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Fission mass widths in ^{19}F + ^{232}Th, ^{16}O + ^{235,238}U reactions at near-barrier energies

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The fission fragment mass ratio distributions of fusion-fission events have been measured for the reactions of ^{19}F + ^{232}Th, ^{16}O + ^{235}U, and ^{16}O + ^{238}U at energies near and below the fusion barrier. It is found that the mass ratio widths follow a decreasing trend with decreasing energy, contrary to recent claims of anomalous mass widths attributed to a quasifission mechanism.

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Recent experimental evidence of an anomalous increase in the width of fission fragment mass distributions in ^{16}O,^{19}F + ^{232}Th reactions [1,2], near and below the fusion barrier, have been attributed to the onset of a new nonstatistical reaction mechanism reminiscent of quasifission. Ghosh *et al.* [1,2] suggest that the observation is a consequence of orientation-dependent quasifission in deformed target-projectile systems, following the arguments put forward by the observation of increased fission fragment anisotropies in the ^{16}O + ^{238}U reaction as compared to spherical projectile-target combinations at beam energies below the fusion barrier [3].

The angular distribution of fission fragments is assumed to be determined by the orientation of the nuclear symmetry axis at the saddle point. A narrower distribution of the projection of the angular momentum onto the nuclear symmetry axis results in larger anisotropies. The increased anisotropies observed in the ^{16}O + ^{238}U reaction, as the energy falls below the barrier, suggest that the saddle point of the system is more elongated than estimated by the transition state model. A more elongated system at the saddle point does not necessarily imply an increase in mass asymmetry. In fact, earlier experimental evidence suggests the mass asymmetry is not increased in this reaction [4]. The recent observation of a dramatic increase of the mass widths with decreasing energy from measurements of similar reactions using a very thick actinide target [1,2] prompted speculation that the contrasting observations in these measurements might be a consequence of a contamination from transfer-induced reactions.

In this Rapid Communication we report the measurement of the width of fission fragment mass ratio distributions for the systems ^{19}F + ^{232}Th, ^{16}O + ^{235}U, and ^{16}O + ^{238}U, at energies near and below the fusion barrier, showing no such anomalous behavior. Special care was taken to minimize contributions from transfer-induced reactions in the analysis, particularly below the fusion barrier where this type of reaction often dominates over fusion-fission-like reactions.

The experiments were carried out at the 14UD tandem accelerator of the Australian National University using pulsed beams of ^{19}F and ^{16}O. A target of ^{232}Th of thickness 50 μg/cm^2 deposited on an Al backing of thickness 30 μg/cm^2 and a thick self-supporting Th target of thickness 2.1 mg/cm^2 were bombarded with ^{19}F projectiles. The latter target was used to investigate the effect of using such a thick target on the deduced mass ratios. Targets of ^{235}U (enriched ^{235}U nitrate) of thickness 50 μg/cm^2 and ^{238}U ($^{\rm nat}$U) of thickness 100 μg/cm^2 deposited on C foils of thickness 12 μg/cm^2 were bombarded with ^{16}O beams.

Fission fragments were detected in two large-area multiwire proportional counters (28 cm × 36 cm), centered at $\theta = 45^\circ$ ($\phi = 90^\circ$) and $\theta = 135^\circ$ ($\phi = 270^\circ$) and located at a distance of 18 cm from the center of the target. With this geometry, the counters subtended polar angles of $5^\circ \leqslant \theta_A \leqslant 80^\circ$ and $95^\circ \leqslant \theta_B \leqslant 170^\circ$, respectively. The targets were tilted by 45° relative to the beam direction to eliminate shadowing of the detectors by the target frames. For each detector, the X-Y positions, the energy loss, and time difference with respect to the pulsed beam were recorded. These quantities were used to construct the velocity vectors of coincident fission fragments, v_A and v_B, respectively. These vectors were corrected for energy losses in the target on an event-by-event basis assuming the reactions took place in the middle of the target. In the reaction with the thick Th target, the corrections were performed assuming the reactions took place at a depth consistent with a projectile energy weighted by the cross section at the entrance and exit of the target.

In Fig. 1(a) we show the fission fragment folding angle distribution for the ^{19}F + ^{232}Th reaction at 97 MeV as a function of the laboratory angle in the back detector (θ_B). The intense band is consistent with fission following full momentum transfer (FMT). The solid line represents the calculated folding angle assuming FMT and the systematics of the total kinetic energy in fission [5]. The less intense group with smaller folding angles corresponds to fission following transfer reactions (TR) or other incomplete momentum transfer reactions. Figure 1(b) shows the coplanarity angle ($\phi_{AB} = \phi_B - \phi_A$) as a function of the folding angle. Fissioning Th-like nuclei following TR do not, in general, recoil along the beam direction. Hence, their coplanarity angle distribution is broad and contaminates the FMT component. The contamination becomes more and more severe as the energy decreases below the fusion barrier since the relative intensity of the FMT component decline steeply with energy. Figures 1(c) and 1(d) show the same distributions using the thick Th target. Since the experimental folding and coplanarity angles are determined by the measured direction of the fission fragments, the increased spread observed in the thick target is mainly a

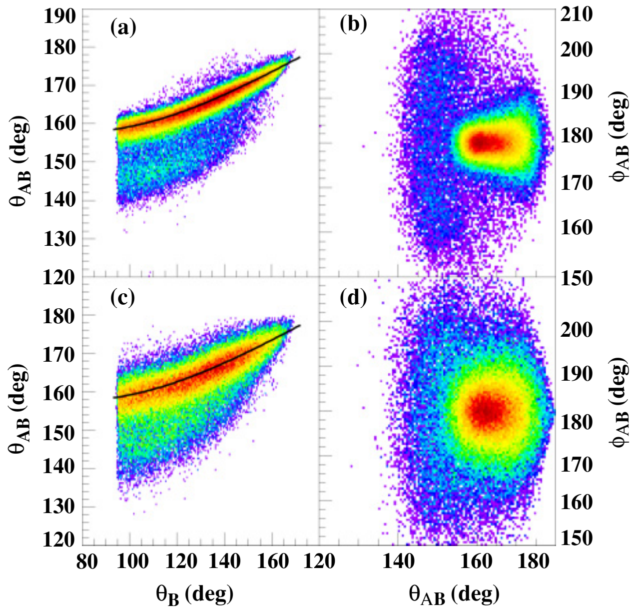

FIG. 1. (Color online) The folding angle θ_{AB} as a function of θ_B and the coplanarity angle ϕ_{AB} as a function of θ_{AB} for the reaction ^{19}F + ^{232}Th at $E_{\mathrm{lab}} = 97$ MeV, using the thin 50 μg/cm^2 target (a and b) and the thick 2.1 mg/cm^2 target (c and d).

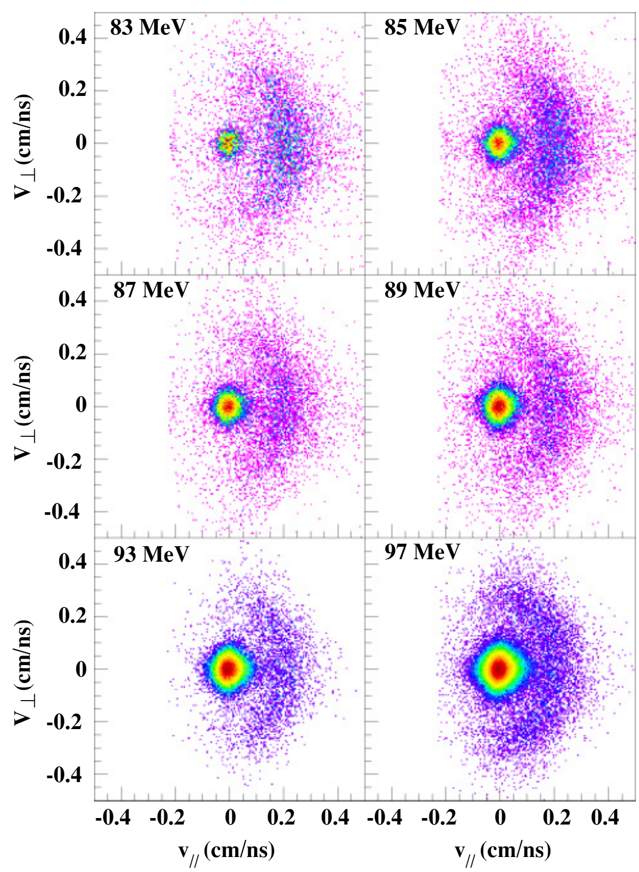

FIG. 2. (Color online) The perpendicular velocity [4] is a measure of off-beam components of the linear momentum transferred to the fissioning system. This quantity is used to separate FMT fission events from TR leading to the fission.

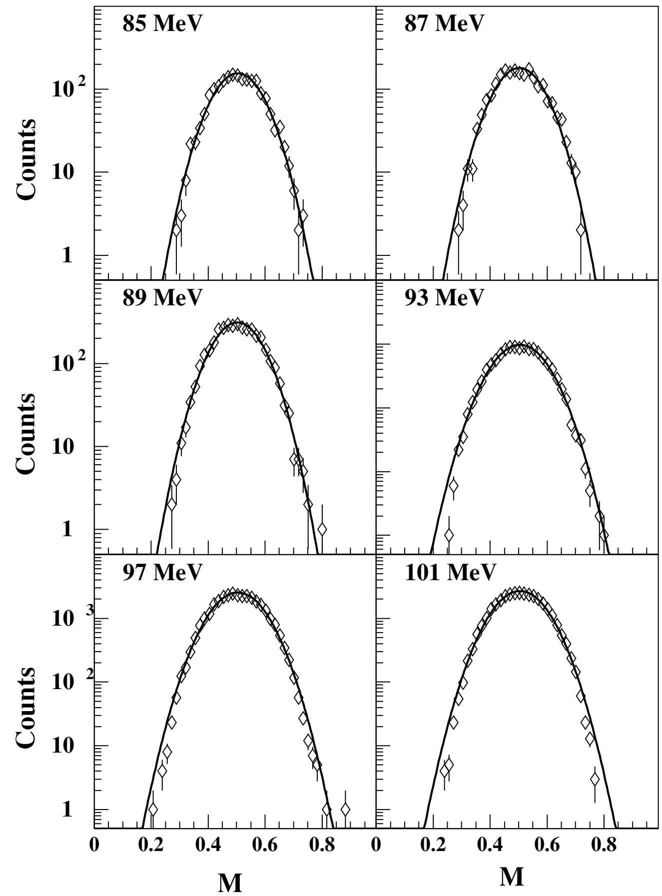

FIG. 3. Fission fragment mass ratio distributions following FMT events in the ^{19}F + ^{232}Th reaction (thin Th target). Gaussian fits are shown as solid lines.

consequence of deflections in the target material, which could be so severe that the FMT and TR components are no longer distinguishable. In other words, using a high-fissility target in which multiple scattering is significant makes separating FMT and TR components very difficult. In the absence of significant scattering the spread of the FMT folding and coplanarity angles reflect the dispersion of the velocity vectors caused by pre- and postfission evaporation of particles from the compound nucleus and fission fragments, respectively.

To separate efficiently the FMT from the TR component we have constructed a quantity that is related to any off-beam component of the total momentum transferred. This quantity, denoted $v_\perp$, is in the plane perpendicular to the beam axis and perpendicular to the projection of the scission axis onto this plane [4]. The distribution of $v_\perp$ as a function of $v_\parallel = v_{\mathrm{FS}} - v_{\mathrm{c.m.}}$, where

$$v_{\mathrm{FS}} = \frac{v_\parallel^A v_\perp^B + v_\perp^A v_\parallel^B}{v_\perp^A + v_\perp^B} \tag{1}$$

is the velocity of the fissioning system and $v_{\mathrm{c.m.}}$ is the velocity of the center of mass, is shown in Fig. 2 for a series of projectile energies in the ^{19}F + ^{232}Th reaction. A two-dimensional gate on the distribution centered around the origin selects the maximum possible fraction of the fusion-fission events,

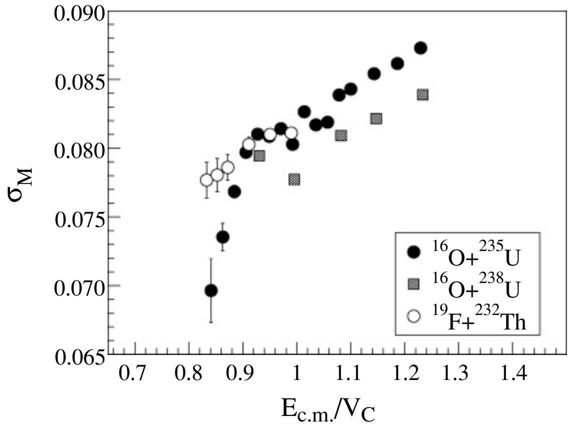

FIG. 4. Fission fragment mass ratio widths following FMT events as a function of $E_{c.m.}/V_C$ for the three systems studied in this work using thin targets.

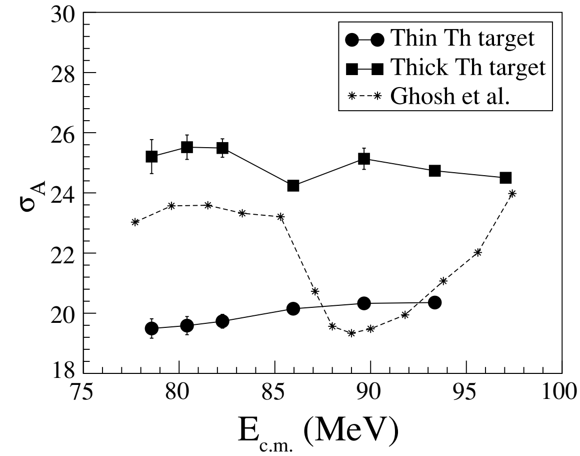

FIG. 5. Fission fragment mass widths following FMT events as a function of $E_{c.m.}$ for the ^{19}F + ^{232}Th reaction using the thin and thick targets. The stars joined by dashed lines are the results reported recently by Ghosh *et al.* [1].

minimizing the TR component. At the lowest energy, the FMT component is about 15% of the total fission yield, whereas at the highest energy this component is ∼85%.

The distributions of $M = (1 + R_M)^{-1}$, where R_M is the fission fragment mass ratio

$$R_M = \frac{A_A}{A_B} = \frac{v_\perp^B}{v_\perp^A}, \tag{2}$$

are plotted in Fig. 3 for the ^{19}F + ^{232}Th reaction in the angular range $135^\circ \leqslant \theta_{c.m.} \leqslant 150^\circ$. Error bars correspond to statistical uncertainties only.

The widths of the M distributions are plotted in Fig. 4 as a function of $E_{c.m.}/V_C$, where V_C is the Coulomb barrier. Error bars correspond to one standard deviation of the width in the fitting procedure. As the plot indicates, the widths show no enhancements as the beam energy falls through the fusion barrier, decreasing smoothly with energy for all reactions.

Figure 5 shows the mass widths for the ^{19}F + ^{232}Th reaction alone, deduced using the thin and thick targets. Here we have assumed the mass of the fissioning system to be A_{CN}, as Ghosh *et al.* [1] did. The widths deduced using the thick target are, on average, 4 mass units larger than those determined using the thin target. The large difference is a consequence of the spread of the velocity vectors caused by scattering in the target material. No indication of anomalous behavior below the barrier is observed using either target. The star symbols joined by a dashed line represent the result reported by Ghosh *et al.* If the thick-target data are analyzed in the same manner as in Ref. [1], applying a cut similar to that indicated in Fig. 2 of Ref. [1], about 40% of the selected events would be considered TR events in our analysis for the lowest energy, and about 10% for the highest energy. Such large TR contaminations give rise to highly asymmetric mass distributions and a Gaussian fit is not meaningful. The anomalous behavior observed by Ghosh *et al.* could be due to a large contamination from transfer-induced fission, although the results presented in this work do not support anomalous behavior in FMT events whatsoever, even using a very thick target. Moreover, the use of a very thick target trivially results in larger mass widths as a consequence of a poorer determination of the fission fragment velocity vectors.

In conclusion, light-projectile fusion-fission reactions induced on actinide targets at energies near and below the barrier may proceed through a narrowing of the K distribution, as evidenced by an increased anisotropy [3], but no anomalous behavior of the fission fragment mass widths are observed in these reactions. In other words, the mass split in near and subbarrier fusion-fission does not seem to be significantly affected by a change in the distribution of the orientation of the nuclear symmetry axis relative to the total angular momentum at the saddle point.

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[1] T. K. Ghosh *et al.*, Phys. Rev. C **69**, 031603(R) (2004).
[2] T. K. Ghosh, S. Pal, T. Sinha, S. Chattopadhyay, P. Bhattacharya, D. C. Biswas, and K. S. Golda, Phys. Rev. C **70**, 011604(R) (2004).
[3] D. J. Hinde, M. Dasgupta, J. R. Leigh, J. P. Lestone, J. C. Mein, C. R. Morton, J. O. Newton, and H. Timmers, Phys. Rev. Lett. **74**, 1295 (1995).
[4] D. J. Hinde, M. Dasgupta, J. R. Leigh, J. C. Mein, C. R. Morton, J. O. Newton, and H. Timmers, Phys. Rev. C **53**, 1290 (1996).
[5] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).