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Spin Excitations in Di-Nuclear Systems

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ABSTRACT: The spin excitations of products from two-body reactions have two sources: transfer of orbital motion into intrinsic spins via tangential friction and thermal excitations of di-nuclear spin modes. The relative importance of these two mechanisms is discussed for deep inelastic scattering, quasi-fission and spontaneous fission processes. The results of simple model calculations are compared to measured γ-multiplicities in ^{238}U induced quasi-fission reactions and it is concluded that the spin-excitation are only partially equilibrated during the interaction.

I. INTRODUCTION

The angular momentum degree of freedom has become an important area of study in recent years, mainly as a result of the availability of heavy-ion beams which can populate high angular momentum states in reaction products. Most of the nuclear structure studies have been carried out on nuclei formed by heavy-ion fusion reactions, where the orbital angular momentum populates the high spin states of the compound system with relatively little angular momentum carried away in the particle evaporation chain. Converting all of the initial angular momentum, L, in the system into intrinsic spin is, however, only possible when the orbital angular momentum does not violate the limits for complete fusion or the limitations imposed by the fission stability of the system, i.e. $L < L_{B_f=0}$. Here $L_{B_f=0}$ is the angular momentum for which the fission barrier vanishes. For higher L-values there are two

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bodies in the exit channel, which allows for a large fraction of the initial orbital angular momentum to remain in orbital motion, with the remaining being carried as intrinsic spins of the two final fragments. This situation applies to all two-body reactions such as elastic, quasi-elastic, and deep inelastic scattering, as well as quasi-fission and compound fission processes. The division of angular momentum between the orbital and the two intrinsic spins is, in principle, constrained only by angular momentum conservation. There is therefore a rich phase space, from which the actual spin excitations can be selected by either the reaction dynamics or by statistical population.

II. TANGENTIAL FRICTION VS. THERMAL EXCITATIONS

In a simple model, one may describe the spin transfer to the final fragments as arising from two different mechanisms, namely tangential friction between the interacting nuclei and thermal excitations of various angular momentum carrying modes of the di-nuclear system. The transfer of spin by tangential friction requires, of course, that there is an orbital angular momentum in the entrance channel. This mechanism would therefore not be able to explain the accumulation of spin in the fragments of e.g. spontaneous fission of even-even actinide nuclei, which have $I^\pi = 0^+$ in the initial state. In this case, the fragment spins are believed to originate from thermal excitations of the di-nuclear system [1,2]. Whether the fission time scale is sufficiently long to approach an equilibrium is not yet clear [3,4], but computationally this is a convenient benchmark with which experimental results can be compared. At equilibrium we expect each of these modes to be excited to a rotaional energy of $S^2/2\mathcal{J} = \frac{1}{2}T$, where s is the accumulated angular momentum and $\mathcal{J}$ and T are the relevant moment of inertia and nuclear temperature, respectively. The mean square spin in each mode is therefore expected to be $\langle S^2\rangle = T\mathcal{J}$.

The accumulation of fragment spin arising from the tangential friction between the two interacting nucleons require, however, an initial orbital angular momentum. In this case a fraction of the orbital angular momentum is transferred to intrinsic spins

[5]. The fraction depends on the degree of spin equilibration achieved during the reaction, where the fully damped situation is one in which the two interacting nuclei "stick" together and rotate as a rigid di-nuclear body. The intrinsic spins carried by the individual nuclei are in this limiting case:

$$S_i = \frac{\mathcal{J}_i}{\mathcal{J}_T}; i = A, B \tag{1}$$

where $\mathcal{J}_A$ and $\mathcal{J}_B$ are the intrinsic moments of inertia of the two nuclei and $\mathcal{J}_T = \mathcal{J}_A + \mathcal{J}_B + \mu(r_A + r_B)^2$ is the total moment of inertia for rigid rotation of the di-nuclear system.

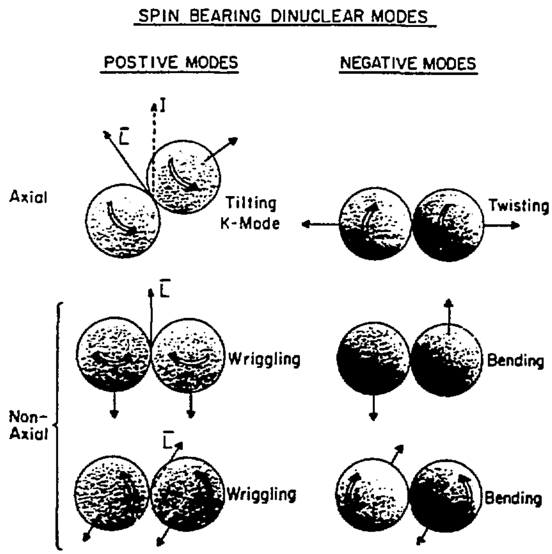

Fig. 1. Spin carrying di-nuclear modes

The relative importance of the aligned spin arising from the tangential friction force and the thermal excitation of the di-nuclear modes therefore depend on the ratio $L^2/T\mathcal{J}$, which maybe vastly different for different reactions. Thus we expect the aligned spin components to dominate in many deeply inelastic scattering reaction with heavy ions, where very high partial waves are involved in the process. An example is found in the $^{86}Kr + ^{209}Bi$ reaction, which was studied at a beam energy of 610 MeV by Dyer et al. [6]. Here it was found that the sequential fission decay of the target-like product of a deeply inelastic scattering reaction was strongly concentrated in the reaction plane of the primary reaction. This shows that the spin of the fissioning system is large [7] and well aligned with the initial orbital angular momentum. The thermal excitation of intrinsic di-nuclear modes is less important in this case, but it does manifest itself by a small, but observable, anisotropy in the reaction plane.

A classic example of the thermal excitation of di-nuclear modes is the spontaneous fission of ^{252}Cf, which has been studied by Wilhelmy et al. [8]. In this case the fissioning system has no initial angular momentum, and the observed spin of the fission fragments must therefore originate from thermal excitations of the di-nuclear modes.

In the present manuscript we shall discuss the spin excitations in quasi-fission reactions, which is a case intermediate between the two examples cited above. The partial waves leading to quasi-fission are believed to be smaller than those resulting in deeply inelastic scattering, and the temperatures are generally larger, which leads to a more central role for the thermal excitations.

III. EXPERIMENTAL RESULTS

The γ-multiplicities for quasi-fission products from ^{238}U-induced reactions [4] are shown as solid points as a function of fragment mass for the different beam energies and targets in Fig. 2. The solid curves are the result of simple calculations using a touching spheres configuration and assuming that both the sticking condition and full thermal equilibrium of the di-nuclear modes have been reached. The conversion from the calculated total spin S of the fragments to γ-multiplicity is done using the relation $M_\gamma = S/2+6$, which is based on the assumption that three statistical γ-rays are emitted from each fragment without removing spin (on the average) followed by a cascade of stretched $E2$ transitions.

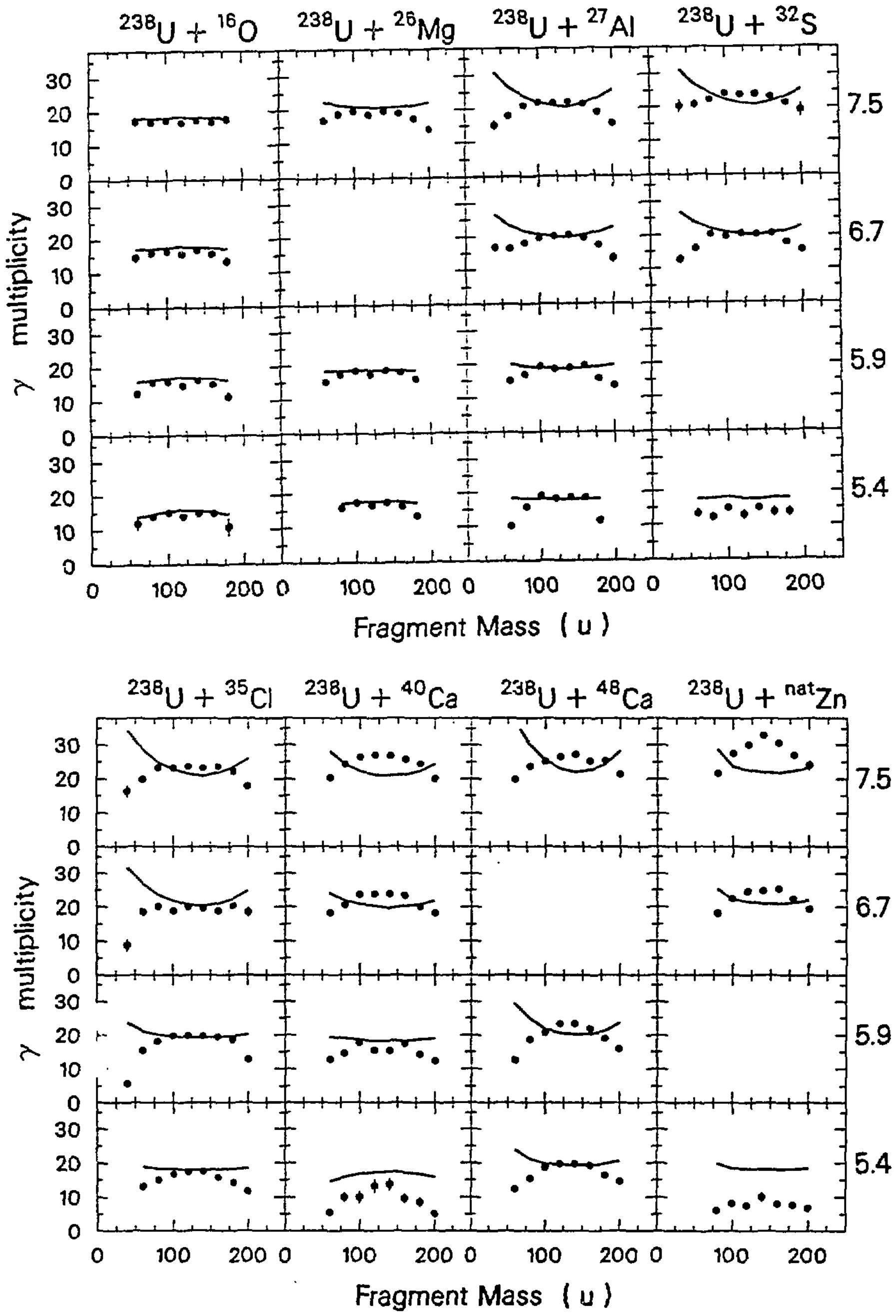

Fig. 2. Average γ-ray multiplicities shown as a function of mass (solid points). Details for the calculated curves are explained in the text.

In the following, we shall concentrate on two aspects of the data, namely the systematics of the γ-multiplicity for symmetric mass splits, and the descrepancy between the measured and calculated mass dependence. The systematics of γ-ray multiplicities for symmetric mass divisions for ^{238}U [4] and ^{208}Pb [9] induced reactions are illustrated in Fig. 3.

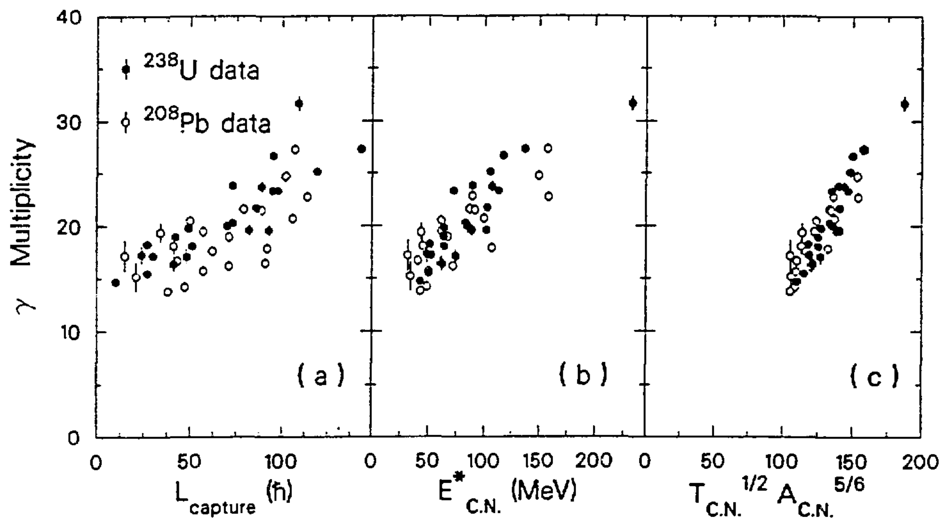

Fig. 3. Average multiplicity at mass symmetry plotted as a function of (a) the critical angular momentum for capture $L_{capture}$, (b) the excitation energy, E^*_{CN}, and (c) the parameter $T^{1/2}A^{5/6}$.

In panel (a) the γ-ray multiplicities are plotted as a function of the maximum partial wave for fission-like reactions $L_{capture}$, which is the relevant parameter to use if the spin excitations are dominated by the transfer from the orbital motion. Although there is some correlation with this parameter, we do observe a large degree of scatter, which is somewhat reduced when the data are plotted against the excitation energy of the compound nucleus, panel (b). In panel (c) we observe, however, that there is a rather tight correlation with the parameter $T^{\frac{1}{2}}A^{\frac{5}{6}}$, which is expected to govern thermal spin excitations, since $S^2 = T\mathcal{J} \propto TA^{\frac{5}{3}}$.

The observed corrrelation with this parameter therefore appears at first glance to indicate that thermal excitation is the dominant source of fragment spins. A closer look reveals a more complicated situation: since the γ-ray multiplicity scales with the total fragment spin according to $M_\gamma = S/2+6$, this description predicts that the γ-ray multiplicities should lie on a straight line in Fig. 3c intersecting the ordinate at the multiplicity value +6. As seen from Fig. 3c the line suggested by the data does not agree with this expectation. It rather appears to have its intersection at a negative value of the multiplicity. From this analysis we must therefore conclude the actual situation is more complicated than assumed in a simple thermal equilibrium model.

IV. INCOMPLETE SPIN RELAXATION

In addition to the behavior of the γ-multiplicity at mass symmetry we also observe a marked descrepancy in the mass dependence, for all targets except ^{16}O. In these calculations it is assumed that there is a correlation between orbital angular momentum and mass transfer such that the most grazing collisions lead to small mass transfers and the most central collisions correspond to symmetric mass divisions [4)].

Despite this correlation, which in addition to the mass dependence of the sticking condition, should lead to large γ-multiplicities at large mass asymmetries ($\smile$-shapes), we observe that the measured γ-multiplicity is highest at mass symmetry and drops off for both lighter and heavier masses ($\frown$-shapes). This discrepancy clearly points to the inadequacy of the equilibrium model.

One possible explanation may be that some of the spin modes are not fully relaxed, i.e. they never achieve full thermal excitation. This has already been observed for the tilting mode [10)] in quasifission reactions, where the observed anisotropy is substantially larger then expected even for equilibration of the tilting mode at the sciaaion point. The relevant time scale is the relaxation time, τ_S foı the various spin modes as compared to the characteristic time for mass relaxation, which has been measured to be in the $\tau_M \approx 5 \times 10^{-21}$ s [11)]. Let's explore the effects of such finite spin relaxation rates.

Suppose that the two macroscopic variables, S (spin) and M (mass), both relax in a diffusion process, S from its initial value of zero towards the value S_{eq}, and M from its initial value M_0 towards the value M_{eq}, with relaxation times τ_S and τ_M, respectively:

$$S = S_{eq}\left[1 - \exp(-\frac{t}{\tau_S})\right], \quad M = M_{eq} + (M_0 - M_{eq})\exp(-\frac{t}{\tau_M}) \tag{2}$$

Eliminating the explicit time dependence, we find

$$S = S_{eq}\left[1 - \left(\frac{|M_{eq} - M|}{|M_{eq} - M_0|}\right)^{\frac{\tau_M}{\tau_S}}\right] \tag{3}$$

which gives S as a power law function of M.

Figure 4 shows examples of such curves of two variables.

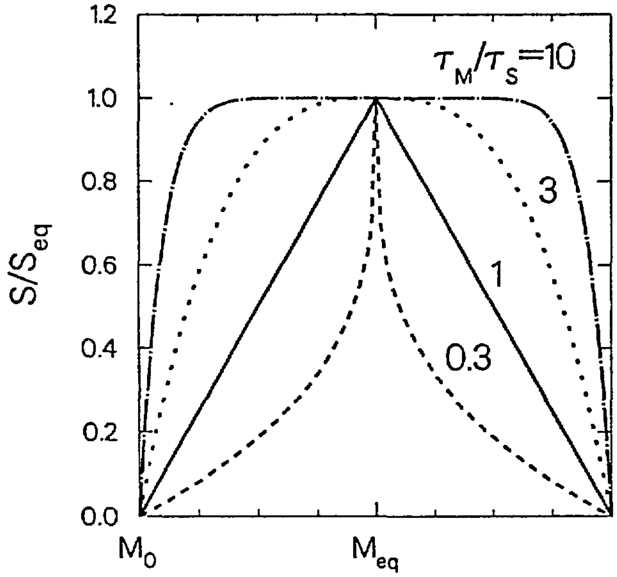

Fig. 4. Schematic relaxation curves for two quantities M (mass) and S (spin) that relax with different time constants τ_m and τ_s. The curves are labeled with the ratio τ_M/τ_S

The ⌒-shaped curves obtained experimentally are seen to indicate that the spin distribution relaxes somewhat faster than the mass distribution, the ratio between relaxation times being of the order of $\tau_S \sim \frac{1}{3}\tau_M$. The ⌒-shape of the experimental data therefore seem to indicate that the characteristic time for spin relaxation is comparable to the mass equilibration time, τ_M. This is in disagreement with calculations using the Nucleon Exchange and Transport Model [3)], which results in spin relaxation times of the order, $\tau_s = 2.5 \times 10^{-22}, 1 \times 10^{-21}, 1 \times 10^{-20}$ sec for *wriggling, bending-twisting*, and *tilting* modes, respectively, for Kr + Bi deeply inelastic scattering. The corresponding prediction for equilibration of the *rolling*, and *sticking* motions are $\tau_s = 5 \times 10^{-22}$, and 2×10^{-21} sec, respectively.

In figure 5 we show calculations where time scales for spin relaxation (except *tilting*, which is unchanged) have all been scaled by the factor indicated in the figure.

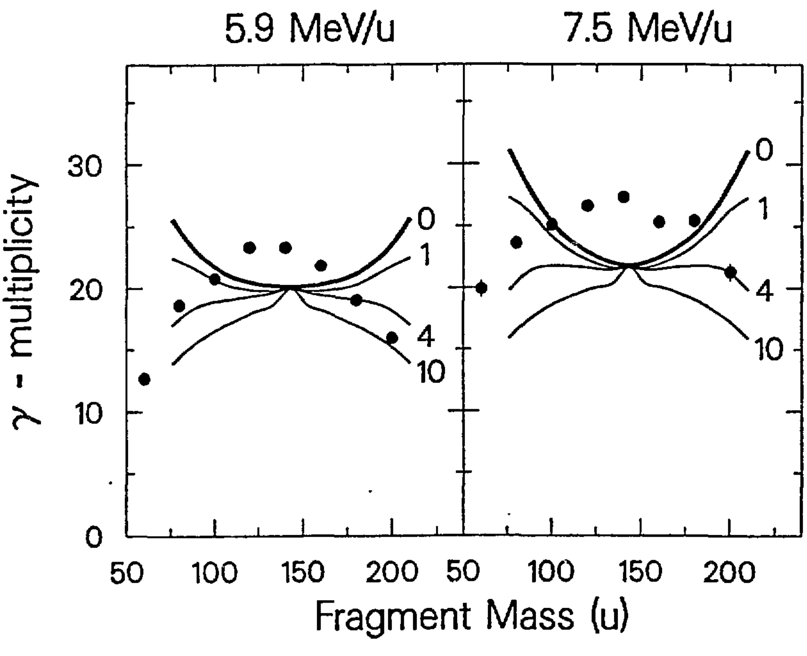

Fig. 5. Calculated average γ-ray multiplicities for the reaction $^{238}U + ^{48}Ca$ at 5.9 and 7.5 MeV/nucleon. The curves are labeled by the scaling factor for the spin relaxation time, τ_S.

The data indicate that the fastest (*wriggling*) spin relaxation time scales are of the order 5-10 times longer than predicted by the model. This discrepancy is exaggerated by the fact that the shapes associated with the quasi-fission reactions of the present study presumably are more compact, with a larger neck connecting the two interacting nuclei than those of the calculated deeply inelastic processes.

V. SUMMARY AND CONCLUSIONS

The present comparison of simple model calculations with the measured γ-multiplicities in ^{238}U induced quasi-fission reactions indicate that the angular momentum modes of the di-nuclear exit channels are only partially equilibrated. This observation is clearly at variance with the theoretical prediction of spin relaxation time scales, which are much shorter than the measured characteristic time for mass equilibration. At present, this discrepancy is poorly understood, and more detailed and specific experiments are required to clearify the situation in the future.

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