Disappearance of entrance channel dependence of fission fragment anisotropies at well-above-barrier energies

R. Vandenbosch, J. D. Bierman, J. P. Lestone, J. F. Liang, D. J. Prindle, and A. A. Sonzogni
University of Washington, Nuclear Physics Laboratory, Seattle, Washington 98195

S. Kailas, D. M. Nadkarni, and S. S. Kapoor
Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay-400085, India

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Fission fragment anisotropies have been measured to energies extending well above the barrier for three entrance channels leading to the same compound nucleus ^{248}Cf. For the ^{12}C + ^{236}U and ^{16}O + ^{232}Th systems, lying on either side of the Businaro-Gallone critical asymmetry, the mean square angular momentum is matched at an excitation energy of 62 MeV. The anisotropies, although different at lower energies, are in agreement within experimental errors at this excitation energy and thus show no entrance channel dependence. [S0556-2813(96)50309-2]

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Recently two puzzles have emerged in the study of fission fragment angular distributions from heavy-ion induced fission. The first of these is the observation that the anisotropies for essentially all target-projectile combinations involving an actinide target do not decrease in the subbarrier region as expected. When interpreted in terms of the generally accepted transition state model, this result implies a larger mean-square value of the compound nuclear spin distribution than expected [1]. Very recently two quite different suggestions have been put forward for the origin of this effect. One [2] involves the large deformation of actinide targets, invoking the idea that collisions with the tip of the deformed nucleus lead to fission without ever forming a compound nucleus (quasifission). The second [3] attributes the large anisotropies to a failure to equilibrate the angular momentum bearing degrees of freedom when the angular momentum is small and the mass asymmetry of the entrance channel is larger than that for the Businaro-Gallone critical asymmetry (defined below). This puzzle has yet to be completely resolved.

The second puzzle, which is the focus of the present work, has to do with anisotropies at bombarding energies above the fusion barrier where uncertainties in the mean-square spin of the compound nucleus are small. It has been observed [4] that the anisotropies for actinide targets are well accounted for by the transition state model (TSM) for lighter projectiles such as ^{12}C, ^{10}B, and ^{9}Be but are larger than expected for the heavier projectiles such as ^{16}O and ^{19}F. The target-projectile combinations having an entrance channel mass asymmetry $\alpha = (A_T - A_P)/(A_T + A_P)$ less than about 0.88 exhibit anomalous anisotropies, whereas systems with α greater than 0.9 generally exhibit the expected anisotropy. These observations have been interpreted [4] as an entrance channel effect arising from contributions of fissionlike events from preequilibrium fission expected to arise only in the case of heavier projectiles such as ^{16}O and ^{19}F, on the basis of the variation of the liquid drop model driving force at the saddle in the mass asymmetry degree of freedom. The α value where the driving force changes direction is called the Businaro-Gallone critical asymmetry (α_{BG}). For values of α greater than α_{BG}, the driving force favors amalgamation of the nascent partners (fusion and compound nucleus formation), whereas for smaller values the smaller partner gains in mass at the expense of the heavier, and the dinuclear system may reseparate as a fissionlike event without K equilibration and formation of a compound nucleus.

The above study [4], however, involved formation of different compound nuclei and the data for the anomalous systems were not very far from the fusion barrier, as only an energy range of up to about 10 MeV above the barrier for the O + Th and F + Th systems were spanned. It is also now known [5] that the ^{12}C + ^{232}Th, as well as the ^{12}C + ^{236}U [6], systems on the other side of the Businaro-Gallone critical asymmetry, also exhibit anomalous asymmetries at the barrier. We report here the results of a more definitive experiment by studying three entrance channels that lead to the same compound nucleus. Two of these entrance channels, ^{11}B + ^{237}Np (α = 0.911) and ^{12}C + ^{236}U (α = 0.903), have α greater than the Businaro-Gallone critical asymmetry and the third, ^{16}O + ^{232}Th (α = 0.871), has α smaller than the critical asymmetry.

A definitive test of an entrance channel mechanism requires making the same compound nucleus at the same excitation energy and angular momentum. Fission fragment anisotropies are sensitive to the mean-square angular momentum of the fissioning system. We show in Fig. 1(a) the excitation energy dependence of the mean-square angular momentum for the three systems. The mean-square angular momentum values have been obtained from fits to fission excitation functions using coupled channels calculations [7] that take into account the static quadrupole deformation, octupole vibration, and most-positive neutron transfer channel. The barrier height is adjusted to reproduce the absolute values of the cross sections measured in this work as well as data at other energies [8,4,9]. The couplings are only very important for the O + Th system where energies closest to the barrier were considered. One sees from the figure that at an excitation energy of about 62 MeV the average angular

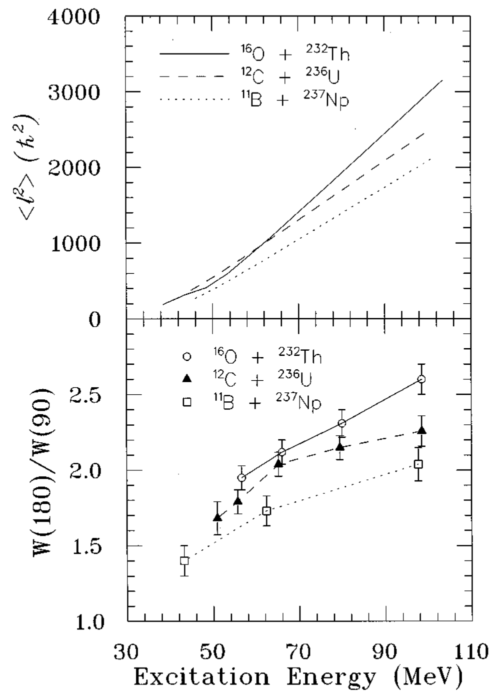

FIG. 1. (a) The mean-square angular momentum as deduced from fits to the fission cross section as a function of excitation energy of the compound nucleus. (b) The experimental anisotropies as a function of excitation energy.

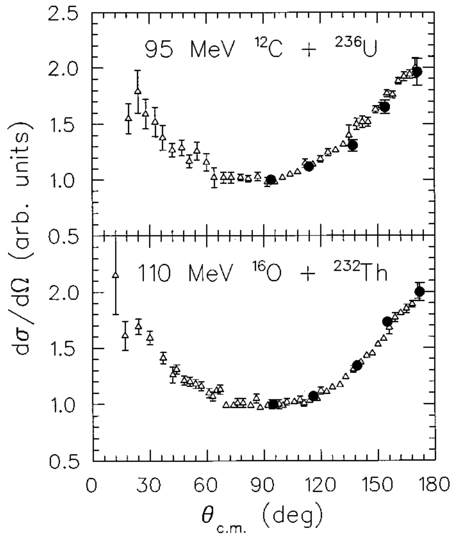

FIG. 2. Fission fragment angular distributions. The open triangles represent data from the segmented gas detectors and the full circles are from the Si detectors.

momentum is the same for the ^{12}C + ^{236}U and ^{16}O + ^{232}Th entrance channels. This corresponds to laboratory energies of 91 MeV for ^{12}C and 105 MeV for ^{16}O. We have measured the fission fragment anisotropies for bombarding energies over a range on either side of this matching energy. For the ^{11}B + ^{237}Np system it is not possible to match excitation energy and angular momentum simultaneously with either of the other two systems. We have measured the anisotropy for this system over the same range of excitation energy.

The experiment was performed using beams from the University of Washington Nuclear Physics Laboratory Tandem-booster accelerator facility. The targets were metal oxide or fluoride of 50 to 300 microgram per cm^2 on 50 to 100 microgram per cm^2 carbon or nickel backings. Two kinds of fission fragment detectors were used. Inclusive single-fragment anisotropies were obtained from Si surface barrier detectors of about 20 micron thickness. At this thickness the projectilelike particles deposit very little energy in the detectors, whereas the fission fragments deposit almost all of their energy. This leads to a clean separation of the fission fragments from the other reaction products. We also used three large-area segmented gas detectors. These were primarily used for measurements of fragment-fragment coincidences in order to determine the folding angle distributions, which will be presented in a later publication. We also determined inclusive (singles) fission fragment angular distributions from the gas detectors, and the anisotropies from these measurements agree well with the Si detector results. We report here the average value of the independent determinations with the two kinds of detectors. In the present communication we focus on the single-fragment anisotropies, as these were the kind of results that led to the motivation of the present measurement. A monitor detector was placed at 27.5 degrees for normalization purposes. The anisotropies from the Si detectors could also be obtained from a single run independent of this normalization. We show examples of the angular distributions in Fig. 2.

The inclusive anisotropies for the different entrance channels are shown in Fig. 1(b). Our results for ^{16}O + ^{232}Th are in good agreement with previous inclusive measurements where they overlap in energy [8,10]. It is seen in Fig. 1(b) that at excitation energies up to around 56 MeV the measured anisotropy for the O + Th system is somewhat larger than for the C + U system, even though the $\langle l^2 \rangle$ for O + Th is somewhat smaller indicating an entrance channel effect up to this energy. The ^{11}B + ^{237}Np anisotropy at the lowest energy is also in good agreement with the results of Liu *et al.* [3], who have separated out fission following transfer. This latter contamination is said to be small [9].

As stated previously, the most model independent test for an entrance channel effect is to simultaneously match excitation energy and angular momentum. The excitation energy and angular momentum for the O + Th and C + U systems are matched at $E^\star = 62$ MeV. Interpolating between the measured anisotropies gives 2.05 $\pm$0.1 for the O + Th system and 1.96 $\pm$0.1 for the C + U system at this excitation energy. As these two values are the same within the experimental error there is no evidence that the entrance channel mass asymmetry relative to the Businaro-Gallone critical asymmetry plays any role in determining the fission anisotropy at energies well above the fusion barrier. This is not very suprising as the potential energy surface is very flat with respect to the mass asymmetry coordinate in this vicinity and the entrance channel mass asymmetry differs little for the two systems.

We turn now to a discussion of the absolute magnitude of the anisotropies in the framework of transition state theory. We make the usual assumption that the orientation of the fission axis with respect to the angular momentum vector is determined at the saddlepoint. The shape and effective moment of inertia of the saddlepoint is taken from the diffuse surface liquid drop model of Sierk [11]. The variation of the shape and moment of inertia on angular momentum was taken into account. The nuclear temperature was deduced using a nuclear level density parameter of $A/9$ MeV^{-1}. We have made two sets of calculations. In one we have not taken into account cooling by neutron emission prior to reaching the saddlepoint. In the second calculation the maximum correction has been made, assuming all prescission neutrons were emitted prior to reaching the saddle point. Prescission neutron multiplicity values were taken or extrapolated from a recent work [12]. It may be mentioned that somewhat larger prescission neutron multiplicity values for the O + Th system as compared to the B + Np system as measured in their work have been used in our calculations. It is assumed that the prescission neutrons for the C + U system are the same as that obtained for the B + Np system. The values range between 0.9 and 3.0 for O + Th and 0.6 and 2.3 for the other two systems for $E^{\star}$ between 40 and 65 MeV. In the calculation it is assumed that 10 MeV (binding + kinetic) is carried away by each neutron. These TSM calculations have been terminated around $E^{\star} = 65$ MeV as beyond this $E^{\star}$ the fraction of fast fission events corresponding to vanishing B_f for large l values become substantial ($>$10%). Also with increasing angular momentum for very low values of B_f the saddle shapes become triaxial before the barrier vanishes. Thus the highest l value considered was $l = 46$ where the fission barrier is about 0.40 MeV. The results of these calculations are shown in Fig. 3 where in addition to the present results other available data in the literature are also plotted. We show two curves in Fig. 3. The dashed curve represents calculations with no correction for neutron emission and the full curve represents calculations with the maximum possible neutron cooling correction. It is seen from Fig. 3 that at lower $E^{\star}$($<$60 MeV) the data for B + Np and C + U agree with calculations within errors whereas for O + Th the experimental anisotropies are substantially larger than TSM calculations, thus indicating an entrance channel dependence at these energies. Liu *et al.* [3] have also shown that ^{16}O + ^{232}Th anisotropies are larger than ^{11}B + ^{237}Np in this energy region. It appears that this anomaly for O + Th does not disappear until one is at a bombarding energy 15 to 20% above the barrier. This is considerably higher than where the barrier anomaly is reported to disappear for the C + Th system [5].

However, in the region between 60 to 65 MeV the anisotropies for the three systems agree with the TSM calculations. This quantitative agreement may be a little fortuitous, as the experimental anisotropies will probably increase a little when corrections for fission following transfer are made. Also the saddlepoint excitation energies were calculated assuming all observed prescission neutrons are presaddle for the full curve that reproduces the data. As pointed out before, at energies around 62 MeV where there is good matching of mean-square l values between the O + Th and C + U systems, there is no evidence for an entrance channel effect. The fact that anomalies disappear at about the excitation energy where the angular momentum is matched for two of the systems is thought to be accidental.

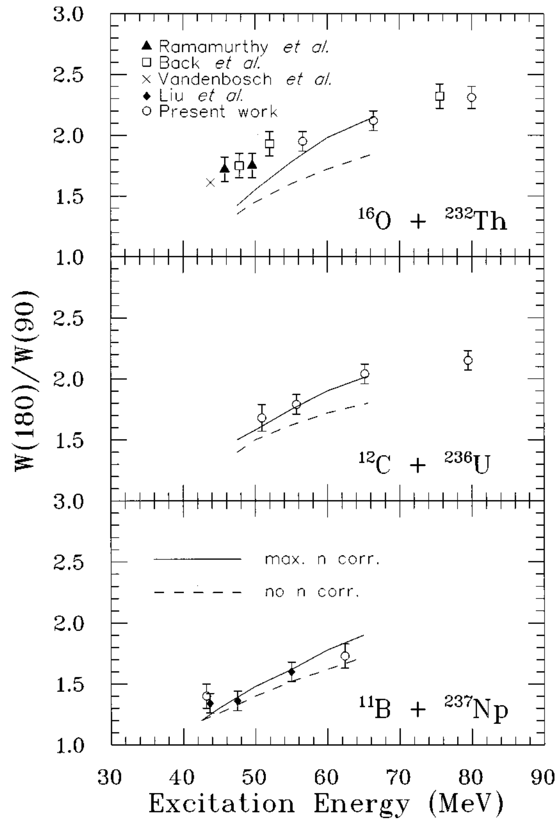

FIG. 3. Comparison of experimental anisotropies with calculated values based on the transition state model. The full curve results when all prescission neutrons are assumed to be presaddle and the dashed curve results if cooling by neutron emission before reaching the saddlepoint is neglected.

The transition state model calculations have not been carried out above about 65 MeV as some of the highest partial waves have a vanishing fission barrier. It is interesting to note, however, that at higher bombarding energies the anisotropies for the three systems follow the expectations from Fig. 1(a) that ^{16}O + ^{232}Th has the largest mean-square angular momentum and will have the largest anisotropy and the ^{11}B + ^{237}Np system with the lowest mean-square angular momentum will have the lowest anisotropy. It is of interest to explore the high-energy anisotropy somewhat more quantitatively to see if there is an entrance channel effect related to the fraction of compound nuclei for which the fission barrier vanishes due to high angular momentum. One can explore this somewhat more quantitatively by assuming a dependence of the form $W(180)/W(90) = 1 + \langle l^2 \rangle / 4\sigma_{K^2}$. In the transition state model $\sigma_{K^2} = K_0^2 = I_{\rm eff} T$ where $I_{\rm eff}$ is the effective moment of inertia of the configuration where the orientation of the fission axis with respect to the angular momentum vector is determined, and T is the nuclear temperature. If we compare anisotropies at the same excitation energy in the same compound nucleus, the temperature will be the same (neglecting the small difference in prescission neutrons for the O + Th and B + Np systems). We can test this scaling by comparing the anisotropies for the three entrance channels. This is done in Fig. 4 using data sufficiently (15%) above the fusion barrier to avoid the near-barrier anomaly discussed earlier. We have arbitrarily taken the

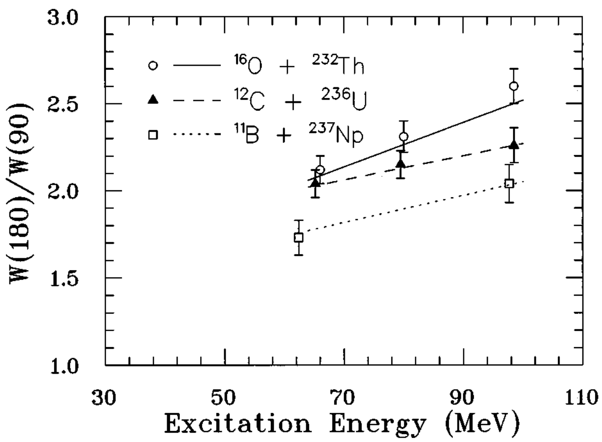

FIG. 4. Scaling of anisotropies as a function of excitation energy. The dashed curve is drawn through the data for the ^{12}C + ^{236}U reference system. The full and dotted curves are obtained by scaling the $W(180)/W(90)-1$ values obtained from the dashed curve by the ratio of the mean-square angular momentum for the comparison system to that of the reference system.

^{12}C + ^{236}U data as a reference line (dashed), and scaled $W(180)/W(90)-1$ values by $\langle l^2 \rangle$ to get the full and dotted lines for the other systems in Fig. 4. This simple scaling seems to adequately account for the difference in anisotropies for the different systems. This is expected to be the case for that fraction of the partial wave distribution where there is a finite fission barrier. This fraction varies from one system to the other, as can be seen from the differing $\langle l^2 \rangle$ at high energies in Fig. 1(a) but becomes of the order of 1/2 at the highest bombarding energy. Further work is required to see if the available data allows a quantitative determination of the dependence of σ_{K^2} with $\langle l^2 \rangle$ to confront the assumption made in some models of nonequilibrium fission that the anisotropy is independent of l [13], or is independent of l for the lowest l [3].

The main conclusion of the present work is that when the same compound nucleus ^{248}Cf is investigated via different entrance channels on either side of the Businaro-Gallone critical asymmetry (^{12}C + ^{236}U and ^{16}O + ^{232}Th), although the anisotropies differ at lower energies, this entrance channel dependence of the anisotropy disappears when both systems are compared at bombarding energies at least 30% above the barrier. This result suggests that there is no significant role played by the entrance channel asymmetry relative to the Businaro-Gallone critical asymmetry in determining the fission anisotropies at sufficiently high energies above the fusion barrier. It does appear that the excitation energy required to wash out the anomalous anisotropies at the barrier increases more or less continuously with increasing entrance channel symmetry or entrance channel charge product $Z_p Z_t$. This may reflect the influence of the latter parameter in the scaling of the extra-extra push model [14] for compound nucleus formation.

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