Systematic study of anomalous fragment anisotropies in subbarrier complete fusion-fission reactions*

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Abstract The complete fusion-fission is separated from the transfer-induced-fission with the fragment folding angle technique. The 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. The present fusion and fission standard models can reproduce both the excitation functions and the fragment anisotropies for the systems of $^{11}B+^{238}U(^{237}Np)$ and $^{12}C+^{237}Np$; but fail to explain both the experimental data for the other 3 systems simultaneously. The evidence of the entrance-channel dependence of fission-fragment anisotropies is revealed by comparison of the $^{11}B+^{237}Np$ and $^{16}O+^{232}Th$ data. Based on the observations, a new version model of preequilibrium fission is put forward to explain the anomaly.

Keywords Complete fusion-fission reactions, Fragment anisotropies, Entrance-channel dependence, Transfer-induced fission, Preequilibrium fission

1 Introduction

The angular momentum distributions or its momenta in sub-barrier fusion reactions have recently been reviewed.[1,2] It was found that the coupled channel theory could give a reasonable self-consistent account for both fusion excitation functions and angular momentum for all fusion-evaporation reactions except the $^{64}Ni+^{100}Mo$ and $^{80}Se+^{80}Se$. Very recently, a good agreement between the experimental data and theoretical calculations was obtained for both excitation function and angular momentum distributions for $^{64}Ni+^{100}Mo$.[3,4] As for the fusion-fission reactions, although the experimental fusion excitation function can be reproduced with theoretical model, the saddle-point transition state model (SPTS) fails to predict the measured mean square angular momentum $<J^2>_{exp}$, which have been deduced from the measured fragment anisotropies.[5-9] This discrepancy has become a great open problem in sub-barrier fusion study. Actually, in comparison between model calculations and measurements, it was assumed on one hand that compound nucleus formed subsequently decays only by fission; on the other hand, except Back's experiment,[10] the all previous experimental measurements included the complete fusion-fission (CFF) and the transfer-induced-fission (TF) at near- and sub-barrier energies. In order to have a sound basis for the comparison and to elucidate the origin of discrepancy, it is necessary to exclude the TF events and to obtain the CFF data. Using the fragment folding angle technique, we have succeeded in separating CFF and TF, and measured CFF cross sections and fragment angular distributions for $^{11}B+^{238}U(^{237}Np)$, $^{12}C+^{237}Np$, $^{16}O+^{232}Th(^{238}U)$ and $^{19}F+^{232}Th$ at near- and sub-barrier energies. The experimental CFF excitation functions for all 6 systems can well be reproduced by the coupled-channel theory (CCDEF code[11]). The SPTS model can explain the fragment anisotropies for $^{11}B+^{238}U(^{237}Np)$, and $^{12}C+^{237}Np$, but not for $^{16}O+^{232}Th(^{238}U)$ and $^{19}F+^{232}Th$. In the latter case, the experiments have provided the conclusive evidence of anomalous anisotropies of fission fragments in sub-barrier CCF reactions. By comparison of the anisotropy data of $^{11}B+^{237}Np$ and $^{16}O+^{232}Th$, a strict evidence of the entrance-channel dependence of

*The Project Supported by National Natural Science Foundation of China under Contract No.19275067 and National Nuclear Industry Science Foundation of China under Contract No.Y41201926001
Manuscript received date:1996-06-20

fragment anisotropies is obtained. Based on the experimental observations and guided by the model presented by DØssing and Randrup[12], We have put forward a new version model of preequilibrium fission to explain this anomaly.

2 Experimental procedures

The experiments were performed 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 350μg/cm^2 thick. A Si(Au) detector was placed at -20° relative to the beam direction as a monitor to detect the elastic scattering. Fission fragments were detected by two $x-y$ position sensitive double grid avalanche counters (DGAC) with an active area of 25 cm × 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) with corresponding angle coverages of $10° \le \theta_{\rm lab} \le 90°$ and $-75° \le \theta_{\rm lab} \le -160°$, respectively. According to the difference of the fragment folding angle distributions, the CFF events were successfully separated from the TF. The CCF angular distributions for all 6 systems at near- and sub-barrier energies have been measured. In the process of data treatments, a cut of a horizontal slice of 4 cm was made in the center region of the forward DGAC, and the condition of $(\theta_{F1})_{\rm c.m.} + (\theta_{F2})_{\rm c.m.} = 180° \pm 2°$ for each event was required. Here, $(\theta_{F1})_{\rm c.m.}$ and $(\theta_{F2})_{\rm c.m.}$ are the emitting angles of the detected particles in center-of-mass system. It is very important to set rather strict conditions to rule out the random coincidence events between projectile-like particles and fission fragments. In previous treatment of our data,[13] we did not impose this condition so that the random coincidence was not completely excluded and a conclusion of no existing the entrance channel dependence of anisotropies in sub-barrier fusion-fission reactions is incorrect. Now we have re-analyzed the experimental data for the ^{11}B +^{238}U and ^{12}C +^{237}Np systems. The experimental details were described elsewhere.[14]

3 Experimental results

The measured CFF angular distributions were fitted and extrapolated to 0° in terms of the Legendre polynomial with even terms up to $P_6(\cos\theta)$, and the corresponding fragment anisotropies, $A_{\rm exp}$ were calculated. The CFF cross sections were obtained by integrating the Legendre polynomial and normalizing them to the Rutherford scattering cross sections. The experimental error sources include the counting statistics, the correction of the fragment folding angle distribution overlap and the extrapolation of the angular distribution. The total relative uncertainties are 0.04~0.08 for $A_{\rm exp}$ and 0.07~0.15 for the fission cross sections.

3.1 Fission excitation function

The experimental CFF excitation functions for all 6 systems can be well reproduced by CCDEF code calculations (see Fig.1), in which the effects of the target static deformations (β_2 = 0.224, β_4=0.050 for ^{238}U and β_2 = 0.26 for ^{237}Np) are taken into account. In these calculations, the following inelastic channels are included: excitation to 0.7744MeV state of ^{232}Th with β_3 =0.0932, to 0.7319 MeV of ^{238}U with β_3 = 0.084 and to 0.0759 MeV of ^{237}Np with β_2 = 0.19 as well as to 0.1976 MeV of projectile ^{19}F with β_2 = 0.55. The data for other systems were published in Ref.[14]. For each bombarding energy, the transmission coefficients and their second momentum $< J^2 >_{\rm theory}$ were obtained from these calculations.

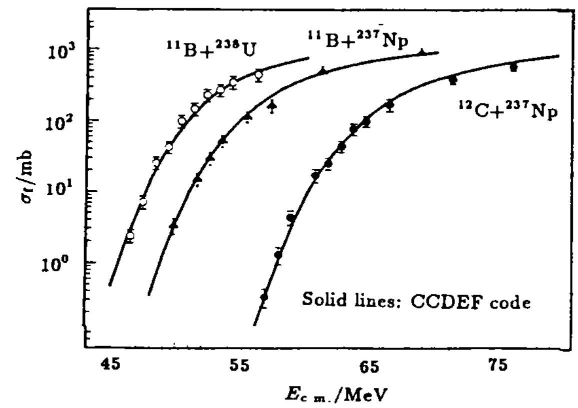


Fig.1 Fission excitation functions for the reactions

3.2 Anisotropies of CFF angular distributions

The anisotropy of fragment angular distribution $W(\theta)$ is defined as $A = W(0°)/W(90°)$.

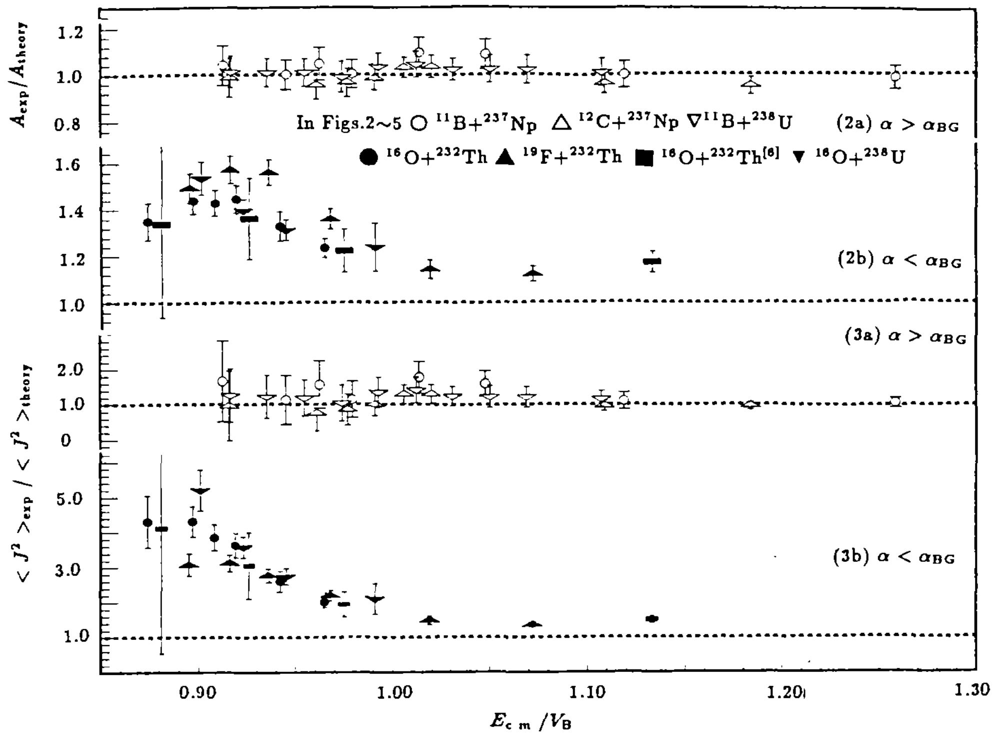
The dependence of the ratio, $A_{\mathrm{exp}}/A_{\mathrm{theory}}$, versus $E_{\mathrm{c.m.}}/V_{\mathrm{B}}$ is shown in Fig.2, where $E_{\mathrm{c.m.}}$ is the center-of-mass energy, V_{B} the height of fusion barrier, and A_{theory} the theoretical fragment anisotropy of the SPTS model. In the calculation of the SPTS model, the K distribution is Gaussian with the variance,

$$K_0^2 = \mathcal{I}_{\mathrm{eff}} T_{\mathrm{sad}}/\hbar^2 \qquad (1)$$

where K is the projection of angular momentum on the symmetric axis of fissioning nucleus; the effective moment of inertia $\mathcal{I}_{\mathrm{eff}}=\mathcal{I}_{\parallel}\mathcal{I}_{\perp}/(\mathcal{I}_{\perp}-\mathcal{I}_{\parallel})$, where $\mathcal{I}_{\parallel}$ and $\mathcal{I}_{\perp}$ are the moments of inertia rotating around the symmetric and perpendicular axes of the nucleus at saddle-point, respectively. They were calculated in terms of the rotating finite-rang model (RFRM).[12] T_{sad} is the nuclear temperature at saddle-point,

$$T_{\mathrm{sad}} = \left[\frac{E_{\mathrm{c.m.}} + Q - B_{\mathrm{f}}(J) - E_{\mathrm{n}}}{A_{\mathrm{cn}}/8}\right]^{1/2} \qquad (2)$$

where Q and $B_{\mathrm{f}}(J)$ are the reaction Q value and fission barrier height of RFRM, respectively; A_{cn} the mass number of the composite system; E_{n} the energy carried away by pre-saddle fission neutron emission. In the calculations of the SPTS model, the transmition coefficients were taken from the CCDEF code fit of the measured CFF cross sections. In Fig.2, α is the entrance-channel mass asymmetry defined as $\alpha = (A_{\mathrm{T}} - A_{\mathrm{P}})/(A_{\mathrm{T}} + A_{\mathrm{P}})$. Here A_{T} and A_{P} are the mass number of target and projectile, respectively. The Businaro-Gallone critical mass asymmetry, α_{BG} is about 0.9 for the range of nuclei studied. The results show some trends. The reaction systems on the different side of α_{BG} have different characters in CFF reactions. For the reaction systems with $\alpha > \alpha_{\mathrm{BG}}$, A_{exp} is in general agreement with A_{theory}. But for the systems with $\alpha < \alpha_{\mathrm{BG}}$, A_{exp} is obviously greater than A_{theory} and there is a trend to coincide with each other as the bombarding energy is above the barrier.



Figs.2,3 $A_{\mathrm{exp}}/A_{\mathrm{theory}}$ or $< J^2_{\mathrm{exp}} >/< J^2 >_{\mathrm{theory}}$ vs $E_{\mathrm{c\,m.}}/V_{\mathrm{B}}$

In the latter case, the present experiment has provided the conclusive evidence of anomalous anisotropies in sub-barrier CFF reactions.

We have compared the anisotropy data of $^{11}B + ^{237}Np(\alpha = 0.91)$ and $^{16}O + ^{232}Th(\alpha = 0.87)$ which both form the same fissioning nucleus ^{248}Cf at the same excitation energies, but α is on the different side of α_{BG}. The results show that the anisotropies exist great difference between the two systems. This experiment provides a strict evidence of the entrance-channel dependence of anisotropies in CFF reactions. It seems that non-compound-nucleus fission with memory of the entrance channel for the systems with $\alpha < \alpha_{BG}$ is the origin responsible for the anomalous anisotropies observed at near- and sub-barrier energies.

3.3 Mean-square angular momentum

It is well established that A can be characterized by the approximate relation,

$$A = 1 + < J^2 > /4K_0^2 \qquad (3)$$

If K_0^2 is known, then $< J^2 >_{exp}$ could be inferred from the measured fragment anisotropy of the fissioning nucleus. In terms of Eq.(3) $< J^2 >_{exp}$ data were deduced with the K_0^2 values taken from RFRM, and the values of $< J^2 >_{theory}$ were extracted from fitting experimental CFF cross sections by the CCDEF code. The results shown in Fig.3 again illustrate the effects of the entrance-channels mass asymmetry on CFF processes. It should be pointed out that the data of $< J^2 >_{exp}$ were extracted on the basis of the K_0^2 values. We will show later that this basis might not be correct for CFF reaction systems with the $\alpha < \alpha_{BG}$.

4 Preequilibrium fission model for low angular momentum

As pointed out by Ramamurthy *et al.*[18], a characterized evidence of preequilibrium fission would be an entrance-channel dependence of fragment anisotropies for target-projectile combination across the Businaro-Gallone ridge in mass degree of freedom, which was clearly verified by our experiments. We have mentioned in Refs.[16,17] that in some cases, the relaxation time of K degree of freedom may be larger than fission life time. If the relaxation process of K is taken into account, then the variance of K distribution, σ_K^2 can be expressed as,

$$\sigma_K^2 = K_0^2[1 - \exp(-t/\tau_K)] \qquad (4)$$

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 saddle point. D⊘ssing and Randrup[12] 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 got the expression of τ_K depending on the rotational frequency ω_R. Under some approximations,[16] the variance equation for preequilibrium fission was obtained as

$$\sigma_K^2(J) = K_0^2[1 - \exp(-\mathcal{G}J^2)] \qquad (5)$$

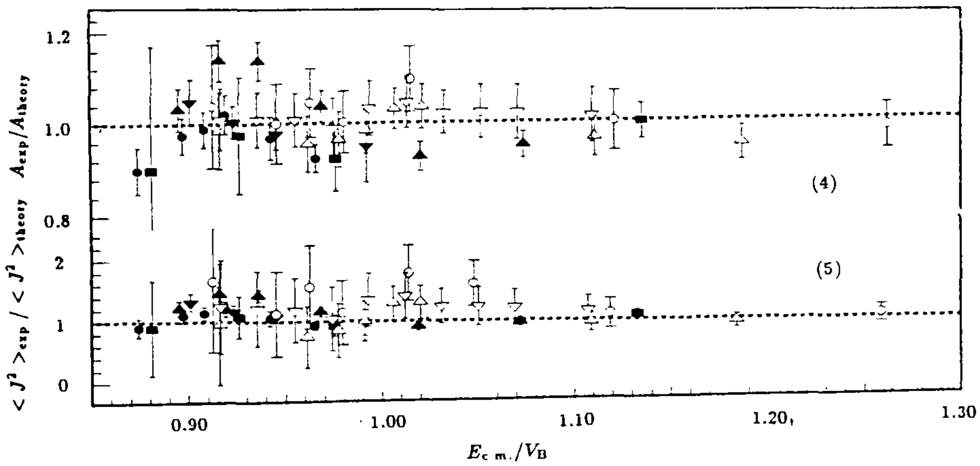
where $\mathcal{G}=2.238\mathcal{I}_{\parallel}^2/(\mathcal{I}_{\perp}^2\mathcal{I}_{eff})$. The constant $2.238\,\mathrm{MeV}^{-1}$ was obtained by using Back's experimental fragment anisotropy and mean square angular momentum data[10] at $E_{c.m.} = 94.1\,\mathrm{MeV}$ for the $^{16}O+^{232}Th$ reaction.

By using this formula, A_{theory} for the three reaction systems with $\alpha < \alpha_{BG}$ was recalculated and compared with the experimental data. The results of the other three systems with $\alpha > \alpha_{BG}$ were calculated by SPTS model. All the results are displayed in Fig.4. It is evident that the theoretical predictions of the fragment anisotropies are in general agreement with the measured results. Therefore, the anomalous fragment anisotropies in sub-barrier CFF reaction systems with $\alpha < \alpha_{BG}$ are rather successfully explained by means of our preequilibrium fission model.

For the reaction systems with $\alpha < \alpha_{BG}$, we also re-extracted $< J^2 >_{exp}$ from the measured fragment anisotropies in terms of the average values of $\sigma_K^2(J)$ that was defined as

$$< \sigma_K^2(J) > = \frac{\Sigma_{J=0}^{\infty}\sigma_F(J)\sigma_K^2(J)}{\Sigma_{J=0}^{\infty}\sigma_F(J)} \qquad (6)$$

where $\sigma_F(J)$ is the angular momentum distribution taken from the coupled channel theoretical calculation to reproduce the fusion excitation function. In Fig.5, the data of $< J^2 >_{exp}$ were extracted in terms of $< \sigma_K^2(J) >$ instead of K_0^2 value in Eq.(3). The results show that the coupled channel theory gives a reasonable self-consistent account of both fusion excitation functions and angular momentum data for CFF reactions at near- and sub-barrier energies.



Figs.4,5 A_e/A_c or $< J^2 >_e/< J^2 >_c$ vs $E_{c.m.}/V_B$

5 Summary

In the present work, we have successfully separated the CFF and TF components in terms of the fragment folding angle technique, and measured the CFF cross sections and fragment angular distributions for 6 reaction systems at near- and sub-barrier energies. All the experimental fusion-fission excitation functions can be well reproduced by the couple -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 guided by DØssing and Randrup's theoretical framework, we put forward a new version model of preequilibrium fission to solve the anomalous anisotropy problem. It is concluded that the couple channel calculations can give a self-consistent account of both fusion excitation functions and angular momentum data simultaneously.

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