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THE ROLE OF ROTATIONAL DEGREES OF FREEDOM IN HEAVY ION COLLISIONS

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Abstract: The degrees of freedom affected by the angular momentum are identified. The relevance of the equilibrium fluctuations in a diffusive evolution of the system is discussed. The statistical limit is described and chosen as a reference for comparing with experiment. The rigid rotation regime is shown to be reached in a variety of reactions. The fragment spin alignment is measured from γ -ray multiplicities and anisotropies as well as from sequential fission angular distributions. Good agreement is obtained with the statistical model for the P_{zz} component of the polarization tensor. The P_{xy} component seems also to reach the statistical limit at large Q -value. The effect of shells on the angular momentum transferred to the fragments and on its misalignment is discussed theoretically and specific predictions are made.

1. Introduction

In contrast with most projectiles stocking the arsenal of nuclear physics, heavy ions can provide the interacting system with huge amounts of angular momentum. This is true even at relatively low velocities (a few MeV/amu over the Coulomb barrier) when the collision can be considered "gentle" under most points of view. Angular momenta as large as 500 $\hbar$ are not unusual with the heaviest target-projectile combinations. At the same time Q -values as large as 400 MeV are observed as the entrance channel kinetic energy relaxes all the way, even at substantial expense of the Coulomb barrier through a shape distortion in the exit channel. How does the system accommodate such a large amount of angular momentum? Clearly not by forming a compound nucleus (which in most cases would be frowned upon even by the Coulomb field). Deep inelastic scattering is a natural solution that allows for the maximum energy dissipation while dealing at the same time with the angular momentum by storing most of it (at least 5/7 of the total) quite inexpensively in the orbital motion of the two pieces of the dinuclear system. In this way the deep inelastic process can produce in a tidy fashion, unmarred by messy fast particle emission, pairs of compound nuclei with excitation energies as large as 200 MeV each, and angular momenta as large as 40-60 $\hbar$, a feat very difficult to achieve with ordinary compound nucleus formation processes.

The simultaneous presence in the dinuclear complex of large amounts of angular momentum and of excitation energy promotes a very characteristic thermodynamic regime that has been very nicely revealed in a rather exhaustive series of experiments and which we shall try to illustrate in this contribution.

2. The relevant degrees of freedom

In order to determine the final destiny of the angular momentum, we must find out first which degrees of freedom of the dinuclear complex can bear angular momentum. In a dinuclear system approximated by two equal touching spheres, the relevant normal modes can be identified by inspection and have been labeled as "wriggling" (doubly degenerate), "bending" (doubly degenerate), "twisting", and "tilting". All of these modes are expected to play a role in determining the magnitude and alignment of the final fragment spin. However, the role of angular momentum extends to other degrees of freedom as well. For instance, to the mass asymmetry mode. The reason for that lies in the change of rotational energy and

thus of the effective potential with mass asymmetry. Figure 1 shows how the overall topology of the potential energy vs mass asymmetry changes with angular momentum. Such changes may introduce dramatic effects in the way the various ℓ -waves populate the mass asymmetry coordinate. In the reaction shown in Fig. 1, diffusion towards masses lighter than that of the projectile is favored for low ℓ -waves and hampered if not forbidden at high ℓ -waves. The experiment demonstrates the effect by showing an abrupt decrease of the γ -ray multiplicity (a measure of the total fragment spin) for Z lighter than that of the projectile. Figure 1 also shows a diffusion calculation, which, by neatly reproducing the effect, clearly supports our explanation².

Fig. 1 (left) Potential energies vs mass asymmetry (fragment atomic number) for various ℓ -waves for the system $340 \text{ MeV } ^{40}\text{Ar} + ^{159}\text{Tb}$ (right) Gamma-ray multiplicities as a function of mass asymmetry for the same system. The solid dots represent a diffusion calculation using the potential energy surfaces on the left.

3. The dynamical and thermodynamical equilibrium limit

The extent of relaxation in other degrees of freedom may prompt the question: after all that could be dissipated has been dissipated, what is the equilibrium regime for the angular momentum? Two answers can be given. The first is a dynamical answer. If one disregards all the internal degrees of freedom, the system will settle into rigid rotation for which the intrinsic and orbital angular velocities are the same. In general, for all asymmetries, rigid rotation partitions the total angular momentum I as follows:

$$L = \frac{ur^2}{ur^2 + I_1 + I_2} I \quad I_{1,(2)} = \frac{I_{1,(2)}}{ur^2 + I_1 + I_2} I$$

where L is the orbital angular momentum, $I_{1,(2)}$ is the spin of fragment 1 or 2, $I_{1,(2)}$ is the measurement of inertia of fragment 1 or 2, and ur^2 is the orbital moment of inertia. This limit can be verified by measuring, for instance, the spin of one or both fragments as a function of mass asymmetry. An increase of the fragment(s) spin with mass asymmetry should strongly suggest rigid rotation.

However, the internal degrees of freedom cannot be disregarded. The large excitation energy commonly associated with them provides a heat bath that can thermally excite the angular momentum bearing modes. Typically the angular momenta associated with these modes are of the order $\sqrt{I\omega}$, where I is the moment of inertia of one of the two fragments. These components can easily reach 10-15 h, thus affecting the mean length and the orientation of the fragment angular momentum. The proper statistical treatment of the problem leads to a simple result expressed in terms of a probability $P(I_x, I_y, I_z)$ to find a fragment with angular momentum components I_x, I_y, I_z . If we assume that the total angular momentum of the system is aligned along the Z axis then

$$P(I_x, I_y, I_z) = \frac{1}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[-\frac{I_x^2}{2\sigma_x^2} - \frac{I_y^2}{2\sigma_y^2} - \frac{(I_z - \bar{I}_z)^2}{2\sigma_z^2} \right]$$

where $\bar{I}_z$ is the expected rigid rotation contribution to the spin of one fragment. The three σ s are approximately the same for a symmetric system (and for two touching spheres!).

$$\sigma_x^2 = \sigma_{\text{twisting}}^2 + \sigma_{\text{tilting}}^2 = \frac{6}{5} I \omega$$

$$\sigma_y^2 = \sigma_{\text{bending}}^2 + \sigma_{\text{wriggling}}^2 = \frac{6}{7} I \omega$$

$$\sigma_z^2 = \sigma_{\text{bending}}^2 + \sigma_{\text{wriggling}}^2 = \frac{6}{7} I \omega$$

The angular momentum fluctuations along the three axes become markedly different as we let the system become more and more asymmetric³⁾, as shown in fig. 2. The dramatic increase of σ_y as compared to σ_x strongly affects the in-plane distribution of the sequential fission decay of one of the two fragments and can be verified experimentally⁴⁾.

As a result of the excitation of the normal modes the fragment angular momentum becomes misaligned. Such a misalignment can be determined by measuring the angular distribution of sequentially emitted particles. With the angular momentum distribution function one can

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Fig. 2 The statistical widths for the normal modes of the dinuclear complex are shown as a function of mass asymmetry of the complex. The mass asymmetries associated with recent measurements of sequential fission angular distributions are also shown.

easily calculate the angular distributions for sequentially emitted gamma rays, particles, or fission fragments⁹⁾.

4. The relevance of equilibrium fluctuations in a diffusive evolution

Having shown what the equilibrium distribution should be is, of course, less than one-half the story, since it may be (and it is frequently the case) that the system does not quite reach the equilibrium limit. A proper discussion would then be on the particular way the system evolves in time. There are reasons to suspect that such a time evolution may be of the kind describable in terms of a Master Equation or Fokker Planck equation possibly in their simplest form⁶⁾. If this is the case, then one can argue strongly for the thermal equilibrium limit as a good predictor for the fluctuating components (not for the first moments as we shall see).

In order to show that⁷⁾, let us assume that the system is harmonically bound along the coordinate under consideration, namely:

$$V(x) = \frac{1}{2}cx^2$$

If we start from $x = x_0$ at $t = 0$ with a delta function distribution, after a time t the distribution is a Gaussian with centroid and width given by:

$$\begin{aligned} x &= x_0 e^{-cBt} \\ \sigma^2 &= \frac{T}{c} (1 - e^{-2cBt}) \end{aligned} \quad (1)$$

where B is the "mobility" of the system. After one relaxation time $\tau = 1/cB$, we have

$$\frac{x}{x_0} = e^{-1} = 0.368 ; \quad \frac{\sigma}{\sigma_{\text{equil}}} = 1 - \frac{1}{2} e^{-2} = 0.93$$

That means that, while, after one relaxation time, the centroid is still at 37% of the initial distance from equilibrium, the width is already 93% of the final equilibrium value. In other words, the width grows rapidly towards its equilibrium value independently of the starting point and can approach its limiting value while the mean may still be quite far away from equilibrium. Even after only one-half the relaxation time, the width is already 82% of its equilibrium value, while the mean is still 60% of the initial distance from equilibrium. Consequently, if the system has an inclination at all to relax towards equilibrium, we can estimate the fluctuations quite reliably by means of the equilibrium fluctuations without worrying too much about the time dependence of the process. Of course, the time dependence is a very important feature that deserves to be studied in detail. However, if we are concerned about the role of fluctuations and about their ability to scramble the experimental picture, a thorough investigation of the equilibrium limit is the most economical way to obtain information about this problem.

5. One example of rigid rotation limit

The rigid rotation limit was observed first in the rapid rise of the gamma-ray multiplicity as a function of mass asymmetry in $\text{Ne} + \text{Ag}^{8)}$. However, several Kr induced reactions failed to show the expected effect⁹⁾. While for the Au and Ho + Kr reaction angular momentum fractionation was postulated¹⁰⁾ in order to explain the lack of rise of the gamma-ray multiplicity with asymmetry, in the case of Ag + Kr one could not make such an argument due to the slight mass asymmetry of the system. On the other hand, Babinet et al.¹¹⁾ were able to infer rigid rotation on the system 280 MeV Ar + Ni by measuring the out-of-plane angular distribution of sequentially emitted alpha particles. In a somewhat similar experiment we measured both the gamma-ray multiplicity and

the out-of-plane α particle angular distribution arising from the Ag-like fragment in the reaction $\text{Ag} + \text{Kr}^{12,13}$). The angular distributions as a function of Z are shown in fig. 3a. The rapid rise of the anisotropy with increasing asymmetry suggests a corresponding rapid rise of the heavy fragment's spin. Figure 3b shows the angular distributions in coincidence with at least two gamma rays in a NaI detector array. The overall increase in anisotropy suggests that such a requirement enhances the fragment's spin, as expected.

The analysis of the angular distributions, incorporating the thermal angular momentum misalignment, leads to the spins shown in fig. 4. The

Fig. 3 Alpha-particle angular distributions as a function of out-of-plane angle for several Z -bins. Each bin is 3 Z units wide and is labeled by the median Z value. The distributions without any coincidence γ -ray requirement a) are expressed in units of differential multiplicity, whereas the distributions with two or more coincident γ rays b) are normalized to those in a) at 90° for the same Z bin. The solid lines are fits to the data.

Fig. 4 a) Center-of-mass energies as a function of the charge of the light fragment. The widths of the symbols indicate the uncertainty in the primary charge (before evaporation). The curves are calculations for two equally deformed spheroids separated by 1 fm and are labeled by the ratio of axes. b) Plotted are: the spin of the heavy fragment extracted from the α -particle distributions (solid circles), the sum of spins calculated from α -particle data (squares), and M_γ data (open circles). The sizes of the solid symbols indicate the statistical error only.

conspicuous rise of the spin with increasing mass asymmetry suggests rigid rotation. Notice how much more sensitive to mass asymmetry is the spin of the heavy fragment near symmetry as compared to the sum of spins inferred from the gamma-ray multiplicity also shown in the figure. The exit channel kinetic energy, in conjunction with the fragment's spin, gives the exit channel deformation. With it one can calculate from the spin of one fragment the spin of the other fragment and their sum, which compares satisfactorily with the same quantity inferred from gamma-ray multiplicities. The rigid rotation limit for the fragment's spin and for the sum of the spins is also shown by the solid line. Overall agreement with the rigid rotation limit is observed. Some angular momentum fractionation is also visible at the largest measured asymmetries.

6. Gamma-ray anisotropies and angular momentum misalignment

The dominance of stretched E2 decay of high spin rotational nuclei not only can be exploited to obtain the total fragment spin in deep inelastic reactions, but it can be used also to infer the spin alignment from the gamma-ray angular distributions.

The reactions 8.5 MeV/amu Ho + Ho^{14,15}) and 8.5 MeV/amu Ho + Tb, Sm, Ag¹⁶) have been studied in detail. I shall report on the last three reactions, since the first has been presented in published papers. The sum of the spins vs Q-value as inferred from the γ -ray multiplicities is shown in fig. 5. Notice that these quantities can be calculated if one knows the

Fig. 5 Sum of the spins of both fragments vs Q-values for the indicated reactions.

contribution of E1 transitions (we infer that from experiment) and the angular momenta removed by neutrons (we perform the correction following ref. 17). The introduction of a reduced ordinate following either rigid rotation or rolling and a reduced abscissa (the temperature of the dinucleus) as presented in figs. 6a,b shows essentially perfect scaling for rigid rotation. The scaling of the abscissa indicates the role of statistical effects in the behavior of the system.

The experimental anisotropies as a function of Q-value for the three systems is shown in fig. 7. A window $0.75 \text{ MeV} < E_\gamma < 0.90 \text{ MeV}$ has been set in the γ -ray spectrum. The characteristic rise and fall of the anisotropy with

increasing negative Q-value has been explained as follows. At small Q-values the rapid angular momentum transfer into fragment spin produces a rapidly rising aligned component that overwhelms the misaligning components. As the Q-value increases, the aligned component saturates or actually starts to decrease while the fluctuating components keep increasing due to the temperature increase. Thus the early rise of the anisotropy produced by the dominance of the aligned component is undone by the late dominance of the misaligned components due to the excitation of the angular-momentum-bearing modes. A quantitative calculation on the basis of the statistical model is also shown in fig. 7. The good agreement between data and experiment is a strong evidence for the thermal excitation of the angular momentum bearing modes.

The rigid rotation limit, verified by the scaling observed in fig. 6, allows one to infer the alignment for each of the two fragments. In fig. 8 the P_{zz} component of the polarization tensor is shown for both fragments. Notice how the heavy fragment always has a greater degree of alignment than the light fragment at all Q-values.

7. Sequential fission in-plane angular distributions and the test of the statistical model

In the statistical model, the fixed aligned components of the fragments' angular momenta couple to angular momentum components associated with the internal modes of the complex causing the total fragment angular momentum to become misaligned. When the reaction partners have equal masses, the thermal widths of the angular momentum components are nearly equal in the usual cartesian coordinates (x axis taken along the line of centers). However, when the reaction partners have different masses, and hence different moments of inertia, the situation changes dramatically. For instance, in the very asymmetric $^{20}\text{Ne} + ^{19}\text{Au}$ and ^{238}U systems which we have investigated⁴⁾, the statistical excitation of a number of angular-momentum-bearing modes is strongly suppressed. In particular, the large difference in the moments of inertia of the two reaction partners increases the amount of energy necessary to excite any mode in which the small fragment is forced to rotate (wriggling, bending, and twisting). The statistical widths of the angular momentum components in the heavy fragment generated by the normal modes are shown individually in fig. 2 as a function of mass asymmetry. An in-plane anisotropy arises when $\sigma \neq 0$. This is the case at large mass asymmetries due

Fig. 6 Reduced spin sum vs temperature for the indicated reactions. The rolling limit has been used for the scaling on top, while rigid rotation has been used for the scaling on the bottom.

$0.750 \text{ MeV} < E_\gamma < 0.900 \text{ MeV}$

Fig. 7 Experimental (symbols) and calculated (solid line) gamma-ray anisotropies vs Q-value.

Fig. 8 The P_{zz} component of the polarization tensor vs Q-value for the individual partners of each reaction.

to the fact that only the tilting mode remains active, while all the other modes are essentially frozen. Thus, very asymmetric reaction systems should provide an excellent test of the excitation of selected normal modes and of the statistical model in general.

In-plane sequential fission studies, which should be the most sensitive to differences between σ_x and σ_y , have given conflicting results. In ref. 18 an in-plane anisotropy was observed at low Q-values that diminished at high Q-values; however, no such anisotropies were found for a similar system in ref. 19. The apparent conflict notwithstanding, the mass asymmetries of all these systems are such that the statistical model predicts $\sigma_x = \sigma_y$ (cf. fig. 2). The $^{20}\text{Ne} + ^{197}\text{Au}$ and ^{238}U systems present a situation where this model predicts a strong in-plane anisotropy (2:1), which should peak perpendicular to the line of centers at contact.

The measured angular distributions are presented in fig. 9 for the $^{20}\text{Ne} + ^{238}\text{U}$ system as a function of Q-value. The data have been integrated over the fission fragment energy and the atomic number of projectile residues ($6 < Z \leq 14$). The direction $\phi^H = 0$ was arbitrarily chosen to coincide with

Fig. 9 The in- and out-of-plane angular distributions of sequential fission fragments in the rest frame of the heavy fragment (H) are shown as a function of reaction Q-value for the $^{20}\text{Ne} + ^{238}\text{U}$ system. The arrows indicate the in-plane angles at which out-of-plane measurements were made. The solid curves are obtained by fitting the data in each Q-value bin.

the laboratory recoil angle as is traditional. The sequential fission events observed at small Q-values have a small in-plane anisotropy. The anisotropy disappears at intermediate Q-values; however, for the most inelastic collisions a strong minimum is seen approximately perpendicular to the lab recoil direction. Statistically significant angular distributions from reactions with ^{19}Au were obtained only at large Q-values. The position of the minimum and the anisotropies of these angular distributions are essentially the same as those shown for the most inelastic ^{238}U data. The results of chi-squared

minimization fitting (K_0 values following ref. 18) are shown by the solid curves in fig. 9. In fig. 10 the z components of the heavy fragment angular momentum are shown as a function of Q-value. The remarkably large values obtained for the Au target are a reflection of the fact that in such a nucleus only the highest spins lead to fission. In fig. 10 the elements of the polarization tensor P_{zz} and P_{xy} are also shown as a function of Q-value. The lines correspond to calculations performed with different deformations of the fragments. In general, the agreement is quite good if a ratio of axes 2:1 is allowed. Also the evolution of the anisotropy of the in-plane angular distributions with Q-value are in agreement with our expectations that the statistical model is valid in the long time limit.

Fig. 10 (left) The measured aligned spin (I_z) of the target-like fragment as a function of Q-value for the 252-MeV $^{20}\text{Ne} + ^{197}\text{Au}$ and ^{238}U reactions. Spins were extracted for a broad Z-bin (6-14) for both systems and an additional narrow one ($Z = 9-10$) for the $^{20}\text{Ne} + ^{238}\text{U}$ system. The statistical errors are of the same size or smaller than the symbols.

(right) The measured alignment parameters for the spin distribution obtained for the $^{20}\text{Ne} + ^{238}\text{U}$ system are shown for $Z = 6$ to 14 (circles) and $Z = 9$ and 10 (squares). The solid and dashed curves represent the statistic equilibrium model calculations (see text).

8. Manifestation of shell effects on the angular-momentum transfer in deep-inelastic reactions

The presence of shell effects in deep-inelastic reactions has been the subject of numerous experimental and theoretical studies in the last several years. In a recent experiment along that line, the charge distribution as a

function of Q-value was measured in the reaction $208\text{Pb} + 208\text{Pb}$ at 7.6 MeV/amu²⁰). The observation of relatively small widths of the distributions when compared to those of similar heavy systems suggests the existence of a correlation between the net mass transfer and the closed-shell structure of the reactants. More generally, it is conceivable that this influence of the internal structure be exerted on other degrees of freedom of the reaction as well. In particular, we have explored the extent to which this argument applies to the angular-momentum-bearing rotational modes of the intermediate dinuclear complex using a very simple model.

In our calculation we describe the dinuclear complex by means of two touching spheres with spins S_1 , S_2 , and orbital angular momentum L . The relaxation of the rotational modes of the system as a function of interaction time is expressed by:⁶⁾

$$S_1 + S_2 = \frac{J_1 + J_2}{J_1 + J_2 + uR^2} \left(1 - e^{-t/\tau_R} \right) I$$

where J_1 and J_2 are the moments of inertia of the nuclei, u is the reduced mass of the system, R is the distance between centers, τ_R is the relaxation time constant, and I is the total angular momentum. For the dependence of the interaction time on I , we assume the following analytical expression:

$$t = \tau_1 \ln \frac{I_{\text{MAX}}}{I}$$

where I_{MAX} is the maximum angular momentum corresponding to a grazing collision and τ_1 is a constant time. From the above equations the spin transferred to the fragments can be related to the total angular momentum:

$$\frac{I}{I_{\text{MAX}}} = \left(1 - \frac{J_1 + J_2 + uR^2}{J_1 + J_2} \frac{S_1 + S_2}{I} \right)^{\tau_1/\tau_R}$$

This relation provides a means to calculate the sum of the spins as a function of the orbital energy $E = (I - S_1 - S_2)^2/2uR^2$, which can be identified with the excess exit-channel kinetic energy if the radial energy is totally dissipated.

The reduced orbital energy $\epsilon = E/E_{\text{MAX}}$ as a function of the reduced total spin $S = \frac{S_1 + S_2}{I_{\text{MAX}}}$ is shown in fig. 11a for a mass-symmetric system and four different values of the ratio τ_1/τ_R . Figure 11b illustrates the prediction of the model for the case in which one of the two fragments is magic and can carry only zero angular momentum (this is of course an extreme approximation). In addition to the expected effects due to closed-shell structure, we note that the slope of the curve in the quasielastic region (ϵ close to 1) is very sensitive to the parameter τ_1/τ_R . A comprehensive study of the dependence of gamma-ray multiplicity M_γ upon Q-value should provide some general information on this parameter, which is closely related to the relaxation time of rotational degrees of freedom.

Shell effects may be alternatively investigated by measuring the spin of the individual fragments. Our calculation indicates that for very asymmetric systems the spin of the light fragment should be very dependent on whether the heavy partner has a closed-shell structure or not. Under the same approximation made above and assuming that the rigid rotation limit is achieved we estimate ~40 percent difference in the spin of the light fragment when comparing the $\text{Kr} + \text{Au}$ and the $\text{Kr} + \text{Pb}$ reactions.

Finally we note that these estimated effects are related to the first moment of the spin distribution. Remarkably the calculation does not predict any noticeable effect on the variances as shown in Fig. 12.

The reduced variance along the symmetry axis is constant as a consequence of an exact cancellation between a stiffer twisting mode and a softer tilting

Fig. 11 Reduced sum of the spins vs reduced orbital kinetic energy for a mass symmetric system, a) for different values of the ratio τ_1/τ_R and b) for two values of l_2/l_1 .

Fig. 12 Fluctuations in the spin of one fragment as a function of the moment of inertia ratios of the two fragments at symmetry. The change in the ratio is to be interpreted as due to a varying degree of magicity of one of the fragments. Notice how the sum of the fluctuations is insensitive to the ratio.

mode as one approaches the closed-shell limit ($\Delta J = 0$). Due to a similar effect, the fluctuations on a plane perpendicular to the symmetry axis, although not constant, are also very insensitive to variations of the ratio J_1/J_2 .

It is unfortunate that, to our knowledge, no experiment has been performed so far in order to test these ideas. A comparison between the γ -ray multiplicities and γ -ray angular distributions resulting from a collision between two nonmagic nuclei, like those described in sect. 7 and those resulting from a collision between a magic and a nonmagic nucleus should hopefully be sufficient to verify the above predictions.

9. Conclusion

The comparison of a variety of experimental data with the statistical model predictions shows that in a large number of cases the rigid rotation limit as well as the statistical equilibration of the angular momentum bearing modes is in fact achieved. Even when the various processes are considered at Q-values for which rigid rotation is not established, the statistical model seems to be able to predict the fluctuations rather accurately. The shell structure of the interacting nuclei should affect the angular momentum transfer and misalignment. Such effects should be easy to detect experimentally.

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