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Some aspects of heavy ion fusion–fission dynamics

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Abstract. Study of heavy ion induced fusion–fission reactions at near and below barrier energies has attracted a great deal of attention in recent years, due to the observations of anomalous features in the fragment angular distributions for many target–projectile systems. Additionally there are also measurements of the fragment spin distributions and time-scales of the fusion–fission reactions, which have provided important information on the dynamics of these processes. In the present paper, the emphasis would be to highlight some of the recent experimental findings and their implications on the dynamics of the fusion–fission reactions in heavy ion collisions at near and above barrier energies.

Keywords. Heavy ions; fission; spin distribution of fission fragments; K-equilibration.

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1. Introduction

Studies of heavy ion induced fusion–fission reactions have provided valuable information on many of the dynamical features underlying these processes. The experimental observations of large scale damping of the collective modes in fission process leading to large dynamical delays in fission decay have led to extensive studies earlier in this field [1–4]. Recently, there have been observations of anomalous anisotropies in the angular distributions of the fission fragments in comparison to the standard saddle point statistical model (SSPSM) predictions in a large number of target-projectile systems. The anomaly is seen to be particularly prominent for heavy ion induced fission reactions using actinides such as Th, Np, U etc. as target nuclei, and many features such as entrance channel mass asymmetry effects at the above barrier energies, peak-like structures and ground state spin effects at sub-barrier energies have been reported. These results suggest the need to invoke new fission modes such as pre-equilibrium fission, quasi-fission etc, in addition to the fusion–fission reactions for these systems even at near barrier energies [5–8]. In a recent review [9], various aspects of the heavy ion fusion–fission reactions dealing with such issues have been discussed.

In pursuant of our earlier investigations on the fission dynamics in these heavy systems, recently we have carried out further work to study the spin distributions of fission fragments in the ^{12}C, ^{16}O, ^{19}F + ^{232}Th and ^{209}Bi reactions [10,11]. The present paper deals with one particular aspect of this work with regard to the fragment emission angle dependence of fragment spins in these systems. This study has convincingly resolved one of the long standing issues that the angular variation of the fragment spin and the fragment angular distribution could not be simultaneously explained within the SSPSM formalism using the same K-distribution [12–14]. From the analysis of the data obtained in the present measurements as well as those available from the literature on the emission angle dependence of the fragment spin, we show that the collective spin modes are suppressed for high K-states in the fission process. The following section gives the experimental details and data analysis procedure. Section 3 contains the discussions of the results and §4 gives the conclusions of the present work.

2. Experimental details and data analysis

The experiments were carried out using ^{12}C, ^{16}O and ^{19}F beams from the 14 MV BARC–TIFR pelletron accelerator at Mumbai. The fission fragments were detected using surface barrier detectors along 90° and 165° to the beam direction. The gamma rays were measured in coincidence with fission fragments with a gamma ray detector array consisting of 15 hexagonal BGO detectors (figure 1). The measured gamma ray multiplicities were analysed to extract the average fission fragment spins for fragment emission along 90° and 165° to the beam. Details of the experimental setup and the analysis procedure have been described in earlier references [10,11]. Figure 2 shows the average values of the fragment spins as a function of bombarding energy for the emission angles of 90° (solid circles) and 165° (hollow circles) with respect to the beam direction for ^{12}C, ^{16}O, $^{19}\text{F} + {}^{232}$Th and ^{209}Bi reactions measured in the present work. The average total fragment spins for fragments emitted along 90° to the beam are observed to be larger than for those emitted along 165° for all the systems. Also the angle dependence is observed to get weaker as one approaches the barrier energy V_{B}.

In the framework of the statistical model, the total fragment spin is given as [12,13]

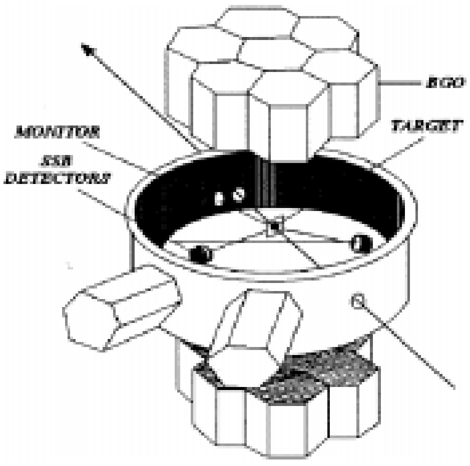

Figure 1. Schematic diagram of the experimental setup.

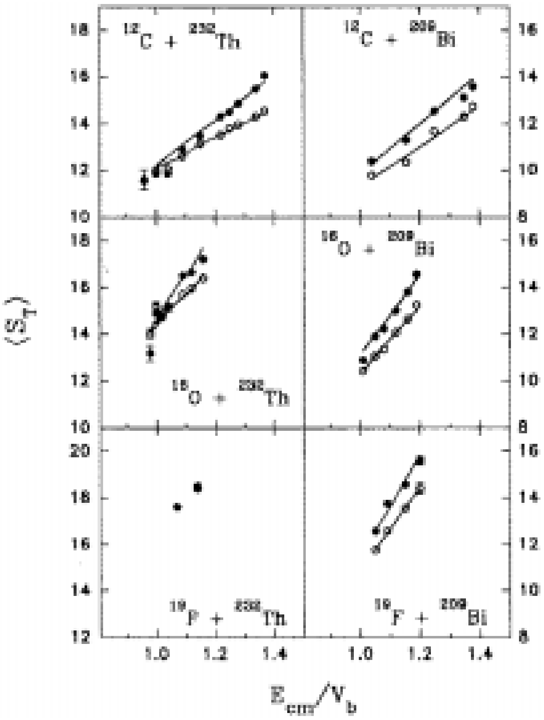

Figure 2. Fragment spin as a function of bombarding energy for emission angles of 90° (solid circle) and 165° (open circle). The solid lines are the modified statistical model calculations as discussed in the text.

$$\langle S_T^2(\theta)\rangle = \langle f^2 I_{CN}^2 + (1-f^2)K^2 + S_{\text{coll}}^2\rangle, \tag{1}$$

where the angular brackets in the above equation correspond to the average over K and I-distributions using the weight factor $W_{M,K}^I \propto \exp(-K^2/2K_0^2)$ and taking the compound nuclear I-distribution. The collective spin S_{coll} is assumed to be angle independent [10,12] and is given as $S_{\text{coll}} \propto A_{CN}^{5/6}T^{1/2} = kA_{CN}^{5/6}T^{1/2}$ where k is a proportionality constant and T is the temperature at the fission saddle point. The emission angle dependence of total fragment spin arises essentially due to the second term, which is governed by the K_0^2 parameter, i.e. the variance of the Gaussian distribution of K-states at the fission saddle point. For fragment emission along $\theta = 165°$ $(\theta \simeq 0°, K \simeq 0)$, the above equation reduces to

$$\langle S_T^2(0°)\rangle = \langle f^2 I_{CN}^2 + (kA_{CN}^{5/6}T^{1/2})^2\rangle. \tag{2}$$

As discussed earlier [11–14], eq. (1) under the usual assumption of the constancy of collective spin magnitude S_{coll}, as a function of fragment emission angle fails to provide adequate description of the emission angle dependence of fragment spin. The calculated angular dependence of fragment spin is much too stronger compared to the experimental

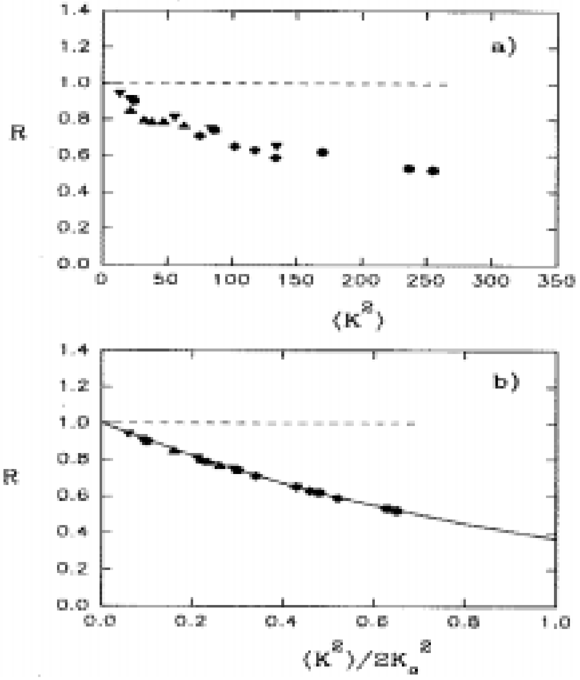

Figure 3. (**a**) The spin suppression factor R as a function of mean square spin in tilting mode $\langle K^2\rangle$. The various symbols correspond to the different systems studied. (**b**) The spin suppression factor R as a function of the quantity $\langle K^2\rangle/2K_0^2$. The dashed lines correspond to the statistical model assumption of angle independent S_{coll}.

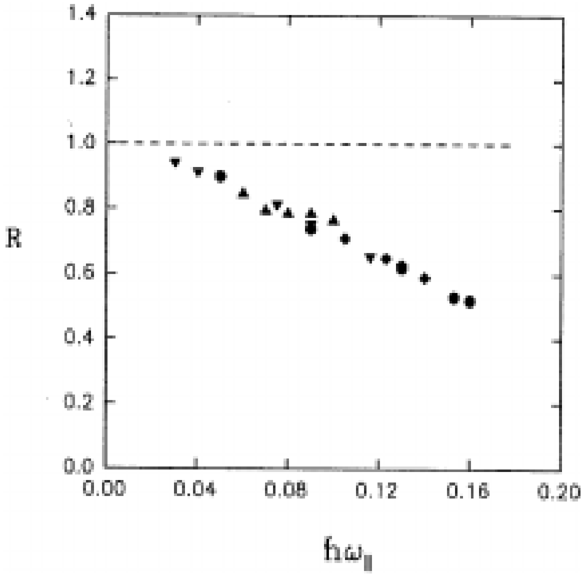

Figure 4. Spin suppression factor R as a function of rotational frequency $\omega_{||}$ of the tilting mode of spin excitation. The dashed line is the statistical model assumption.

results. In what follows, we show that all the available experimental data on the fragment spin versus emission angle require that $S_{\rm coll}$ depends on K, thereby implying that $S_{\rm coll}$ varies with emission angle θ. Under this assumption we write the total fragment spin as

$$\langle S_T^2(\theta)\rangle = \langle f^2 I_{CN}^2 + (1-f^2)K^2 + S_{\rm coll}^2(\theta)\rangle, \tag{3}$$

where $S_{\rm coll}(\theta)$ is angle dependent and can be written as $S_{\rm coll} = kA_{CN}^{5/6}T^{1/2}R(\theta)$, where $kA_{CN}^{5/6}T^{1/2}$ is the collective spin magnitude for fragment emission along 0° or 180° direction and $R(\theta)$ is the angle dependent reduction factor for emission along other angles. Of course, for fragment emission along $\theta \simeq 0°$, eq. (3) goes over to eq. (2).

The data from present measurements as well as from the earlier measurements were analysed as follows. The experimentally determined spins for fragment emission along $\theta = 165°$ direction were first analysed using eq. (2) to obtain the quantities f and k by a two variable least square fit using the above barrier data for all the systems. The average compound nucleus angular momentum $\langle I\rangle$, required for the calculation was taken from the coupled channel calculations which explain the fission excitation functions for all the systems. The spins measured for fragment emission at $\theta = 90°$ to the beam were then analysed using eq. (3). The values of $\langle K^2\rangle$ required in eq. (3) were deduced from the Gaussian K-distribution corresponding to the values of K_0^2, which are consistent with the measured fragment angular anisotropies [5,6,7,15–19] as given by

$$A = 1 + \frac{\langle I^2\rangle}{4K_0^2}. \tag{4}$$

Using the values of $\langle K^2\rangle$ and the deduced values of f and k from eq. (2), the values of $S_{\rm coll}(90°)$ could be deduced that explain the fragment spins at $\theta = 90°$. It was found that the $S_{\rm coll}(90°)$ values are lower than the $S_{\rm coll}(165°)$ values in all cases, as was reported earlier in ref. [11]. The collective spin for perpendicular emission of fragments is, thus, observed to be suppressed in comparison to the forward–backward emission. This suppression factor represented by $R = S_{\rm coll}(90°)/S_{\rm coll}(165°)$ is shown in figure 3(a) as a function of mean square spin in the tilting mode $\langle K^2\rangle$ for the various systems studied. It is seen that there exists a definite correlation between the suppression factor R and $\langle K^2\rangle$ for all the reactions. The correlation is observed to be even more systematic and universal when plotted as a function of the mean square spin in the tilting mode $\langle K^2\rangle$ normalised to the variance K_0^2 of the K-distribution at the saddle point as shown in figure 3(b). The observed correlation also implies that the collective spin is suppressed when the rotational frequency $\omega_{||} = \sqrt{\langle K^2\rangle}/J_{||}$ of the fissioning nuclei along the fission symmetry axis increases, as shown in figure 4. Higher the rotational frequency of the fissioning nucleus along the fission symmetry axis, more is the suppression of the statistical collective modes of the fissioning system. The statistical model predicts a constant magnitude for the value of $S_{\rm coll}$ as shown by the dashed lines in figures 3 and 4.

3. Discussion

From the above observed features in the variation of R with the tilting mode spin, as seen in figure 3, we have assumed a functional dependence of the form (shown by solid curve in figure 3(b)), $S_{\rm coll}(\theta) \propto \exp(-\langle K^2\rangle/2K_0^2)S_{\rm coll}(0°)$ to represent the suppression of

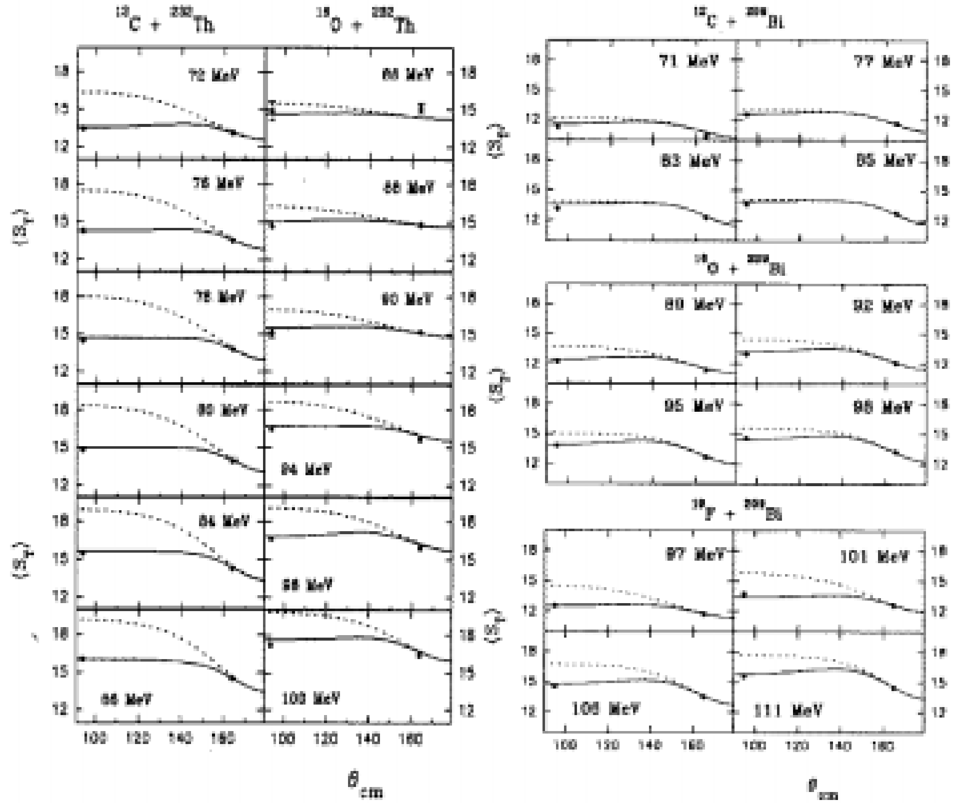

Figure 5. Total fragment spin as a function of emission angle. The dotted curves are the results of the statistical model calculations of Schmitt *et al* [12]. The solid curves correspond to the calculations assuming angle dependence of collective spin.

collective spin modes for high K-states. Using this functional form, we have calculated the average total fragment spin as a function of fragment emission angle for all the systems. The results of the calculations for the total fragment spin for fragment emission along 90° and 165° are shown in figure 2 for all the systems as a function of the bombarding energy. This is also shown as a function of emission angle for several bombarding energies in figure 5. The agreement between the calculated results and the experimental data is seen to be quite good. To test the predicted angle dependence of the present model, we carried out calculations for various other systems in 120 MeV ^{16}O induced reactions for which Schmitt *et al* [12] have carried out measurements of fragment spin at several different fragment emission angles. These results are shown in figure 6. It is seen that the angle dependence of fragment spins can be explained very well with the modified expression given by eq. (3).

The physical reason for the suppression of the collective spin modes for high K-states could be due to the fact that the spins in the individual fragments due to collective spin modes such as wriggling, bending and twisting are oppositely directed and the presence of the spin component due to the tilting mode (for which the individual fragments spins are

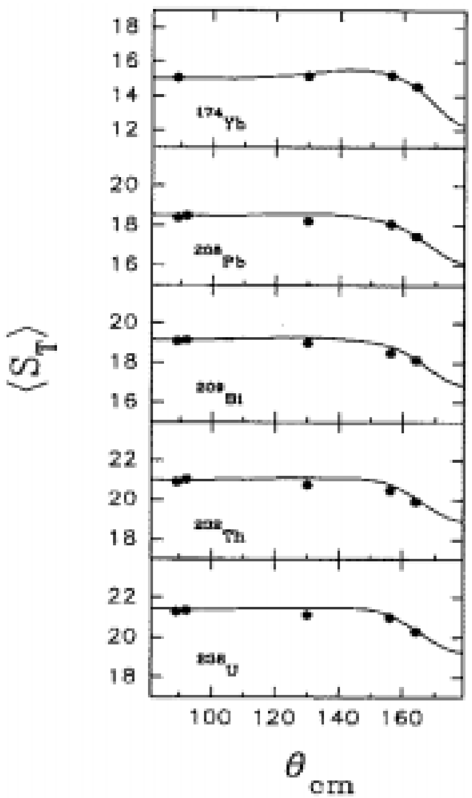

Figure 6. Modified statistical model calculations for 120 MeV ^{16}O induced reactions studied by Schmitt *et al* [12].

aligned in the same direction) results in individual fragments having unequal velocity fields in otherwise equally spinning fragments from the collective modes. This difference in the velocity field between the two fragments may act to retard the spinning motion in the two fragments. The suppression in the collective spin is then expected to depend on the amount of excess energy required to excite the tilting component. For $K = 0$, the collective spin is fully excited and is given by $S_{\rm coll}(0^{\circ})$. For higher K values the collective spin modes are suppressed by an amount given by $S_{\rm coll}(\theta, K) \propto \exp(-\Delta E/T) S_{\rm coll}(K = 0)$, where ΔE is the energy required to excite the tilting mode and T is the temperature at the fission saddle point. The above results can thus be represented by means of a suppression factor R as a function of $\Delta E/T$. It thus follows that there exists a universal scaling of the collective spin suppression factor R on $\langle K^2\rangle/2K_0^2$ or on the rotational frequency $\omega_{||}$ along the fission axis as shown in figures 3 and 4.

4. Conclusion

The present work has shown that there exists a dynamical coupling of the tilting mode to the collective spin degrees of freedom. It is found that the collective spin modes in heavy ion induced fission reactions are fully excited only when the fragments are emitted along the beam direction $(K \simeq 0)$ and there is a suppression of collective spins at other angles corresponding to higher K-states. The suppression of collective spins exhibits a universal behaviour with respect to the $\langle K^2 \rangle / 2K_0^2$ parameter or the rotational frequency of the fissioning nucleus along the fission symmetry axis.

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