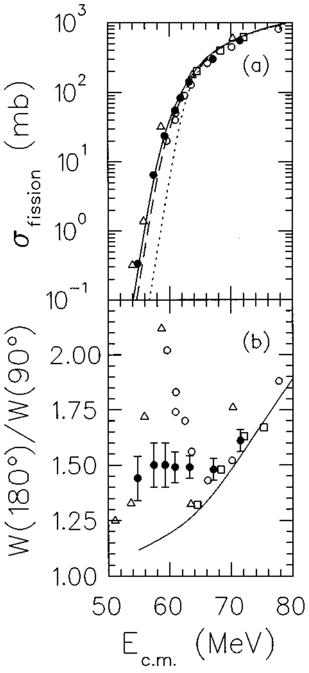

FIG. 2. ^{12}C+^{232}Th fission cross sections $\sigma_{\mathrm{fission}}$ and fission fragment anisotropies $[W(180°)/W(90°)]$ as a function of the center-of-mass kinetic energy. The solid circles show the present experimental work. The open triangles, circles, and squares show the measurements of Refs. [8], [13], and [15], respectively. The three curves in (a) are calculations performed with the code CCDEF [14] (see text). The solid curve in (b) shows the transition state model calculation from Ref. [8].

direction and ±4° in the vertical direction. Singles fission fragments were identified using time-of-flight and energy-loss signals. Fission fragment yields were converted into the center-of-mass reference frame assuming symmetric mass division following complete fusion. The center-of-mass kinetic energy of the symmetric fission fragments was estimated using Viola systematics [10]. Simultaneous measurement of elastically scattered ^{12}C projectiles into a collimated Si surface barrier detector at $\theta_{\mathrm{lab}}=27.5°$ to the beam direction enabled the determination of the fission cross sections relative to Rutherford scattering. In order to obtain anisotropies and total fission cross sections, we fitted our measured fission fragment angular distributions with the transition state model, with the mean square of the fusion spin distribution treated as an adjustable parameter at each ^{12}C beam energy.

Our anisotropy $[W(\theta_{\mathrm{c.m.}}=180°)/W(\theta_{\mathrm{c.m.}}=90°)]$ and cross section measurements are compared with the data of others in Fig. 2. Our fission cross section measurements are in good agreement with the corresponding measurements of Karnik *et al.* [13]. Our anisotropies are, however, in dramatic disagreement with the work of both Karnik *et al.* and Majumdar *et al.* It is important to realize that this disagreement cannot be due to some subtle influence of the transfer fission, since we disagree with both the singles data of Karnik *et al.* and the folding angle transfer fission corrected analysis of Majumdar *et al.* The curves in Fig. 2(a) show various calculations of the ^{12}C+^{232}Th fusion cross section as a function of center-of-mass kinetic energy, performed using the code CCDEF [14]. The dotted curve is obtained assuming spherical and inert ^{12}C and ^{232}Th nuclei. Taking into account the static deformation of ^{232}Th gives the dashed curve. Including the effects of the first excited 2^+ and 3^- states in ^{12}C along with the ^{232}Th deformation yields the solid curve. Our ^{12}C+^{232}Th data show an anomalous plateau in the anisotropy of the fission fragments at $W(180°)/W(90°)\sim 1.5$ but give no indication of either the peaklike structure reported by Majumdar *et al.* or the sharp increase in the anisotropy as the beam energy decreases through the fusion barrier region as seen by Karnik *et al.* Further study of the angular distribution of fission fragments in near- and sub-barrier ^{12}C+^{232}Th reactions is needed to resolve the disagreement between the results presented here and those of Karnik *et al.* and Majumdar *et al.*

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