Effects of prefission neutron emission on the fission fragment angular distributions in heavy-ion-induced fission

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Earlier calculations of fission fragment anisotropies made with the use of the standard saddle point statistical model have been corrected to include the effects of prefission neutron emission. These calculations are compared with the data reported earlier for the fissioning systems formed by projectile-target combinations of ^{10}B, ^{12}C, ^{16}O, and ^{19}F on ^{232}Th and ^{237}Np and ^{9}Be on ^{232}Th. It is seen that for these systems the conclusions reached earlier regarding the entrance channel dependence of the fission fragment anisotropy as a function of mass (charge) asymmetry are not affected by the inclusion of corrections due to prefission neutron emission.

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It has been found that in several cases [1,2] of heavy-ion induced fission, the measured fission fragment angular distributions show larger anisotropies than compared to the predictions of the standard saddle point statistical model (SSPSM). This deviation has been observed for a range of bombarding energies and target-projectile combinations. It has been suggested that at sub-barrier and near-barrier energies, this deviation arises due to the broadening of the spin distribution of the compound nucleus due to effects such as channel coupling [3] leading to a larger $\langle I^2 \rangle$ than that used in the SSPSM calculations. Another suggested mechanism for these anomalous angular distributions, which can contribute at all energies, is based on the proposition that in the observed fission events there is, in general, an admixture of fission-like events from a preequilibrium fission process characterized with incomplete equilibration in the K degree of freedom [4]. It was also pointed out that a characteristic signature of such a nonequilibrium process would be an entrance channel dependence of the fragment anisotropies for target-projectile combinations across the Businaro-Gallone (BG) ridge in the mass (charge) degree of freedom [5]. Subsequently, such an entrance channel dependence in the fragment anisotropies was inferred [6–8] from the analysis of the experimental data for the fissioning systems formed with target-projectile combinations of ^{10}B, ^{12}C, ^{16}O, and ^{19}F on ^{232}Th and ^{237}Np targets and $^{9}Be+^{232}Th$ systems, at center of mass energies mostly above the fusion barrier. In the analysis, the anisotropies expected from SSPSM were calculated taking the "experimental" values of J_{eff} deduced from the fragment anisotropy data for alpha-induced fission [9]. In the earlier analysis, while making comparison with the predictions of the SSPSM, it was assumed that all the fission events correspond to the first chance fissions. In other words, the nuclear temperature at the saddle point used as an input to the SSPSM was taken to correspond to the full excitation energy available at the saddle point.

In view of the recent observation of significant prefission neutron multiplicties in heavy-ion-induced fusion-fission reactions [10–12] we have carried out calculation of fragment anisotropies taking into account the effect of prefission neutron emission to make a better comparison of SSPSM predictions with the experimental results. Rossner *et al.* [13] have also incorporated this effect in calculating the fission fragment angular distribution for the system $^{16}O+^{208}Pb$. But in their analysis, they have used the effective moment of inertia of the fissioning system at the saddle point J_{eff} as calculated from the rotating liquid drop model. They have found that for the above system their calculated results, after incorporating effects due to emission of prefission neutrons, are in better agreement with the experimental values. However, one still notices a small discrepancy in their comparison of model predictions with the data at higher bombarding energies.

In the present work, we have studied the effects of prefission neturon emission on the fission fragment anisotropies calculated using the statistical model for the systems reported in Refs. [6–8].

If $W(\theta)$ represents the fragment angular distribution with respect to the beam direction, the fission fragment anisotropy, $W(180°/90°)$, in the framework of SSPSM is given by [14,15]

$$A=W(180°)/W(90°)\approx 1+\langle I^2\rangle/4K_0^2 \ , \tag{1}$$

where $\langle I^2 \rangle$ is the mean square spin of the compound nucleus, which is calculated from a reaction model that describes the fusion excitation function data. K_0^2 is the variance of the K distribution of the fissioning nucleus at the transition state [14,15], where K is the projection of the total angular momentum I on the symmetry axis of the fissioning nucleus. According to SSPSM, the value of K_0^2 is given by

$$K_0^2=J_{\mathrm{eff}}\sqrt{(E_x^s/a_f)}/\hbar^2 \tag{2}$$

$$=J_{\mathrm{eff}}T/\hbar^2 \ , \tag{3}$$

where E_x^s and T are the excitation energy and temperature of the fissioning nucleus at the saddle point and a_f is the level density parameter for the transition state nucleus.

We report here calculations of the fission fragment anisotropies for systems reported in Refs. [6–8] by determining the saddle point temperatures after taking into account the appropriate number of prefission neutrons based on actual measurements for these systems [16] or as taken from the systematics of the excitation energy and fissility dependence of the prefission neutron multiplicity data [10]. In this analysis, we have made an assumption that all the prefission neutrons are emitted prior to reaching the saddle point to estimate an upper limit of this effect on the calculation of K_0^2. A small fraction of prefission neutrons is expected to be emitted between saddle to scission or during fragment acceleration and, therefore, the present calculation will be an upper limit of the prefission neutron emission on the calculated K_0^2 or anisotropy. In one set of calculations we have used J_{eff} from the systematics of suitable alpha-induced fission fragment angular distribution data [9] (as per Refs. [2,6,7]). In this case the appropriate correction for prefission neutron emission also needs to be made for alpha-induced fission. However, as experimental information on prefission neutron emission in alpha-induced fission is not available for all the systems studied here, we have calculated the theoretical curves for different assumed values of prefission neutrons in alpha-induced fission. Excitation energy at the saddle point E_x^s was calculated using the relation

$$E_x^s = E_{\text{c.m.}} + Q - B_f - E_n \ , \tag{4}$$

where Q is the reaction Q value for the formation of the compound nucleus. B_f in the above expression is the fission barrier at an average angular momentum $\langle I \rangle$ and is typically in the range of 1.0–3.0 MeV depending on the system. E_n is the energy removed from evaporated prefission neutrons and is typically around 8 MeV/neutron. For heavy-ion-induced reactions, the quantity $\langle I^2 \rangle$ was calculated from the fluctuating barrier models of Wong and Esbensen [17,18] that described the measured fusion excitation function. Further, for both alpha-induced fission as well as for heavy-ion-induced fission, $\langle I^2 \rangle$ was also suitably corrected to take into account prefission neutron emission assuming each neutron

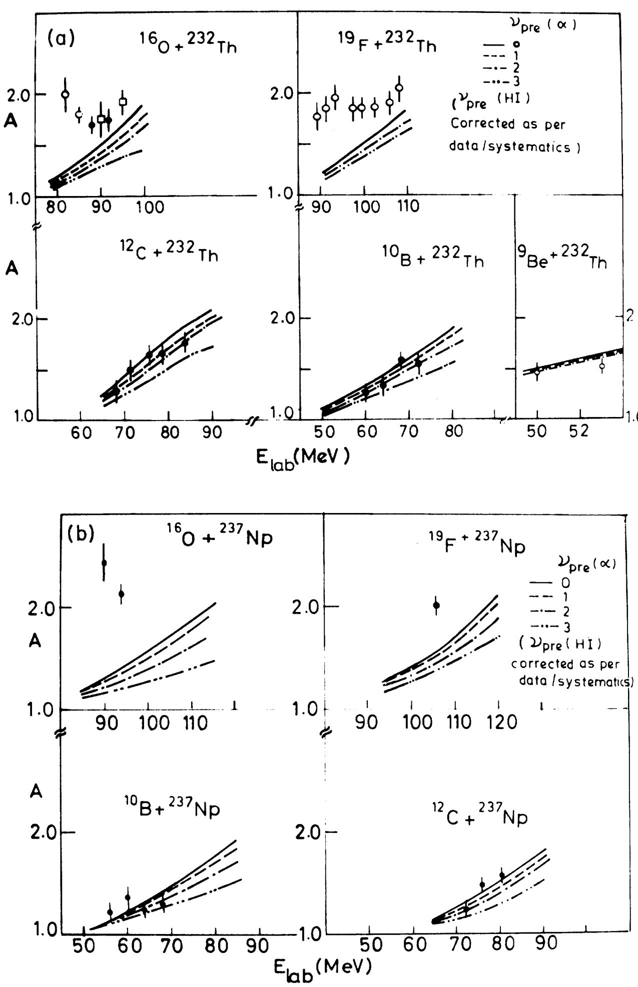

FIG. 1. (a), (b). The experimental and the calculated values of anisotropies, A, for the various target-projectile systems. The curves represent the SSPSM calculations after taking into account the effects of prefission neutron for heavy-ion-induced fission as well as alpha-induced fission. Various curves correspond to the different values of prefission neutrons assumed in alpha induced fission.

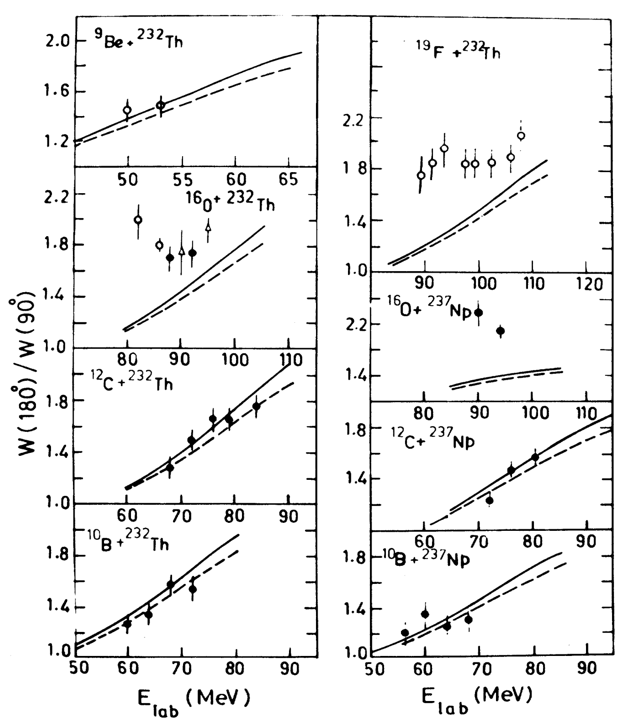

FIG. 2. The experimental and the calculated values of anisotropies, $W(180°)/W(90°)$, for the various target-projectile systems. The curves represent the SSPSM calculations after the inclusion of the effects of prefission neutron emission in the heavy-ion-induced fission. The dashed and continuous curves correspond to the calculations for the two values of level density parameter, $A_{\text{CN}}/10$ and $A_{\text{CN}}/7.5$ MeV^{-1}, respectively.

on an average carries an angular momentum of 0.5. This change in $\langle I^2 \rangle$ is about 5–7 % depending on the number of neutrons emitted. The values of K_0^2 thus deduced for alpha-induced fission cases were scaled by the relation $\sqrt{E_x(\text{H.I.})}/\sqrt{E_x(\alpha)}$ to obtain K_0^2 for the corresponding case of heavy-ion-induced fission. In this procedure, the values of K_0^2 and anisotropies for the heavy-ion-induced fission case do not depend on the assumption about the level density parameter a_f. As the values of $\langle I^2 \rangle$ in heavy-ion-induced fission reactions are significantly larger than in alpha-induced fission, one expects small differences in J_{eff} for the two cases due to a weak angular momentum dependence of J_{eff} [19]. The deduced values of J_0/J_{eff} were therefore corrected as follows:

$$(J_0/J_{\text{eff}})_{\text{corr}} = (J_0/J_{\text{eff}})_{\text{uncorr}} - \beta \langle I^2 \rangle \ , \quad (5)$$

where β is obtained by fitting Sierk model [20] predictions of J_0/J_{eff} for various $\langle I^2 \rangle$. β values are in the range of 10^{-4}–10^{-5} depending on the fissioning system. This correction is found to be rather small for most of the $\langle I^2 \rangle$ values determined in the present work. The results of these calculations are shown in Figs. 1(a) and 1(b) along with the experimental data. It may be noted that, while the calculations give satisfactory agreement with the data for ^{9}Be, ^{10}B, and ^{12}C projectiles, they are significantly lower than the observed fragment anisotropies for ^{16}O- and ^{19}F-induced fission. These conclusions are the same as the earlier calculations [6–8] made without prefission neutron correction.

In a second set, the fragment anisotropies were calculated from the values of K_0^2, using the values of J_{eff} given by the model of Sierk [20]. The saddle point temperatures were calculated taking into account loss of excitation energy due to neutron emission and assuming level density parameter $a_f = A_{\text{CN}}/7.5$ and $A_{\text{CN}}/10$ MeV^{-1} (A_{CN} is mass of the compound nucleus). These calculated theoretical curves for $a_f = A_{\text{CN}}/7.5$ and $A_{\text{CN}}/10$ MeV^{-1} along with the experimental data are shown in Fig. 2. It is clear that the larger anisotropies observed for ^{16}O- and ^{19}F-induced fission continue to remain anomalous with respect to transition state model predictions in this set of calculations as well. It is also seen that the theoretical predictions of both the procedures do not significantly differ from each other and, hence, the Sierk model can be applied, with confidence to calculate J_{eff} for those compound systems where the alpha-induced fission data do not exist.

To summarize, after incorporation of prefission neutron corrections in the calculations, the fission fragment angular distributions for the cases involving ^{16}O and ^{19}F projectiles continue to be anomalously large and the conclusions reached earlier [6] are not affected by the inclusion of prefission neutron corrections in the model predictions.

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