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Angular Momentum, Statistical Equilibrium and Sequential Fission in Very Asymmetric Systems

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The in- and out-of-plane angular distributions for fission fragments in coincidence with projectile-like products from the reaction of 252 MeV ^{20}Ne with ^{197}Au and ^{238}U have been measured. The results are compared to a statistical model which has successfully explained γ-ray anisotropies from a heavy symmetric system. The agreement is rather good after proper consideration of the direction of the line-of-centers at contact.

The measurement of the internal spin and its alignment for reaction partners from deep-inelastic heavy-ion collisions (DIC) has become an important tool for studying the process of angular momentum transfer. The measurement of fluctuations in the spin components provides a good test of whether statistical equilibrium of the angular momentum bearing modes of the dinuclear complex is achieved in a DIC [1]. Evidence for statistical equilibrium has been observed in symmetric reactions which have been studied by means of γ-ray angular distributions. In the very asymmetric ^{20}Ne$+^{197}$Au and ^{238}U systems the statistical excitation of a number of angular momentum bearing modes is strongly suppressed. In particular, a large difference in the moments of inertia of the two reaction partners will increase the amount of energy necessary to excite any mode in which the small fragment is forced to rotate (wriggling, bending and twisting) [1–3]. Excitation of the only surviving mode (tilting) predicts a minimum in the angular distribution of sequential fission fragments along the line-of-centers [4]. But the direction of the line connecting the centers of the two nuclei at contact is not generally colinear with the laboratory recoil direction and is dependent on energy loss.

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The statistical equilibrium model that we employed has been developed by Moretto and Schmitt [1] and Moretto, Blau and Pacheco [2]. In this model the fixed aligned components of the fragments angular momenta couple to angular momentum components associated with the internal modes of the complex [3] 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 cartesian coordinates (x-axis taken along the line-of-centers). However, as one considers partners with progressively different masses, and hence different moments of inertia, the situation changes dramatically [4]. The statistical widths of the angular momentum components in the heavy fragment generated by the normal modes are shown individually in Fig. 1 as a function of mass asymmetry. These widths are projected onto the cartesian coordinates such that $\sigma_x^2=\sigma_{\text{tilt}}^2+\sigma_{\text{twist}}^2$ and $\sigma_y^2=\sigma_z^2=\sigma_{\text{bend}}^2+\sigma_{\text{wrig}}^2$. In general terms, if the angular momentum is predominantly perpendicular to the line-of-centers, an in-plane anisotropy arises when $\sigma_x^2 \neq \sigma_y^2$, i.e., at large mass asymmetries ($\sigma_x^2 \approx \sigma_{\text{tilt}}^2 > \sigma_y^2 \approx \sigma_{\text{bend}}^2$). Thus very asymmetric reaction systems should provide an excellent test of the excitation of selected normal modes and of the statistical model in general.

Experimental techniques used to measure the spin and its alignment for DIC products include continuum γ-ray [5, 6], alpha particle [7, 8] and sequential fission fragment [9–12] angular distributions. If one considers only reactions with the *most negative*

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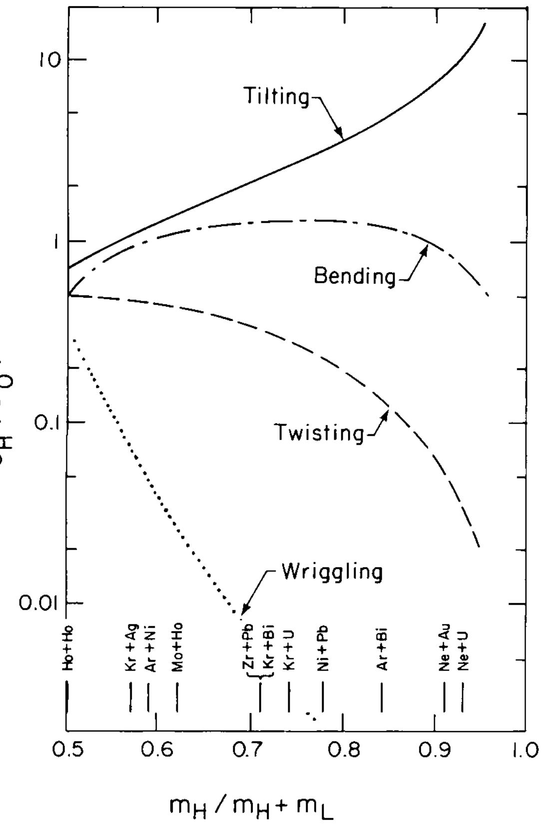

Fig. 1. The statistical widths for the normal modes of the dinuclear complex are shown as a function of mass asymmetry of the complex. The mass asymmetries associated with recent measurements of the angular distributions [5-12] are also shown

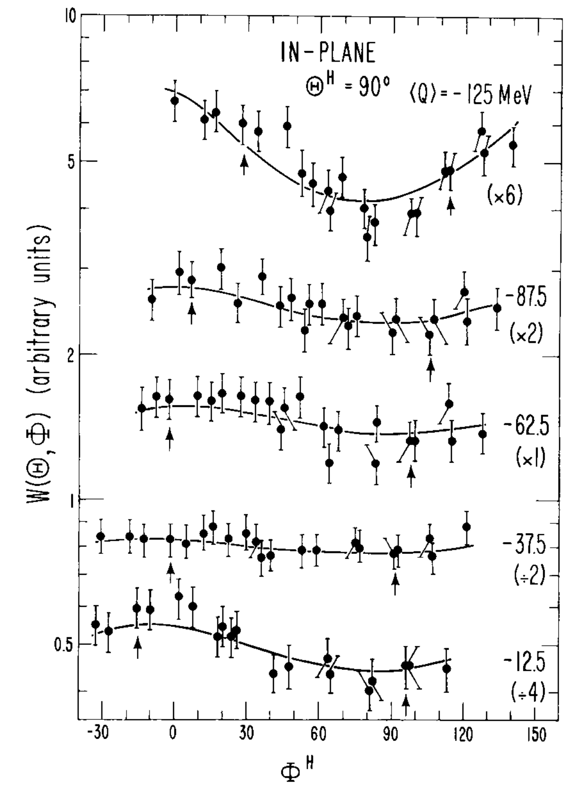

Fig. 2. The in-plane angular distributions of sequential fission fragments in the rest frame of the heavy fragment (H) are shown as a function of reaction Q-value for the $^{20}Ne + ^{238}U$ system. The arrows indicate the in-plane angles at which out-of-plane measurements were made. The solid curves result from fitting the $W(\Theta, \phi)$ function from [13] to the data in each Q-value bin

Q-values, these studies have shown that the in-plane anisotropies are small or moderate [9-12]. Admittedly, each technique has some drawback, continuum γ-rays are rather insensitive to σ_x and σ_y, whereas alpha-particle distributions must contend with large values of K_0 (the width of the projection of the total spin on the separation axis) relative to σ_x or σ_y. In-plane sequential fission studies, which should be the most sensitive to differences between σ_x and σ_y, have given conflicting results. In [9] and [10] an in-plane anisotropy was observed at low Q-values which diminished at high Q-values; however, no such anisotropies were found for a similar system in [11]. For such systems (asymmetry of 0.7) the statistical model predicts only a very small in-plane anisotropy ($\sim 1.1:1$). The $^{20}Ne + ^{197}Au$ 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.

A beam of 252 MeV ^{20}Ne from the Lawrence Berkeley Laboratory 88″ cyclotron was incident on targets of either 915 μg/cm² ^{197}Au or 922 μg/cm² $^{238}UF_4$. Projectile-like products were detected in a solid state telescope (11 μm ΔE, 300 μm E, $d\Omega = 3$ msr) fixed at $-30°$. This angle is slightly behind or right at the classical grazing angles (26° and 30°, respectively). Fission fragments were detected in coincidence on the opposite side of the beam in an array of ten single element surface-barrier detectors ($d\Omega = 9$ msr/detector), five in-plane and five out-of-plane. This array was moved to cover the angular region between $+30°$ and $+160°$ in-plane as well as between 0° and 75° out-of-plane along and perpendicular to the laboratory recoil axis. Fission fragments were unambiguously identified in a two-dimensional map of fission fragment energy versus time. The data were transformed event by event into the rest frame of the recoiling target nucleus using the energy, charge and angle of the light product and the energy and angles (Θ, Φ) of the fission fragment.

The measured angular distributions are presented in Figs. 2 and 3 for the $^{20}Ne + ^{238}U$ system as a function of Q-value. The data have been integrated over the fission fragment energy and the atomic number of projectile residues ($6 \leq Z \leq 14$). The direction $\Phi^H = 0$ was arbitrarily chosen to coincide with the labo-

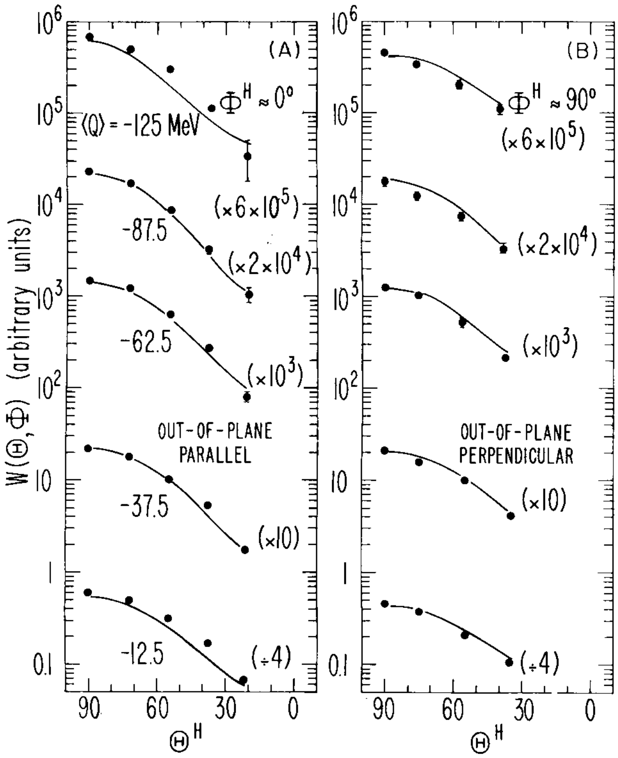

Fig. 3. The out-of-plane angular distributions that correspond to the Q bins of Fig. 2 are shown (solid points) along with the fitted functions (solid curves)

ratory recoil angle calculated as a function of Q as is traditional [9–11] (negative angles lie between the recoil direction and the beam). 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. In order to insure that evaporation was not biasing the kinematics, the data was also gated on $9 \leqq Z \leqq 10$. This gating does not alter the results, it only decreases the statistical accuracy. Statistically significant angular distributions from reactions with ^{197}Au (not shown) 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.

In order to extract quantitative values for the spin polarization of the heavy fragment we have fit the angular distribution data to the generalized function of the statistical model of Broglia et al., [13, 2]. In this description the three cartesian widths σ_x, σ_y and σ_z (defined such that x lies along the line-of-centers) appear explicitly along with the projection of the spin on the alignment axis, I_z, and the projection of I on the fission separation axis, K_0. Finally, one

Table 1. Results of angular distribution fitting including the rotation angle χ_{HF}, statistical errors are given in parenthesis

Q Value (MeV)	K_0	I_z ($\hbar$ units)	σ_x	σ_y	σ_z	χ_{HF} (degrees)
−12.5	7.3	17.7(0.5)	3.0(0.6)	6.5(0.4)	2.8(0.4)	8.0(7.0)
−37.5	10.4	27.2(0.2)	7.7(0.2)	8.8(0.2)	1.9(0.5)	16.0(9.0)
−62.5	12.0	31.1(0.3)	9.5(0.5)	5.8(0.7)	3.1(0.7)	90.0(9.0)
−87.5	13.1	37.9(0.3)	13.0(0.7)	8.6(0.9)	5.3(0.5)	94.0(9.0)
−125.0	14.3	42.4(0.6)	20.1(0.7)	0.7(4.0)	9.2(1.1)	80.0(3.0)
−125.0	Statistical model	24.1	8.7	8.7		80°

must determine the direction of the line-of-centers of the intermediate complex with respect to the traditional reference direction, the laboratory recoil angle. The appropriate choice for the line-of-centers in an equilibrium statistical model is the line connecting the centers of the two fragments at scission when the directions and magnitudes of thermally induced spin components are frozen in. In the limit of an elastic collision between rigid spheres, without loss of orbital angular momentum, the two directions coincide. But whenever there is a decrease in orbital angular momentum between the entrance and exit channels, the direction of the line-of-centers shifts backward in the laboratory system. In the limit of zero orbital angular momentum, as in spontaneous fission, the line-of-centers corresponds to the direction of the separation axis. The shift must be included in the fit, but an unconstrained angular shift creates a periodic minimum chi-squared. Rotation of $\pi/2$ commutes σ_x with σ_y, rotation of π returns the values without rotation.

An estimate of the shift angle can be made by tracing the projectile-like product backward along the coulomb trajectory that corresponds to the average orbital angular momentum, L_f, for each bin. These average values can be calculated as $L_f = L_i - I_u$, where L_i is the average initial orbital angular momentum obtained by dividing a triangular l distribution according to the observed cross section, and where I_u is the spin of the uranium nucleus obtained from the out-of-plane data. The estimated average shift angles, χ_{HF}, are ~45°, 60°, 70°, 75°, and 80° from the quasielastic to deep-inelastic bins, respectively. Variation of χ_{HF} inside a Q-bin will wash out the angular distribution, thus sharp angular distributions can be observed only for narrow ranges of L_f. The range of L_f values contributing at $Q = -125$ MeV is estimated to be quite narrow ($\lesssim 10\,\hbar$). The results of chi-squared minimization fitting (K_0 values following [9]) are shown by the solid curves in Figs. 2 and 3 and contained in Table 1.

From the results of the fitting we find that the statistical model predictions are in good agreement with all of the out-of-plane angular distributions. For the more stringent test afforded by the in-plane angular distributions this model overpredicts the anisotropy, except for the most negative Q-value where the agreement is good. These trends agree with our expectations that the statistical model represents the long-time limit which is attained in collisions with the largest energy-losses.

A statistical model prediction that the spins of the primary reaction partners would be nearly confined to the plane parallel to the line-of-centers was made on the basis of the energetics of the normal modes for a very asymmetric intermediate complex. Such confinement gives rise to large in-plane anisotropies of sequential fission fragments. After due consideration of the direction of the line-of-centers in the rest frame of the heavy recoil (where the data are presented), the statistical model prediction was shown to compare well in the limit of large Q values.

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