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# Is quasifission responsible for anomalous fission fragment anisotropies?

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The excitation function for the $4n$ evaporation residue from the $^{12}C+^{236}U$ reaction has been measured for beam energies between 62 and 73 MeV. The shape and magnitude of the residue excitation function is not consistent with appreciable quasifission competition. [S0556-2813(98)50610-3]

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There exists a persistent puzzle about the behavior of experimental fission fragment anisotropies in heavy ion induced fission of heavy targets at bombarding energies near the Coulomb barrier [1]. As the bombarding energy decreases the anisotropy starts to rise rather than to continue to decrease with decreasing initial angular momentum as expected from a transition state statistical model [2]. Early interpretations of this anomaly attributed it to larger than expected angular momentum depositions in the compound nucleus [2]. This interpretation has not been supported by more recent developments. Anomalies of this magnitude in average angular momentum have not been seen by other probes of this quantity [3–5]. After a reevaluation of the evaporation residue cross section and its implication on the amount of post-neutron-emission fission, it is now recognized that fission angular distributions for lighter targets, such as in the $^{16}O+^{208}Pb$ reaction, need not be interpreted as being anomalous [6,7]. An early suggestion of Ramamurthy *et al.* [8] that fission for systems with entrance channel mass asymmetry less than the Businaro-Gallone critical asymmetry exhibit preequilibrium fission without formation of an equilibrated compound nucleus has been revisited by Liu *et al.* [9]. This interpretation has been compromised by the recent observation that fission angular distributions for systems on both sides of the critical asymmetry are anomalous [10]. It had earlier been suggested [11] that if the fission barrier is sufficiently small that the fission lifetime may become comparable to the $K$ equilibration time so that even if all other degrees of freedom are equilibrated the system may still have some remembrance of the $K=0$ dinuclear system. ($K$ is the projection of the angular momentum on the nuclear system symmetry axis.) This suggestion was made to account for anomalous anisotropies for heavier projectiles at energies well above the barrier where sufficient angular momentum could be brought in to significantly reduce the fission barrier. More recently Vorkapić and Ivanišević [12] have suggested that the origin of the discrepancy at sub- and near-barrier energies is that fusion only occurs when the tip of a prolate deformed nucleus is pointing in the beam direction, leading to an initial $K$ distribution strongly peaked at $K=0$. Furthermore it is assumed that the time for equilibration of the $K$ degree of freedom is not short compared to the fission lifetime so that a time-dependent $K$ distribution has to be used. Lestone *et al.* [10] have extended the model to take into account the effect of a nonzero target spin on the initial $K$ distribution and obtained a good description of $^{12}C+^{235}U$ ($I=7/2$), $^{236}U$ ($I=0$), and $^{238}U$ reactions. An alternative proposal [13,14] for the origin of this discrepancy is that quasifission competes with fusion-fission for collisions with the tips of prolate deformed nuclei. A consequence of this last suggestion is that nucleon emission leading to evaporation residues should be suppressed when quasifission is important.

To test this idea we have measured the yield of the $4n$ evaporation residue for the $^{12}C+^{236}U$ reaction at near-barrier energies where the anisotropy changes from normal to anomalous. We have measured the evaporation residue yield of 20-minute $^{244}Cf$ by an activation technique. The target was approximately 100 $\mu g/cm^2$ thick and was prepared by electrodeposition. The isotopic purity of the target was 99.6%. A thin (400 $\mu g/cm^2$) Al foil was placed downstream to catch the recoiling residues. This thickness was chosen to assure that the recoils would be stopped in the catcher foil. After a bombardment of about 40 minutes the catcher foil was rotated to a position in front of a surface barrier detector located to observe $\alpha$ particles emerging from the downstream side of the catcher foil. Range straggling in the catcher foil prevented resolution of the close-lying lines of $\alpha$ particles from the different evaporation residues produced. The $\alpha$ activity was followed for several half-lives and the resulting decay curve was resolved into components from the 44 minute $3n$, 20 min $4n$, and 10 min $5n$ channels. An example of a decay curve and its resolution into its different time components is shown in Fig. 1. In the important bombarding energy range near the barrier the $4n$ channel is the dominant evaporation channel. Simultaneous measurements of the fission cross sections were made by direct observation of the fission fragments during the bombardments. The excitation function we have obtained is shown in Fig. 2. The full curve shows an excitation function calculated with the statistical model code PACE2 [15], with a normalization based on the scaling of the Sierk droplet model [16] fission barrier to approximately reproduce the evaporation residue yield at the higher energies where the quasifission contribution is expected to be small. It is shown that the experimental evaporation yield at lower energies, where the anisotropy becomes

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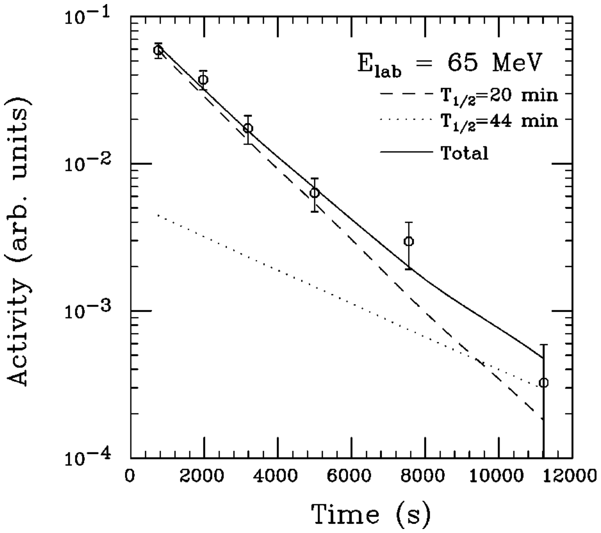

FIG. 1. Decay curve of $\alpha$ activity at a bombarding energy of 65 MeV. The curves are from a least-squares fit.

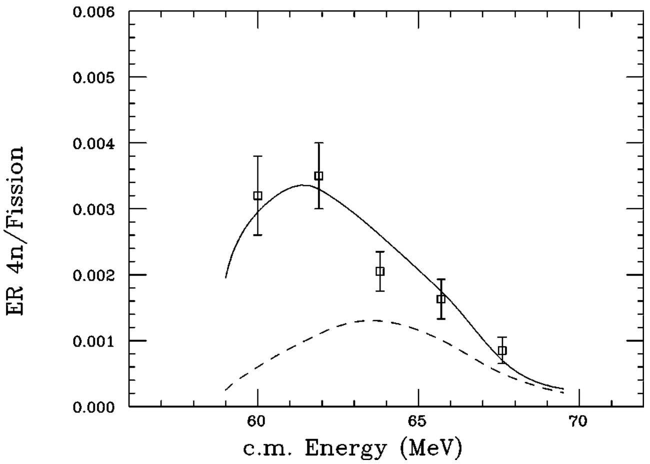

FIG. 2. The ratio of the $4n$ channel evaporation residue yield to the fission cross section as a function of bombarding energy in the center of mass. The circles represent the experimental data and the full curve represents a standard statistical model calculation. The dashed curve represents the result expected when interactions with the tips of the nucleus result in quasifission.

anomalous, is consistent with competition from fusion-fission. Also shown is a curve making the assumption that all collisions corresponding to an angle between the beam axis and the target nucleus symmetry axis of less than 30 degrees lead to quasifission. At low beam energies most of the collisions are with the tips due to the lower Coulomb barrier for such orientations. Hinde *et al.* suggested that for the $^{16}O+^{238}U$ reaction the critical angle was 35 degrees. This assumption is inconsistent with our observed evaporation residue yields at low energies. The observation of the expected amount of evaporation residues for fusion reactions is consistent with the formation of a compound nucleus with most of its degrees of freedom equilibrated, but with a lifetime too short for full equilibration of the $K$ degree of freedom. It is interesting to note that the $K$ degree of freedom is the slowest degree of freedom to equilibrate in quasifission reactions [17].

The magnitude of the fission barriers required to account for the evaporation yields provides further illustration of the importance of neutron evaporation in competition with fission. The Sierk droplet model barrier for the compound nucleus $^{248}$Cf is only 2.1 MeV. In order to reproduce the absolute magnitude of the evaporation residue cross section with PACE2 it was necessary to increase the Sierk barriers by a factor of 2.33, yielding a barrier of 4.85 MeV for $^{248}$Cf. This is comparable to the deduced barriers for neighboring Cf isotopes deduced from fission near threshold [18], suggesting that shell effects are important in suppressing fission even at the larger excitation energies associated with our experiment. If the effective fission barriers were close to the droplet values we would have observed much less evaporation residue yield. Thus our evaporation residue yields are if anything surprisingly large, not surprisingly small as would be expected for quasifission competition. Although not important for the present purpose, it would be of interest to investigate what dependence of the loss of shell structure with excitation energy would be consistent with this result. In summary, we have measured the $4n$ evaporation residue yield for the $^{12}C+^{236}U$ reaction. We find no evidence for suppression due to quasifission. Thus we conclude the origin of the anomalous fission fragment anisotropies is not due to quasifission.

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