Systematic Study of Anomalous Fragment Anisotropies in Near- and Sub-barrier Fusion-fission Reactions

H. Q. Zhang,* Z. H. Liu, J. C. Xu, M. Ruan, C. J. Lin, and X. Qian
China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China

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The fission cross sections and fragment angular distributions for the complete fusion-fission reactions of $^{11}B + ^{238}U, ^{237}Np$, $^{12}C + ^{237}Np$, $^{16}O + ^{232}Th, ^{238}U$, and $^{19}F + ^{232}Th$ at near- and sub-barrier energies have been measured by the fragment folding angle technique. It is revealed that the anomalous anisotropies of fission fragments in latter three systems are existence. Based on the experimental observations and Døssing and Randrup's theory, a new version model of preequilibrium fission is put forward to explain the anomaly.

1. Introduction

We have succeeded in separating complete fusion-fission (FF) and transfer fission (TF) events by the fragment folding angle technique.[1] The fission cross sections and fragment angular distributions for the FF reactions of $^{11}B + ^{238}U, ^{237}Np$, $^{12}C + ^{237}Np$, $^{16}O + ^{232}Th, ^{238}U$, and $^{19}F + ^{232}Th$ at near- and sub-barrier energies have been measured. It is found that standard theories can reproduce the experimental data for the former three systems, but not simultaneously explain both fusion-fission excitation functions and fragment anisotropies for the rest systems. In the latter case, the experiments provided the conclusive evidence of anomalous anisotropies of fission fragments in near- and sub-barrier FF reactions. The comparison of $^{11}B + ^{237}Np$ and $^{16}O + ^{232}Th$ gave strict evidence of the entrance-channel dependence of fragment anisotropies. Based on the experimental observation and the model presented by Døssing and Randrup,[2] we put forward a new version model of preequilibrium fission[3] to explain this anomaly.

2. Experimental Procedure

The experiments were carried out using the collimated ^{11}B, ^{12}C, ^{16}O, and ^{19}F beams from HI-13 tandem accelerator at CIAE. The ^{232}Th, ^{238}U, and ^{237}Np targets were about 350 $\mu g/cm^2$ thickness. Fission fragments were detected by two X-Y position sensitive double grid avalanche counters (DGAC) with an active area of 25 cm $\times$ 20 cm, placed at either side of the beam. The distances from the centers of these counters to the target were 15 cm (forward counter) and 16 cm (backward counter), and the corresponding angle coverages were $10^\circ \le \theta_{Lab} \le 90^\circ$ and $-75^\circ \le \theta_{Lab} \le -160^\circ$, respectively. According to the fragment folding angle distributions,[1] the FF events were successfully separated from the TF events. A Si(Au) detector was placed at -20° relative to the beam direction as a monitor to detect the elastic scattering. The measured FF angular distributions were fitted and extrapolated to 180° in terms of the Legendre polynomial with the even terms up to $P_6(\cos\theta)$, and the corresponding fragment anisotropies, A_{exp}, were obtained. The FF cross sections were achieved by integrating the Legendre polynomial and normalizing to the Rutherford scattering cross sections.

3. Experimental Results

3.1. Fusion-fission Excitation Functions. The experimental complete fusion-fission excitation functions for all six systems[4] can be well reproduced by the CCDEF code calculations considering the nuclear static deformations and inelastic channels couplings, as shown in Figure 1. For each bombarding energy, the compound nuclei angular momentum distributions $\sigma_F(J)$ and their mean square angular momentum $\langle J^2 \rangle_{theory}$ were obtained from these calculations.

3.2. Anisotropies of FF Angular Distributions. The anisotropy of the FF fragment angular distribution $W(\theta)$ is defined as $A_{exp} = \frac{W(180^\circ)}{W(90^\circ)}$. The anisotropy A is characterized by the approximate relation,

$$A_{theory} = 1 + \frac{\langle J^2 \rangle}{4K_0^2}. \tag{1}$$

In the calculation of the saddle-point transition statistic (SPTS) model, the K distribution is Gaussian with a variance

$$K_0^2 = I_{eff} T_{sad}/\hbar^2, \tag{2}$$

where the effective moment of inertia $I_{eff} = I_\parallel I_\perp/(I_\perp - I_\parallel)$, and $I_\parallel$ and $I_\perp$ are the moments of inertia rotating around the symmetric and perpendicular axes of the nucleus at the saddle point, respectively. The K is the projection of angular momentum J on the symmetric axis of fissioning nucleus. T_{sad} is the nuclear temperature at the saddle point,

$$T_{sad} = \left[\frac{E_{c.m.} + Q - B_f(J) - E_n}{A_{CN}/8}\right]^{1/2}, \tag{3}$$

where Q and $B_f(J)$ are the reaction Q value and the fission barrier height, respectively. The B_f, $I_\parallel$ and $I_\perp$ can be calculated in terms of the rotating finite-range model (RFRM). A_{CN} is the mass number of the composite system and E_n the energy carried away by the pre-saddle fission neutrons.

The dependence of the ratio, A_{exp}/A_{theory} versus $E_{c.m.}/V_B$ for all six systems[4] is shown in Figure 2. Where $E_{c.m.}$ is center-of-mass energy and V_B the fusion barrier. In the figure, α is the entrance-channel mass asymmetry defined as $\alpha = \frac{A_T - A_P}{A_T + A_P}$, α_{BG} the Businaro-Gallone critical mass asymmetry and about 0.9 for the range of nuclei studied. The reaction systems with α in different side of α_{BG} have different characters. It can be seen from the figure that the A_{exp} are in general agreement with A_{theory} for the $\alpha > \alpha_{BG}$ reaction systems of $^{11}B + ^{238}U, ^{237}Np$ and $^{12}C + ^{237}Np$. But for the $\alpha < \alpha_{BG}$ systems, A_{exp} are obviously larger than A_{theory} at sub-barrier energy whereas trends to A_{theory} at energy above the barrier. Therefore, the present experiments have provided the conclusive evidence of anomalous anisotropies for the $\alpha < \alpha_{BG}$ systems in near- and sub-barrier FF reactions.

We compared the anisotropy data of $^{11}B + ^{237}Np$ ($\alpha = 0.91$) and $^{16}O + ^{232}Th$ ($\alpha = 0.87$) both of which form the same compound nucleus ^{248}Cf at the same excitation energies but α is on the different side of α_{BG}.[3] The results show that there exists great difference in anisotropy between the two systems, as shown in Figure 3. The experiment provides a strict evidence of the entrance-channel dependence of anisotropies in FF reactions. It indicates that non-compound-nucleus fission with

*Corresponding author. E-mail: huan@iris.ciae.ac.cn. FAX: +86-10-6935-7787.

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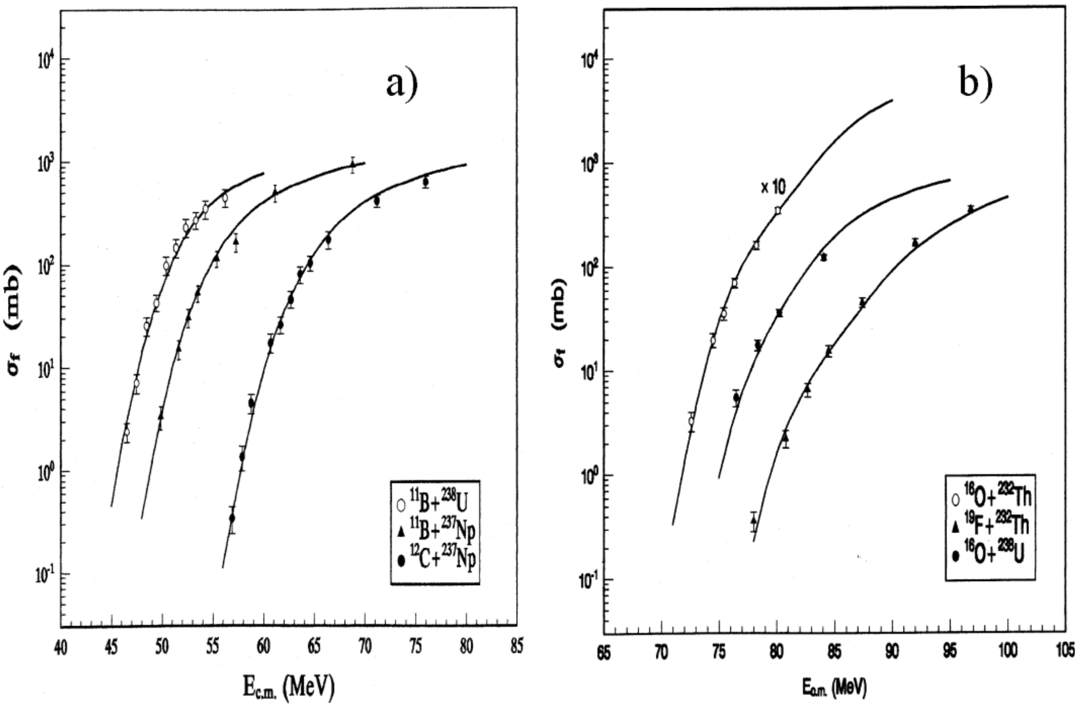

Figure 1. Fusion-fission excitation functions for all six systems. The solid curves are the results of the CCDEF code calculations.

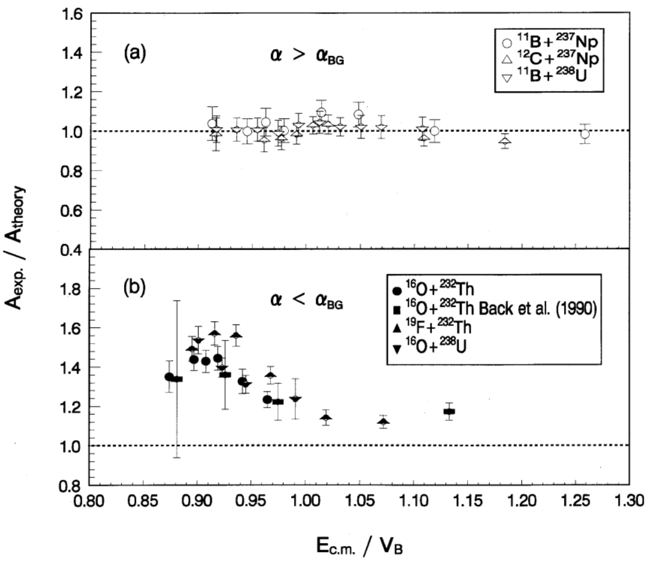

Figure 2. $A_{\text{exp}}/A_{\text{theory}}$ versus $E_{\text{c.m.}}/V_B$ for all six systems.

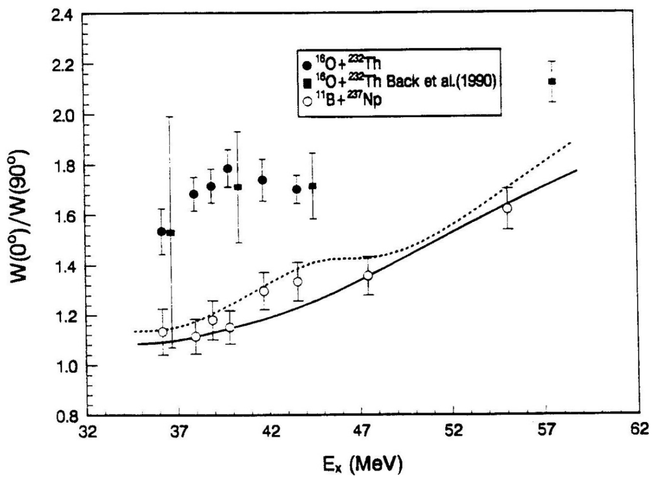

Figure 3. Comparison of anisotropy data of $^{11}B + ^{237}Np$ and $^{16}O + ^{232}Th$ systems. The solid and dashed lines are the predictions of SPTS for $^{11}B + ^{237}Np$ and $^{16}O + ^{232}Th$, respectively.

memory of the entrance channel for the systems with $\alpha < \alpha_{BG}$ is originally responsible for the anomalous anisotropies observed at near- and sub-barrier energies.

4. Preequilibrium Fission Model for Low Angular Momentum

As pointed out by Ramamurthy et al.,[5] a characterized evidence of preequilibrium fission would show the entrance-channel dependence of fragment anisotropies for target-projectile combination across the Businaro-Gallone ridge in mass degree of freedom. This is clearly verified by our experiments. We mentioned in our previous work[3,4] that, in some cases, the relaxation time of K degree of freedom may be larger than fission lifetime. If the relaxation process of K is taken into account, the variance of K distribution, σ_K^2 can be expressed as,

$$\sigma_K^2 = K_0^2\left[1-\exp(-t/\tau_K)\right], \tag{4}$$

where τ_K is the relaxation time of K degree of freedom and K_0^2 the statistical equilibrium value of σ_K^2, assuming equilibrium at the saddle point. Døssing and Randrup[2] studied the dynamical evolution of angular momentum in damping nuclear reactions and derived the coupled equations which governed the evolution of K distribution. They have gotten the expression of τ_K depending on the rotational frequency ω_R. Under some approximations,[3,4] the variance equation for preequilibrium (quasi) fission was obtained,

$$\sigma_K^2(J) = K_0^2\left[1-\exp(-gJ^2)\right], \tag{5}$$

where $g = 2.238 I_\parallel^2/(I_\perp^2 I_{eff})$. The constant 2.238 MeV^{-1} was obtained by using Back's experimental fragment anisotropy and mean square angular momentum data[6] at $E_{\text{c.m.}} = 94.1$ MeV for the $^{16}O + ^{232}Th$ fusion-fission reaction.

The A_{theory} values for the $^{16}O + ^{232}Th$,^{238}U and $^{19}F + ^{232}Th$ systems with $\alpha < \alpha_{BG}$ were recalculated with eq 5 and compared with the experimental data. The results for other three systems with $\alpha > \alpha_{BG}$ were calculated by the SPTS model. All the results are displayed in Figure 4. It is evident in the figure that the theoretical predictions of the fragment anisotropies are in general agreement with the measured ones. Therefore, the anomalous anisotropies of fission fragments in near- and sub-barrier FF reaction systems with $\alpha < \alpha_{BG}$ are successfully explained by means of our preequilibrium fission model.

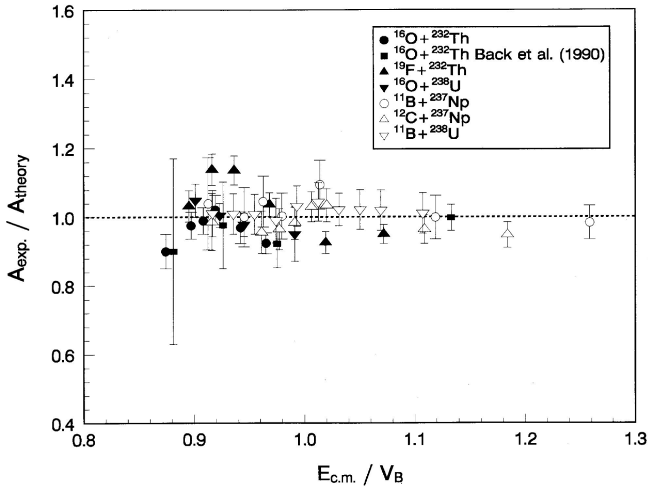

Figure 4. Same as Figure 2 but A_{exp}/A_{theory} are recalculated for the $\alpha < \alpha_{BG}$ systems.

5. Summary

In this work, we have successfully separated the FF and TF events in terms of the fragment folding angle technique, and measured the FF cross sections and fragment angular distributions for the $^{11}B + ^{238}U, ^{237}Np$, $^{12}C + ^{237}Np$, $^{16}O + ^{232}Th, ^{238}U$, and $^{19}F + ^{232}Th$ systems at near- and sub-barrier energies. All the experimental fusion-fission excitation functions can be well reproduced by the coupled-channels theory. As for the fragment anisotropies, the experimental data clearly show the entrance-channel dependence for target-projectile combination across the Businaro-Gallone ridge. Based on the observation and Døssing and Randrup's theory, we put forward a new version model of preequilibrium fission to solve the anomalous anisotropy problem.

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