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Anomalous anisotropies of fission fragments for the $^{16}O+{}^{232}Th$ sub-barrier fusion-fission reaction

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Fission cross sections and angular distributions have been measured for the $^{16}O+{}^{232}Th$ reaction at the bombarding energies from 76 to 86 MeV. The fission excitation function is rather well reproduced on the basis of the Wong model. However, the model that reproduces the enhancement observed in the sub-barrier fusion excitation function fails to account for the experimental anisotropies. It is found that the observed anisotropy is much larger than expected, and as a function of center-of-mass energy it exhibits a peak around 76 MeV with a width (FWHM) of 3.7±0.5 MeV. A comparison with our previous data of $^{19}F+{}^{232}Th$ reaction reveals that the anomaly is strongly related to the nuclear structure property of the projectile nucleus.

I. INTRODUCTION

The near- and sub-barrier fusion of heavy ions is an important process of nuclear reaction which has captured the great interest of many nuclear physicists because of the observations of the significant enhancement[1] of fusion cross sections as compared to one-dimensional barrier penetration calculations. It seems that the enhancement of fusion cross sections has been explained rather satisfactorily on the basis of the coupled-channels theory.[2] This theoretical explanation has met some support from the measurements[3] of the moments of angular momentum, which revealed the spin distribution broadening of compound system formed at the energies near the Coulomb barrier. Apart from the enhancement observed, Vandenbosch *et al.*[4] and Zhang *et al.*[5] have reported the anomalous anisotropies of the angular distributions of fission fragments resulting from the heavy-ion-induced fusion-fission reactions at near- and sub-barrier energies. It is obvious that the broadening of the spin distributions is also in favor of increasing the anisotropy of fission-fragment angular distributions, which is calculated in terms of the transition state theory with the transmission coefficients extracted from the calculation of the fusion excitation function. However, the models that are able to explain the enhancement of the fusion cross sections and obtain the broader spin distributions of compound nuclei still fail to account for the fission-fragment angular distribution data,[4,5] especially the bump[5] in the anisotropies as a function of center-of-mass energy.

The anomaly observed in the angular distribution of sub-barrier fusion-fission reactions puts forward an intriguing puzzle. It is, therefore, meaningful to extend a systematical survey of the sub-barrier fusion-fission reactions. In this paper, we present our experimental results of the fission cross sections and fission-fragment angular distributions for the $^{16}O+{}^{232}Th$ fusion-fission reaction which we have extended the measurement to lower energies than Ref. 4. It is interesting to notice that as a function of center-of-mass energy, the anisotropies observed in this reaction system exhibit a peak around 76 MeV, which has not been previously observed in Ref. 4. In addition, our experimental results continue to show the anisotropies greater than the theoretically expected results.

One may wonder if the sequential fission following transfer would be responsible for the anomalous anisotropies. Recently, Lestone *et al.*[6] have reported the experimental results of fission angular distributions following transfer reactions for the ^{232}Th + ^{16}O system. Their results show that the effect of transfer fission on the observed anisotropies is minimal. We will quote their data in our discussion.

The outline of the paper is as follows. In Sec. II the experimental procedure is described. The experimental results are presented and analyzed in Sec. III, and a discussion and summary are given in Sec. IV.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at HI-13 tandem Van de Graaff accelerator of the Institute of Atomic Energy, Beijing. The experimental arrangement is similar to Ref. 5. A ^{232}Th target of thickness 250 $\mu g/cm^2$ was bombarded by a collimated ^{16}O beam with a spot size on the target of ≈ 2 mm in diameter. Fission fragments were detected by a mica track detector[7] spanning the laboratory angular range between 79° and 171°. The distance between the target and the mica, which was placed on the inner surface of a stainless steel cylinder, was 4 cm. In order to discriminate the background, the mica was pre-etched before irradiation. Two surface-barrier-semiconductor detectors were set at $-40.8°$ and $+19°$ from the beam, respectively, as monitors to detect the elastic scattering. The solid angles subtended by the semiconductor detectors were determined using a standard ^{241}Am alpha source. A quartz plate that was placed at the target position was used to check the beam position and profile. In addition, the counting ratios between the two monitors and the Faraday cup counting rates indicated the beam quality during the period of the measurement. After irradiation, the mica was etched in 40% HF at 25 °C for 1.5 h and scanned under a microscope with 10×40 magnification. The mica detector is, due to its detection threshold, insensitive to the reaction products with

$Z \leq 10$. The tracks of other projectilelike products with $Z > 10$ can be distinguished clearly from fission fragments by the track size and depth. The number of the fission-fragment tracks in an area 1 mm wide × 5 mm high of mica were counted to obtain the fission-fragment counts within successive bias angle. The corresponding angular resolution was 1.4° (including the divergence and spot size of the beam). The total fission cross sections were obtained by integrating the angular distributions and normalizing to the cross sections for Rutherford scattering. In the transformation from the laboratory to the center-of-mass frame of reference we used the kinematics relevant for symmetric fission with the kinetic energy taken from Viola's systematics.[8] The experimental errors include the counting statistics, the uncertainties of the angle, the solid angle, the extrapolation of the angular distribution and transformation of the reference systems, etc. The total uncertainties of the angular distribution data range between 2.4% and 3.7%, while for the fission cross sections, between 6% and 14%.

III. EXPERIMENTAL RESULTS

A. Fission excitation function

The fission excitation function of the $^{16}O + ^{232}Th$ reaction has been measured in the energy range from 70.8 to 80.1 MeV in the center-of-mass frame and the results are shown in Fig. 1. The data represented by the pulses, solid triangles, and circles are the experimental results of Back *et al.*,[9] Vandenbosch *et al.*,[4] and ours, respectively. The dotted and dashed curves in the figure are resulting from the Wong model[10] calculations with deformation β_2 and without deformation, respectively. The input parameters are $V_b = 80.5$ MeV, $\hbar\omega_b = 4.0$ MeV, $r_b^0 = 1.35$ fm, and $\beta_2 = 0.22$. When the deformation of the target nucleus is properly taken into account, the agreement between the experimental and theoretical fission excitation function is satisfactory over the whole energy range. The transmission coefficients T_l for each bombarding energy were obtained from this calculation.

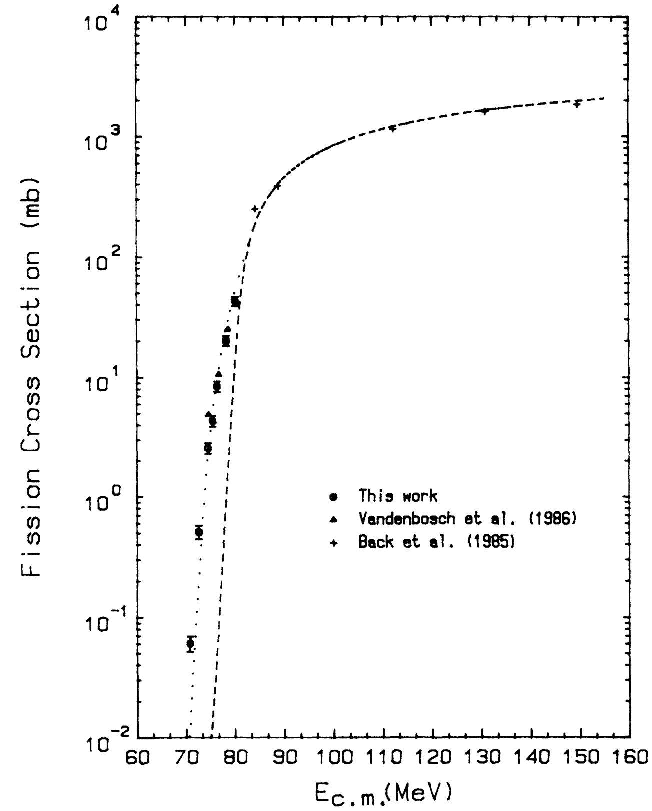

FIG. 1. Fission excitation function for the $^{16}O + ^{232}Th$ fusion-fission reaction. The dotted and dashed curves are the theoretical calculations of the Wong model with $\beta_2 = 0.22$ and $\beta_2 = 0$, respectively.

B. Fission-fragment angular distributions

The fission-fragment angular distributions of the $^{16}O + ^{232}Th$ reactions have been measured at the center-of-mass energies 72.6, 74.5, 75.4, 76.4, 78.2, and 80.1 MeV. The results are shown in Fig. 2 as solid triangles. Under the assumption that a compound nucleus is formed which decays subsequently only by fission, the statistical transition state model for the fission angular distribution is

$$W(\theta) = \pi \lambda\!\!\!^{-2} \sum_{l=0}^{\infty} (2l+1) T_l \sum_{k=-l}^{l} 0.5(2l+1) |d_{0k}^{l}(\theta)|^2 \exp(-k^2/2k_0^2) / \sum_{k=-l}^{l} \exp(-k^2/2k_0^2) , \quad (1)$$

where the transmission coefficients T_l, extracted from the calculation of excitation function. The distribution of K values is a Gaussian with a standard deviation $K_0^2 = J_{\rm eff} T/\hbar^2$ which is related to the nuclear temperature T and the effective moment of inertia $J_{\rm eff} = J_{\parallel} J_{\perp}/(J_{\perp} - J_{\parallel})$ at the saddle point. $J_{\parallel}$ and $J_{\perp}$ are the moments of inertia rotating around the symmetric axis and perpendicular axis, respectively. The temperature T is calculated as $T = (E_x - B_f - E_{\rm rot})/a$ with a level-density parameter of $a = A/8$; here A and E_x are the mass number and the excitation energy of the fissioning nucleus, B_f is the height of fission barrier, and $E_{\rm rot}$ the rotational energy at the saddle point. The solid and dashed curves in the figure are the theoretical calculations with the T_l values obtained from the reproduction of the excitation function with the Wong model, and the K_0^2 values from the $\alpha + ^{244}Cm$ reaction[11] and the Sierk model,[12] respectively. For the K_0^2 from the $\alpha + ^{244}Cm$ reaction, we deduce $J_{\rm eff}$ value from the K_0^2 data[4] which was extracted from the fission-fragment angular distribution of the $\alpha + ^{244}Cm$ reaction. Under the assumption that J_{eff} does not obviously vary with excitation energy and spin, we have calculated K_0^2 values with the relation of $K_0^2 = J_{eff}T/\hbar^2$ for the $^{16}O + {}^{232}Th$ system. The K_0^2 values obtained are in the range of 187 for 70.7 MeV to 215 for 80.1 MeV. It may be seen from the figure that the experimental angular distributions are much more anisotropic than the theoretical ones.

C. Anisotropy of fission-fragment angular distributions

In order to illustrate systematically the discrepancy between the observations and predictions, the anisotropies as a function of the center-of-mass energy are shown in Fig. 3. The circles, solid triangles, and pulses in the figure are the experimental data of Back *et al.*,[9] Vandenbosch *et al.*,[4] and ours, respectively. The anisotropies of Vandenbosch were deduced from the $\langle l^2 \rangle$ values in Fig. 3 of Ref. 4 in terms of the relation of these two quantities which we will discuss later.

The solid and dotted curves present the calculations based on the transition state theory with T_l values from the Wong model and the J_{eff} values extracted from the $\alpha + {}^{244}Cm$ reaction and Sierk model, respectively. It can be seen in the figure that the two calculations are very similar over our measured energy range. The most striking feature of the data is a peak in the anisotropy centered near 76 MeV with the width (FWHM) of 3.7 ±0.5

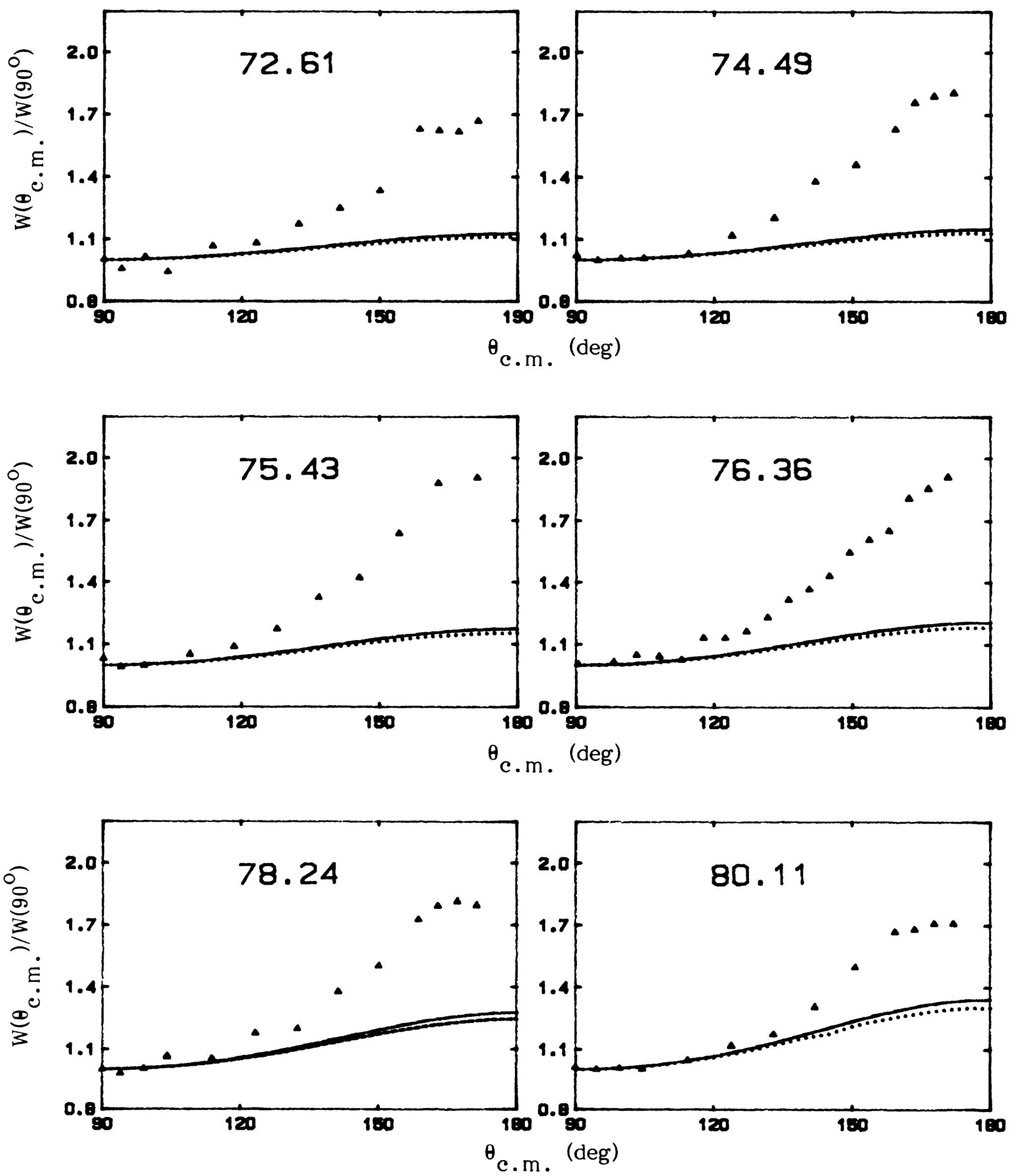

FIG. 2. Fission-fragment angular distributions for the $^{16}O + {}^{232}Th$ fusion-fission reaction. The solid triangles are our experimental results. The solid and dotted curves are the calculations in terms of the transition state theory using the transmission coefficient values T_l from the Wong model and K_0 values extracted from the $\alpha + {}^{244}Cm$ reaction and Sierk model, respectively. The numbers in the figure are the center-of-mass energies.

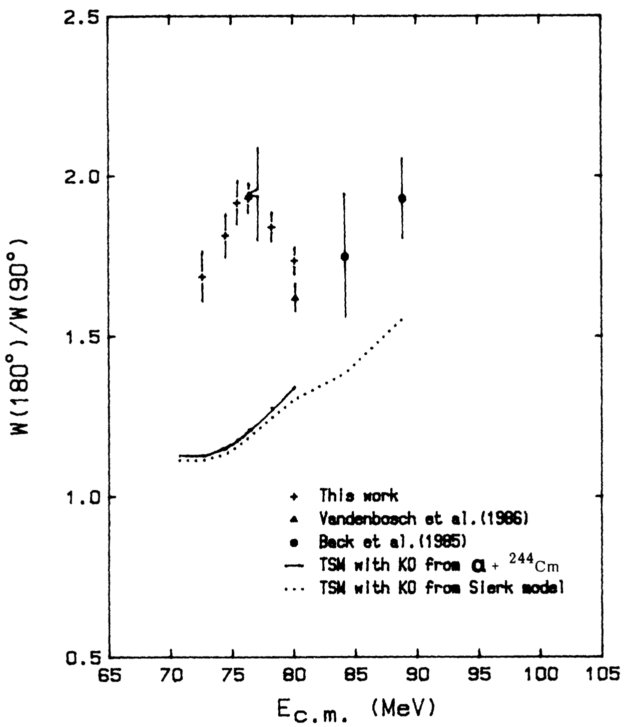

FIG. 3. Fission-fragment anisotropies as a function of center-of-mass energy for the ^{16}O + ^{232}Th.

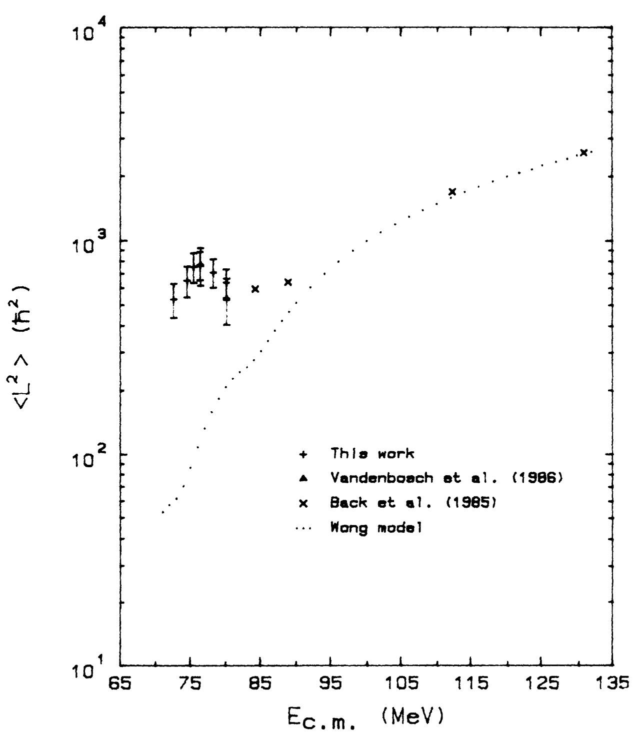

FIG. 4. Comparison of mean-square spin values deduced from experimental fission-fragment anisotropies with the theoretical calculation.

MeV. Also the experimental anisotropies are obviously greater than expected.

The anisotropy of the fission-fragment angular distribution could be characterized by the approximate relation

$$W(180°)/W(90°) \approx 1 + \langle l^2 \rangle / 4K_0^2 \ , \qquad (2)$$

for the values of $l_m^2/4K_0^2$ not much larger than unity, where l_m and $\langle l^2 \rangle$ are the maximum spin and mean-square spin of the compound system, respectively. In our case, the prerequisite for the approximate relation (2) is satisfied. A measured anisotropy therefore determines the ratio $\langle l^2 \rangle / K_0^2$. If the K_0^2 values are known, the information about the spin distributions of the compound system could be inferred from the anisotropy of the fission-fragment angular distribution. We take the K_0^2 values from the $\alpha + {}^{244}Cm$ reaction. The mean-square spin values, $\langle l^2 \rangle$, of the compound system were deduced from the experimental anisotropies and they are shown in Fig. 4 as the pluses. The solid triangles and crosses denote the experimental data of Vandenbosch *et al.*[4] and Back *et al.*,[9] respectively. The dotted curve is the expectation based on the Wong model, which reproduced the excitation function. It seems that the present approaches fail to account for the spin distributions of the compound nucleus ^{248}Cf formed at near- and sub-barrier energies.

IV. DISCUSSION AND SUMMARY

It is not clear about what is responsible for the anomalous anisotropies of the fission-fragment angular distributions observed in the near- and sub-barrier fusion-fission reactions. One of the possibilities might be that the reaction mechanisms other than the complete fusion-fission reaction, for example, the sequential fission following transfer[13,14] and/or deep inelasticlike reactions, might be at work in the near- and sub-barrier energies. Apart from the difference of the excitation energies, the effective moment of inertia J_{eff} for fissioning nucleus formed in the transfer reaction is smaller than the one from complete fusion. So, the transfer fission can have large anisotropies when appropriate reaction Q values are involved. Lestone *et al.*[6] have measured the fragment angular distributions of fission following transfer for the ^{16}O + ^{232}Th system at energies of 86 and 90 MeV. The distributions for a given scattering angle are strongly peaked forward and backward of the recoil direction. However, when all recoil angles are considered, the integrated angular distributions for transfer fission relative to the beam direction, have anisotropies of $A_B^T = 1.3$ and 1.2 for 86 and 90 MeV, respectively, which are less pronounced than that observed when both fusion-fission and transfer-fission reactions are included in the measurement. Thus removing the effects of transfer has little effect on the total fission-fragment angular distributions. Indeed the anisotropy becomes larger by 5% for 86 MeV and anomalously large mean-square spin values still persist. However, the detailed energy dependence of the fraction of the total fission arising from transfer, as well as anisotropies for the fusion-fission and for the transfer-fission reactions are all unknown from the experiment in the range of lower

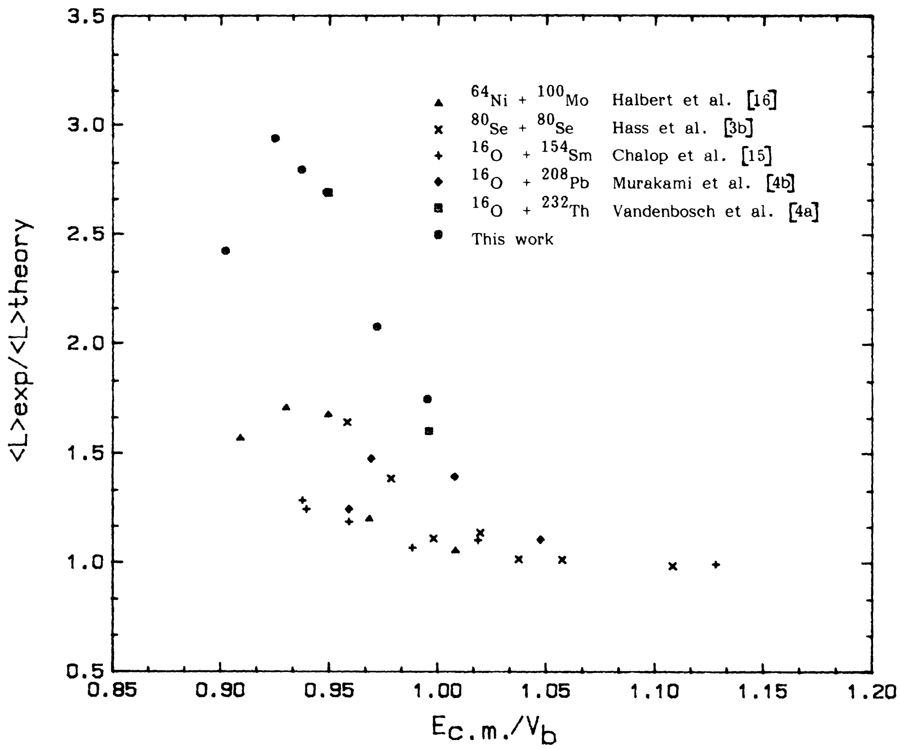

FIG. 5. Comparison of ratio of experimental to theoretical mean spin values (or ratio of rms values in case of fission angular distribution) as a function of ratio of center-of-mass energy to barrier energy.

energy. At present it is still not possible to exclude the transfer fission as an origin of the anomaly.

The mean-square spin values $\langle l^2 \rangle$ deduced from fission-fragment angular distributions are much larger than expected ones, extracted from the excitation function calculation, as shown in Fig. 4. From this fact, and if the effects of the reaction mechanisms other than complete fusion-fission reaction could be neglected, one would wonder if there might be something wrong with the sub-barrier fusion reaction models in the entrance channel and/or the transition state theory, at the saddle point in the fission exit channel for the sub-barrier heavy-ion reactions.

It is quite appealing to compare the different measurements of spin distribution, for example, the gamma multiplicity or fission angular distribution measurements. Following Charlop *et al.*,[15] we have compared the first[3,16] or second[4,5] moments of spin distribution with theoretical expectation in Fig. 5. A common thing to all systems shown is that the experimental spin distributions are much broader than the model predictions at sub-barrier energy, even though those model calculations have been made to fit the fusion excitation functions. It is possible that this discrepancy is a rather common phenomenon at least for medium heavy and heavy systems.

A comparison of our present data with our previous data of the $^{19}F + ^{232}Th$ reaction[5] is very natural and interesting. For this, the anisotropies versus center-of-mass energy are plotted for both reaction systems in Fig. 6. The $^{16}O + ^{232}Th$ reaction system is the second case we have observed which exhibits a peak in the anisotropy as a function of center-of-mass energy. It indicates that this

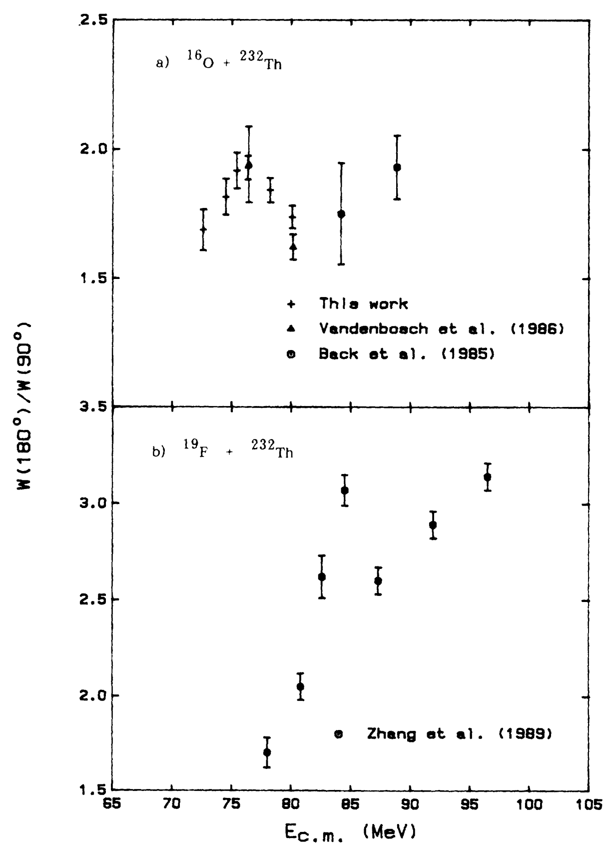

FIG. 6. Comparison of fission-fragment anisotropies as a function of center-of-mass energy for the $^{16}O + ^{232}Th$ with the $^{19}F + ^{232}Th$ fusion-fission reaction.

anomaly structure might be rather general behavior, and therefore is of essential physical significance. The main difference one might note between the two systems is that the magnitude of anomaly is much larger for the $^{19}F + ^{232}Th$ system than for the $^{16}O + ^{232}Th$ system. As to the former system the projectile ^{19}F is an odd Z nucleus, while projectile ^{16}O of the latter system is a spherical magic nucleus. It might imply that the anomalous peak is strongly related to the nuclear structure properties of the reaction partners.

In summary we have measured fission cross sections and angular distributions to energies considerably lower than Coulomb barrier for the $^{16}O + ^{232}Th$ reaction. The fission excitation function is well reproduced on the basis of the Wong model with the static deformation of target. However, the measured fission-fragment angular distributions are much more anisotropic than the predicted ones. Moreover, the anisotropies as a function of center-of-mass energy show a peak around 76 MeV with a width (FWHM) of 3.7 ±0.5 MeV.

Up to now, the origins responsible for the anomalous anisotropies observed in the near- and sub-barrier heavy-ion fusion-fission reactions have not been found yet.

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