Anomalously Broad Spin Distributions in Sub-barrier Fusion Reactions

R. Vandenbosch, T. Murakami, C.-C. Sahm, D. D. Leach, A. Ray, and M. J. Murphy
Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195
(Received 9 December 1985)

The mean square spin value of the compound nucleus ^{248}Cf has been determined from fission-fragment angular distributions for the ^{12}C + ^{236}U and ^{16}O + ^{232}Th reactions. The anisotropy and, hence, the mean square spin values are much larger than expected. Models which reproduce the enhancement observed in the sub-barrier fusion excitation functions fail to account for the spin-distribution observations.

PACS numbers: 25.70.Jj

The roles of permanent target deformations and of shape fluctuations in the enhancement of sub-barrier fusion excitations are well established. These factors are also expected to lead to a broadening of the spin distributions, and indeed evidence for such broadening has been reported for near-barrier energies.[1-4] The origin of this broadening can be qualitatively understood in terms of replacing the single set of l-dependent barriers for a static spherical target by an ensemble of barriers which will include both smaller and larger barriers for each partial wave, depending on whether the internuclear separation is larger or smaller when the nuclear surfaces come in contact. In this work we probe spin distributions in the sub-barrier region at appreciably lower energies than have been studied. We find that at these energies the spin distribution is much broader than expected on the basis of the best theoretical estimates, even though the enhancements of the cross sections are well predicted by the same models.

Gamma-ray multiplicity techniques have been employed previously in studies of spin distributions in near-barrier fusion. In such studies fusion events are selected by triggering on a discrete gamma transition in a particular evaporation residue. This is most easily done if the residue is a deformed even-even nucleus, in which case almost all of the deexcitation strength ends up in the ground-state rotational band. This approach is only applicable when the particular evaporation residue is the dominant product. At lower energies this particular product will become preferentially fed by the lower-spin part of the population, with the higher-spin part going to the evaporation product corresponding to one fewer neutron being emitted. In order to measure spin distributions at low energies without channel-selection bias we have chosen in this work to utilize fission-fragment angular distributions. For the targets employed essentially all of the fusion cross section leads to fission, and so no spin fractionation can take place.

The parameter which characterizes the anisotropy of fission-fragment angular distributions in the transition-state model is the ratio of the mean square spin of the fissioning system to the product of the nuclear temperature and the effective moment of inertia at the saddle point. This dependence arises from the Boltzmann factor characterizing the phase space for rotations about axes parallel or perpendicular to the internuclear symmetry axis of the deformed transition state. Rather than rely on a theoretical model to calculate the latter product, we have chosen to study a system where this product can be determined from a measurement of the anisotropy for a reaction at above-barrier energies whose spin distribution can be reliably calculated. (We note that the use of fission-fragment anisotropies does not depend on the validity of the transition-state model, but only on the assumption that a compound nucleus has been formed.) Specifically, we have studied the fission of the compound nucleus ^{248}Cf produced in several different reactions. Reising, Bate, and Huizenga[5] have measured the anisotropy for 42.8-MeV alpha-induced fission of ^{244}Cm. From this measurement we deduce the product of the effective moment of inertia at the saddle point $\mathscr{I}_{\text{eff}}$ and the nuclear temperature at an excitation energy of 36 MeV. We have then used this result to interpret the anisotropy observed in ^{12}C + ^{236}U and ^{16}O + ^{232}Th reactions, both leading to the same compound nucleus at similar excitation energies.

The experiments were performed with the University of Washington Nuclear Physics Laboratory Model FN tandem Van de Graaff accelerator. Targets were typically several hundred μg/cm^2 thick. An array of surface-barrier detectors of 10–20-μm thickness was used to detect the fission fragments. For these thicknesses, elastically and inelastically scattered oxygen or carbon ions deposit only a fraction of their energy in the detector, permitting unambiguous identification of fission fragments. The detector array spanned a laboratory angular range between 85° and 170°. The geometrical solid angles subtended by the detectors were verified by calibration with a ^{252}Cf spontaneous-fission source. The absolute fission cross sections were determined by normalization to Rutherford scattering with a monitor counter at forward angles.

Several of the angular distributions obtained are shown in Fig. 1. These exhibit much larger anisotro-

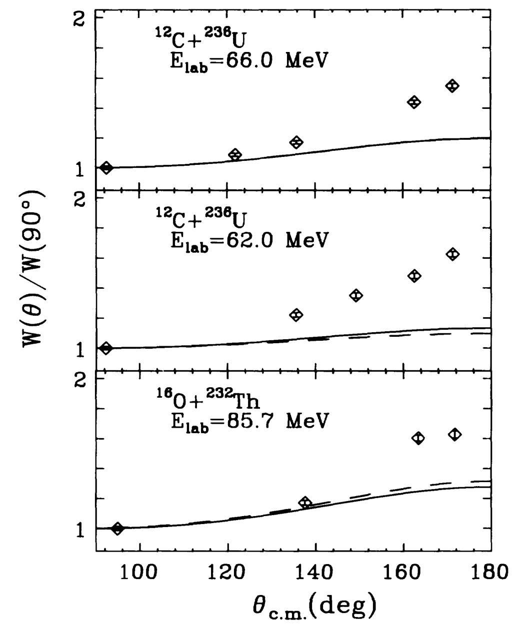

FIG. 1. Angular distributions at selected bombarding energies. The full and dashed curves are expectations based on models (Refs. 6 and 7) which incorporate the effects of the deformed target and which fit the excitation functions.

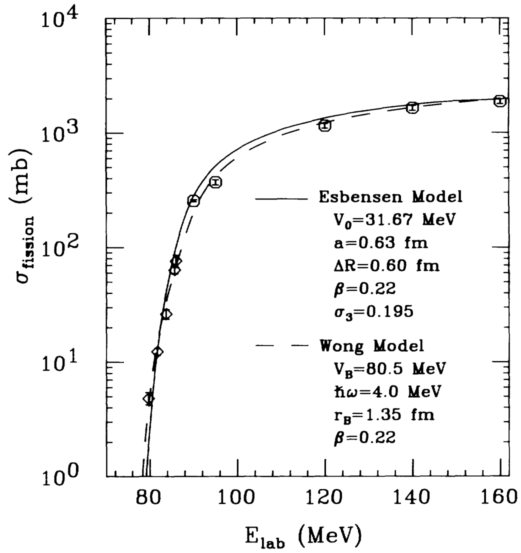

FIG. 2. Fission excitation functions for the $^{16}O + ^{232}Th$ reaction. The higher-energy points are from the work of Back *et al.* (Ref. 8). The full and dashed curves are a theoretical fit with the parameters indicated.

pies than expected, as will become apparent in the discussion that follows. The fission excitation function for $^{16}O + ^{232}Th$ is shown in Fig. 2. Also included in this figure are results obtained at higher energies by Back *et al.*[8] An excellent fit to this excitation function can be obtained by use of a model developed by Esbensen.[6] In this model the permanent quadrupole deformation as well as the zero-point motion associated with the octupole vibration is taken into account. The known deformation ($\beta = 0.22$) and $B(E3)/B_w(E3)$ values (29) of ^{232}Th were used. The nuclear potential is based on the proximity potential, with a slight adjustment to reproduce the barrier height. This model has been shown to be in good agreement with coupled-channels calculations[9] when the collective-motion time is long compared to the collision time, as is very well satisfied for these strongly deformed nuclei. Similar fits can be obtained by use of the Wong[7] model, which averages over the orientation dependence of the interaction potential for a permanently deformed nucleus, or a generalization of the Wong model by Back *et al.*[8] Thus there is nothing anomalous in the fusion excitation function, which exhibits the amount of enhancement expected. Similar fits are obtained for the $^{12}C + ^{236}U$ excitation function.

We have then used the spin distributions obtained from these models which reproduce the excitation function to calculate the expected angular distributions. This requires a knowledge of $K_0^2 = \mathscr{I}_{eff}T/\hbar^2$, which we deduce from the above-barrier $\alpha + ^{244}Cm$ anisotropy and a calculated spin distribution. Since in this case the bombarding energy is nearly twice the barrier energy, the spin distribution is not very sensitive to model assumptions. A Wong-model calculation or an optical-model calculation, with a 7% correction for fission following inelastic processes, gives similar values for $\langle I^2 \rangle$ of about $230\hbar^2$. From this value we deduce a K_0^2 parameter of 192 at a compound nuclear excitation energy of 36 MeV. (This leads to an $\mathscr{I}_0/\mathscr{I}_{eff}$ ratio of 0.77, for a level-density parameter of $a = A/8$.) This K_0^2 value is scaled slightly to account for the small variations in excitation energy and in the effective moment of inertia with spin, leading to values ranging from 215 for 85.7-MeV $^{16}O + ^{232}Th$ to 188 for 62-MeV $^{12}C + ^{238}U$. These values, together with the spin distribution from the Esbensen model or Wong model, lead to the full and dashed curves shown in Fig. 1. The similarity of the predictions of the two models may be related to the observation[10] that for certain model assumptions the distribution of spins populated by the fusion process is intimately connected to the fusion excitation function. Thus models based on similar assumptions will predict similar spin distributions if they describe the fusion excitation function properly. It can be seen that for either model the anisotropy is qualitatively underestimated. This appears to be an uniquely sub- or near-barrier phenomenon. At higher energies (e.g., 120 MeV) our procedure successfully reproduces the anisotropy reported by Back *et al.*[8] We note, however, that it is now recognized[11] that the anisotropies observed by Back *et al.* at their lowest energies can only be simulated by use of an artificially large deformation ($\beta = 0.46$) rather than the known value of $\beta = 0.22$. Thus, these results also point to a major discrepancy between experiment and theory as the barrier is approached.

In view of the very surprising nature of our results, we have looked very carefully for possible artificial causes of the discrepancy. One possible cause would be a significant contribution of incomplete fusion or sequential fission. Although such contributions would not be expected on the basis of the known energy-dependence systematics of these mechanisms, we have confirmed that full momentum transfer was achieved by measuring the folding-angle distribution of the coincident fragments at several energies and for both systems. We have also measured the fission-fragment mass distribution for the $^{12}C + ^{236}U$ reaction at 66 MeV and obtained a distribution whose shape is as expected for complete fusion, rather than the very asymmetric distribution expected for sequential fission following inelastic scattering. These results will be reported in further detail elsewhere.[12]

In order to illustrate the discrepancy with the theoretical models discussed and to facilitate comparison with possible new models, we show in Fig. 3 the $\langle I^2 \rangle$ values deduced from the experimental anisotropies. The error bars include both the statistical error in the angular distribution and the systematic error from the uncertainty in the K_0^2 value obtained from the $\alpha + ^{244}Cm$ reaction. Sample calculations indicate that corrections for spin distributions having different functional forms than the assumed distributions would be less than 10% and in a direction to increase the discrepancy with theoretical expectations. Also shown are mean square spin values calculated from various models. The deduced spin values are several times larger than expected, and appear to have saturated at a high value at the lowest energy studied.

We have also performed an experiment[12] to see if the unusually broad spin distributions are unique to deformed targets, as for example might be the case if Coulomb excitation played a dominant role. We have measured the fission-fragment angular distributions for sub-barrier fusion of ^{16}O and ^{208}Pb. The interpretation of these results is less quantitative because of the necessity of using a model calculation of the transition-state moment of inertia, but the mean square spin values deduced are considerably larger than given either by the Esbensen model or by a coupled-channels calculation.[13]

We do not presently understand the origin of the discrepancy between the expected and observed mean spin values. In order to have a complete understanding of sub-barrier fusion cross-section enhancements it is necessary to be able to account for the spin distributions as well as the cross sections. We hope that these results will stimulate further work in this direction.

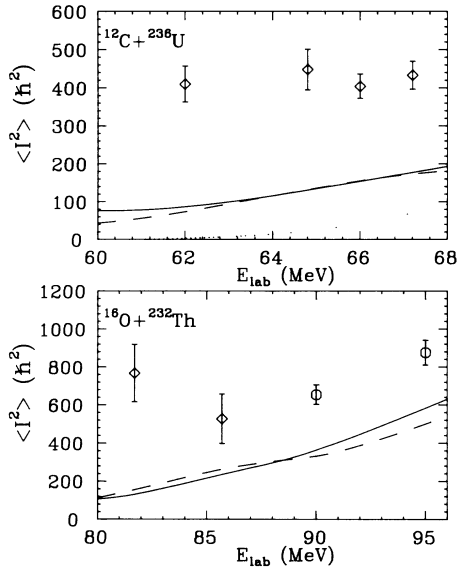

FIG. 3. Mean square spin values deduced from fission-fragment angular distributions as a function of bombarding energy. The full and dashed curves are based on the Esbensen and Wong models, respectively. The dotted curve is based on the observed total fusion cross section together with the sharp-cutoff approximation and is shown to provide a frame of reference.

We thank Gorm Nykreim for performing some of the model calculations. This work was supported in part by the U.S. Department of Energy.

[1]R. Vandenbosch *et al.*, Phys. Rev. C **28**, 1161 (1983).

[2]P. J. Nolan *et al.*, Phys. Rev. Lett. **54**, 2211 (1985).

[3]B. Haas *et al.*, Phys. Rev. Lett. **54**, 398 (1985).

[4]S. Gil *et al.*, Phys. Rev. C **31**, 1752 (1985).

[5]R. F. Reising, G. L. Bate, and J. R. Huizenga, Phys. Rev. **141**, 1161 (1966).

[6]H. Esbensen, Nucl. Phys. **A352**, 147 (1981).

[7]C.-Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).

[8]B. B. Back *et al.*, Phys. Rev. C **32**, 195 (1985).

[9]H. Esbensen, Jian-qun Wu, and G. F. Bertsch, Nucl. Phys. **A411**, 275 (1983).

[10]K.-H. Schmidt *et al.*, in *Proceedings of the International Conference on Fusion Reactions below the Coulomb Barrier, Cambridge, Massachusetts, 1984,* edited by S. G. Steadman, Lecture Notes in Physics Vol. 219 (Springer, Berlin, 1985); W. Reisdorf *et al.*, Nucl. Phys. **A438**, 212 (1985); C.-C. Sahm *et al.*, Nucl. Phys. **A441**, 316 (1985).

[11]B. B. Back *et al.*, Phys. Rev. C **33**, 385(E) (1986).

[12]T. Murakami, C.-C. Sahm, R. Vandenbosch, D. D. Leach, A. Ray, and M. J. Murphy, to be published.

[13]S. C. Pieper, M. J. Rhoades-Brown, and S. Landowne, Phys. Lett. **162B**, 43 (1985).