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Properties of fission induced by the complete capture of ^{40}Ar by ^{238}U at $E_{c.m.} = 291$ MeV

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We have performed a coincidence measurement of the angular distribution of fission fragments for the complete capture reaction ^{40}Ar(^{238}U,f) and have discriminated against fission fragments from incomplete capture reactions. The angular distribution is consistent with a $1/\sin\theta$ dependence, in contrast to expectations assuming statistical equilibrium and saddle shapes given by the rotating liquid drop model.

[NUCLEAR REACTIONS ^{40}Ar(^{238}U,f), $E_{c.m.} = 291$ MeV, $\sigma(\theta_{c.m.})$ $\theta_{c.m.} = 119°-164°$, angular distribution compared to RLDM.]

Fission fragment angular distributions provide a uniquely important probe of the angular momentum bearing degrees of freedom of deformed nuclei. The assumption that K, the projection of the angular momentum on the nuclear symmetry axis, is frozen in at the fission saddle with a probability distribution given by a simple Boltzmann factor for the rotational degrees of freedom has been remarkably successful. A semiquantitative description for a wide variety of fissioning systems has been achieved using saddle point shape moments of inertia given by the rotating liquid drop model[1] (RLDM). In particular, the model accounts for a sharp drop in the anisotropy for very fissile systems as the increased Coulomb repulsion leads to more compact shapes. Recent investigations[2–5] have begun to probe a new realm of fusion and fission, where a fraction of the incident partial waves may lead to a compound nucleus having a vanishing fission barrier. For these high angular momentum states the centrifugal and Coulomb forces combine to cancel the attractive nuclear force and create a system which is unstable to fission in its most compact shape.

As the saddle point shape approaches a sphere and as the fission barrier vanishes for an increasing number of partial waves, one would expect the angular distribution of fission fragments to become increasingly isotropic. This is expected because, as the saddle point shape becomes more spherical, the K distribution becomes increasingly broad. The wider the K distribution the more the angular distribution becomes isotropic. In the limit of a nucleus fissioning from a spherical shape there is no preferred symmetry axis and the K vector can assume any value up to the magnitude of the full angular momentum vector. The opposite limit of a very narrow distribution is the classical analog of the system rotating about an axis orthogonal to the body symmetry axis and the angular distribution becomes $1/\sin\theta$.

A difficulty in using fusion reactions between heavy projectiles and targets at high energies to produce nuclei with high angular momentum is that only a fraction of the reaction cross section leads to complete capture. For our system of ^{40}Ar on ^{238}U at $E_{c.m.} = 291$ MeV, only about half of the reaction cross section leads to complete capture.[6,7] The remainder consists of reactions which produce the very similar experimental signature of two coincident heavy fragments, but these arise from incomplete momentum transfer reactions; either sequential fission of the target after a deeply inelastic collision or incomplete fusion of the beam and target accompanied by the emission of light charged particles. It is important to discriminate against these other reactions, since their angular distributions arise from differing saddle shapes, excitation energies, angular momenta, and kinematics, than the complete momentum transfer reactions.

We have devised a novel scheme to measure the angular distribution of fission fragments following the complete capture of ^{40}Ar by ^{238}U at $E_{c.m.} = 291$ MeV. The detection system was designed to identify and veto with good efficiency those events which are characterized by incomplete momentum transfer. This is the first measurement which has not been compromised by contamination with incomplete momentum transfer reactions arising from either preequilibrium light particle emission or sequential fission following quasi- and deeply inelastic scattering. The critical angular momentum is larger in this system than in any other system for which the angular distribution of the complete capture events has been determined, with a large majority ($\approx 90\%$) of the capture cross section leading to nuclei having vanishing fission barrier.

A ^{238}U target (≈ 1 mg/cm^2) was bombarded with a beam of 340 MeV ^{40}Ar from Lawrence Berkeley Laboratory SuperHILAC. One fission fragment was detected in a time of flight spectrometer (TOF) consisting of a channel plate start detector and a silicon surface barrier stop detector. The TOF was rotated in the reaction plane to measure the angular distribution for $\theta_{c.m.} = 119°-164°$. The other coincident fission fragment was detected in a large area position-sensitive avalanche detector[8] (PSAD) centered at 0°. A beam stop which subtended a 12° half angle was suspended in front of the PSAD. The first active element of the PSAD was situated 6.0 cm from the target and subtended a half acceptance angle of 42° in the laboratory. The grazing angle for the reaction was 39°.

The PSAD was configured in a manner to distinguish between fission fragments, scattered projectiles, and fast light charged particles by sequentially ranging out the various particles in several absorber foils. The latter two classes of particles are characteristic of incomplete momentum transfer reactions. The PSAD contained three 12 by 12 cm position-sensitive elements. The first two determined the x and y positions of the fission fragments and were separated from the third element by two thin aluminum absorbers totaling 8.2 mg/cm^2. These ranged out any fission fragments continuing through the first two elements. The third element of the PSAD determined the x position of beamlike projectiles. A 0.028 mm thick nickel absorber foil followed the third element stopping the beamlike projectiles. An exit window allowed the fast, light particles to exit the PSAD and be detected in a thin (2 mm) 15 by 15 cm plastic scintillator of NE-102. The scintillator was shielded from γ rays produced in the beam stop by a lead absorber between the PSAD exit window and the scintillator.

The velocity and energy of one fragment was determined in the TOF, which allowed the calculation of the particle's mass. The measured position of the second fragment, along with the constraint of energy and momentum conservation, permitted verification of two-body kinematics for the two fragments and permitted a further veto of incomplete momentum transfer events. Figure 1 illustrates the kinematic veto procedure for a typical run. The events are sorted into two-dimensional arrays; the y axis is the mass of the fragment determined from the TOF and the x axis is the difference of the observed and calculated positions for the complementary fragment in the PSAD. A sample gating condition is indicated by the open circles. The limiting angle differences due to the finite acceptance of the PSAD are shown by the vertical hashed lines.

The resulting angular distribution of coincident fission fragments from the complete capture of ^{40}Ar on ^{238}U is shown in Fig. 2. A noncoincidence measurement at $\theta_{c.m.} = 43.6°$ confirmed the symmetry of the angular distribution about 90°. At this angle the kinematics of the complete fusion reactions cleanly

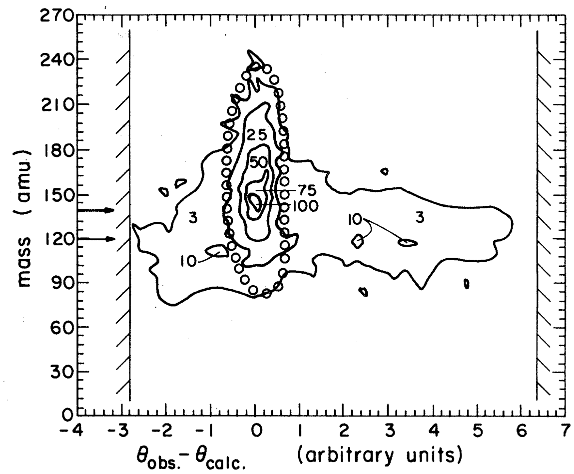

FIG. 1. Typical kinematic veto procedure. The difference of the observed and calculated position of the fission fragment in the PSAD (x axis) is plotted against the mass of the complementary fragment observed in the TOF (y axis). The open circles indicate a typical gating condition separating the fragments of complete capture from those associated with incomplete momentum transfer. The two horizontal arrows indicate the expected mass distribution centroids for fusion fission (upper) and fission following inelastic scattering (lower). The vertical hashed lines indicated the limited acceptance of the PSAD.

separated those fission fragments from incomplete fusion fragments. This measurement is shown reflected about 90° in Fig. 2. Absolute cross sections were obtained by normalizing the TOF to a monitor, which was subsequently calibrated with elastically scattered beam. We show a $1/\sin\theta$ distribution for comparison (solid curve). The veto procedure eliminated the following events, expressed as a percentage of the final yield of valid two-body fission fragments: (1) those accompanied by argonlike particles, 1–10%; (2) those accompanied by p's or α's, 4–5%; and (3) those violating two-body kinematics, 10–30%. As Fig. 2 shows, our data are consistent with a $1/\sin\theta_{c.m.}$ dependence. Assuming a $1/\sin\theta$ distribution, the resulting integrated fusion-fission cross section is $\sigma_{capture} = 1146 \pm 110$ mb, in good agreement with a recent measurement of Kildir et al.[9] With the sharp cutoff model, this corresponds to a critical angular momentum of $l_{crit} = 131\hbar$.

The RLDM predicts that the fission barrier B_f should vanish for this system for $l > 31\hbar$. For those partial waves leading to a compound nucleus with $B_f = 0$, conventional saddle-point models would predict an isotropic angular distribution. Those partial waves leading to a compound nucleus with a nonvanishing fission barrier can, however, contribute to an anisotropy. We estimated the anisotropy for these partial waves using the RLDM to be $W(180°)/W(90°) \approx 1.7$. The sum of these two contributions

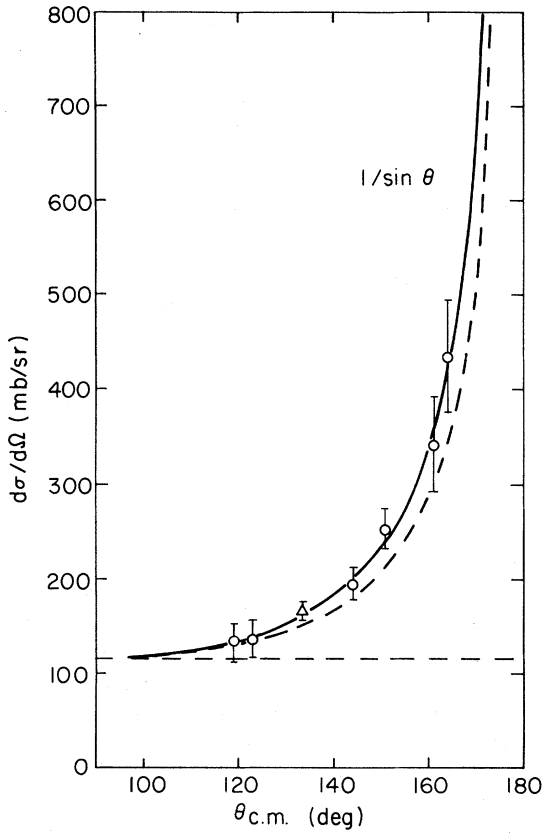

FIG. 2. Angular distribution of coincident fission fragments for complete capture reactions. The solid curve is $1/\sin\theta$. The thin dashed curve indicates the sum of the statistical model expectations for both $B_f=0$ and $B_f\neq 0$ partial waves. The thick dashed curve is the composite of a satistical model calculation for the $B_f>0$ partial waves and $1/\sin\theta$ for those partial waves with a vanishing fission barrier.

is shown by the thin dashed curve in Fig. 2, normalized to the 90° value.

We suggest two possibilities for understanding the failure to observe an nearly isotropic angular distribution. First, it is possible that the assumption that the K distribution is frozen-in at the saddle point (or in the case of $B_f=0$ at the equilibrium configuration) may not be valid for the most compact shapes. Rather, the relatively small deformation of the saddle-point shape, and consequently large neck size, could allow substantial angular momentum reorganization before the K distribution is frozen-in. A second possibility is that the dynamics of the collision are such that a significant fraction of the higher partial waves never lead to a completely fused, nearly spherical equilibrium shape. If the most compact configuration is achieved rather rapidly, there may be no reorientation of the original angular momentum, and the fragments may be emitted in the reaction plane defined by the initial impact parameter. For such events with a memory of the entrance channel reaction plane a $1/\sin\theta$ angular distribution is expected. (A nearly $1/\sin\theta$ distribution can also be obtained even if angular momentum reorientation occurs, provided the shape of the reaction intermediate is sufficiently nonspherical.) If one makes the assumption that (1) complete fusion occurs and that (2) the K distribution is frozen-in at the RLDM saddle for all partial waves for which a finite fission barrier exists ($l \leq 31\hbar$), and that for the higher partial waves with $B_f=0$ ($32 \leq l \leq 131$) the distribution is given by a $1/\sin\theta_{c.m.}$, the resulting angular distribution shown by the heavy dashed line in Fig. 2 is obtained. The assumption of a $1/\sin\theta$ distribution for the higher partial waves is valid in the limit of $l \gg K$. These simple assumptions, in addition to being consistent with our observations, are also qualitatively consistent with the anisotropies observed recently by Back *et al.*[3] in ^{32}S-induced fission of Th and U where a smaller, but still significant, fraction of the fission cross section is associated with l values greater than that for which the fission barrier vanishes. A very recent comparison[10] of ^{16}O- and ^{32}S-induced fission leading to nearly the same compound nucleus, however, indicates the importance of entrance channel effects in determining the anisotropy.

A more definitive comparison will require better theoretical understanding of the dynamics of the collision. In particular, one needs to know for what range of impact parameters the reaction intermediate is sufficiently compact to result in mass equilibration yet sufficiently deformed or short-lived to lead to a nearly $1/\sin\theta_{c.m.}$ angular distribution. Some progress is now being made in this direction.[11,12]

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