Rise and Fall of the Spin Alignment in Deep-Inelastic Reactions


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Both the magnitude and alignment of the transferred angular momentum in the reaction $^{161}$Ho + $^{165}$Ho have been measured as a function of $Q$ value via continuum $\gamma$-ray multiplicity and anisotropy techniques. Two regimes are observed: A low-$Q$ value regime where the aligned angular momentum component dominates over the random components, and a large-$Q$ value regime where the random components dominate and decrease the spin alignment.

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Angular momentum is known to be transferred from orbital to intrinsic degrees of freedom in heavy-ion collisions. Information regarding the mechanism of this process can be obtained from determinations of the magnitude and alignment of the fragment spin as a function of $Q$ value. The correlation of spin transfer with energy damping has been investigated with both $\gamma$-ray multiplicity ($M_{\gamma}$) and sequential-fission techniques. These studies have shown that the angular-momentum transfer increases with increasing $Q$ value until it saturates in the deep-inelastic region. For both light and heavy systems, anomalously large second moments of the $\gamma$-ray multiplicity distributions have been observed as well as small continuum $\gamma$-ray anisotropies. These data have been interpreted as evidence for the presence of random spin fluctuations. Although large anisotropies have been observed with discrete lines, doubts have been expressed regarding the feasibility of using continuum $\gamma$ rays to study either the spin transfer or alignment in deep-inelastic (DI) reactions. However, if one chooses a system where the random spin fluctuations can be made to vary from small to large relative to the magnitude of the aligned component, one may observe large corresponding changes in the continuum $\gamma$-ray anisotropy.

In this Letter we report the simultaneous measurement of the magnitude and alignment of the angular-momentum transfer in the 8.5 MeV/nucleon $^{161}$Ho + $^{165}$Ho reaction as a function of $Q$ value via continuum $\gamma$-ray multiplicity and anisotropy techniques. This system was chosen because large amounts of angular momentum can be transferred into the intrinsic spin (1) of these nuclei, which are known to have good rotational properties. Furthermore, the steep mass-asymmetry potential causes the reaction products to lie within a narrow range of $Z$ values centered around symmetry (as verified with a $\Delta E-E$ telescope). As a consequence, both of the essentially identical DI fragments emit similar continuum $\gamma$-ray spectra which are strongly enriched in $E2$ transitions (~80%) as discussed below.

A schematic diagram of the experimental setup is shown as an inset in Fig. 1. A beam of 8.5-MeV/nucleon $^{165}$Ho ions from the Lawrence Berkeley Laboratory Super HILAC bombarded a 0.85-mg/cm$^2$ self-supporting $^{10}$B target. Two silicon $E$ detectors with 4.4° acceptance angles were placed 27° from the beam axis in two perpendicular

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FIG. 1. (a) In-plane and out-of-plane $\gamma$-ray pulse-height spectra associated with reaction products having a $Q$ value of ~140 MeV. Data points are shown only for the in-plane spectrum. Detectors NaI(1) and Si(1) are in the same plane. (b) In-plane $\gamma$-ray pulse-height spectra for representative $Q$-value bins.

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lar planes. In each of these planes a 12.7-cm-diam by 15.7-cm-deep NaI detector was placed at 90° to the beam axis and at 60 cm from the target.

Figure 1(a) illustrates the general features of both the in-plane and out-of-plane γ-ray spectra emitted from the reaction fragments. The spectral shapes are similar to those observed in compound-nucleus (CN) reactions and display the characteristic "E2 bump" at ~1 MeV and the higher-energy "statistical tail" (2–5 MeV). A comparison of these two spectra indicates that the tail region is nearly isotropic, as seen in CN reactions, whereas the "bump" region is more pronounced in plane where the angular distribution for stretched E2 transitions peaks for nuclei aligned essentially perpendicular to the reaction plane.

In-plane γ-ray energy spectra, normalized so that the integral of each curve is equal to $\langle M_γ \rangle$, are shown in Fig. 1(b) for several Q-value regions. The upper edge of the "bump" moves to higher γ-ray energies as Q increases in the quasielastic (QE) region and stabilizes in the DI region. This is an indication of the Q-value dependence of the angular-momentum transfer since for rotational nuclei $E_γ \approx I$.

The angle-integrated γ-ray multiplicity was calculated from

$$\langle M_γ \rangle = N_γ / W(\text{90°}) N_{\text{sing}},$$

where $N_γ$ is the efficiency-corrected number of coincident γ rays. The angular-distribution function, $W(θ)$, is normalized such that $\int W(θ) dθ = 4π$, and $N_{\text{sing}}$ is the number of particle singles. The fragment spin after particle emission was calculated from

$$\langle I \rangle = \frac{1}{2}(I_A + I_B) = \langle M_γ \rangle + 2H - 2B,$$

where $H$ is the number of E2 transitions below the 0.3 MeV threshold (set to exclude the backscatter region) and $B$ is the number of statistical transitions per fragment. We assumed that the statistical transitions carry away angular momentum on the average, and selected the value $H = 3$ after inspecting the γ-decay schemes of even- and odd-mass products between $A = 165$ and $A = 150$.

Figure 2(a) shows the fragments' energy spectrum obtained at an angle slightly greater than the grazing angle. Figure 2(b) shows the intrinsic spin of one of the two reaction fragments after neutron emission (circles) as calculated from Eq. (2). The primary fragment spin obtained from $\langle M_γ \rangle$ with correction for neutron emission (solid line) is also shown. As seen in the data, the transferred spin rapidly increases with Q value in the QE region and saturates at about 35ℏ in the DI region. The ratio of in-plane to out-of-plane γ-ray yield ("anisotropy") for energies between 0.6 and 1.2 MeV (squares) is also shown in Fig. 2(b). This anisotropy rises with increasing spin transfer; it peaks at a value of ~2.2, slightly before the spin saturates, and then drops to near unity for large Q values.

The initial rise of anisotropy with increasing Q value indicates that during the early stages of energy damping there is rapid buildup of aligned spin. The subsequent fall observed at larger Q values suggests that the aligned component of spin has saturated or is decreasing, whereas randomly oriented components continue to increase, causing a decrease in the alignment of the fragments' spin. These qualitative features are similar to those observed with discrete lines from the $^{16}$O-$^{40}$Ti system. However, in this much heavier system, the rise and fall of the anisotropy is observed over a substantially larger Q-value range with continuum γ rays.

Interpretation of these data may be approached in several ways, e.g., dynamical models, non-
equilibrium statistical mechanics, etc. We choose to utilize the statistical-equilibrium model of Moretto and Schmitt which applies to the long-time thermal limit toward which all other models should tend. This model describes a primary depolarization mechanism which is the thermal excitation of angular momentum bearing collective modes (wriggling, tilting, bending, and twisting) in a rotating dinuclear system of equal touching spheres. The resulting distribution for the Cartesian components of the angular momentum is Gaussian:

\[ P(I_x, I_y, I_z) \propto \exp \left[- \frac{I_x^2}{2\sigma_x^2} - \frac{I_y^2}{2\sigma_y^2} - \frac{(I_z - \langle I_z \rangle)^2}{2\sigma_z^2} \right] \tag{3} \]

and, for this model,

\[ \sigma_x^2 \approx \sigma_y^2 \approx \sigma_z^2 = \sigma^2 = sT, \tag{4} \]

where \( s \) is the moment of inertia for one of the spherical nuclei and \( T \) is the temperature. This distribution function has been used to derive an expression for the \( \gamma \)-ray angular distribution in terms of \( \langle I \rangle \). Corrections have been made for contributions from the secondary depolarization process of neutron evaporation which precedes the \( \gamma \)-ray cascade.

Figure 3(a) shows experimental values of the anisotropy for \( E_\gamma \) greater than 0.3 MeV compared to several stages of the model calculation. The number of statistical transitions per fragment, \( B \), was estimated from the shape of the \( \gamma \)-ray spectra for each \( Q \)-value bin under the assumption that the intensity of the statistical transitions is described by \[ P(E_\gamma) \propto \exp(-E_\gamma/T) \], where \( T = 0.6 \text{ MeV} \). With this value for \( B \), the measured \( \langle M \rangle \), and \( H = 3 \), the spin \( \langle I \rangle \) was determined from Eq. (2), and the anisotropy was then calculated [Fig. 3(a), solid line]. This calculation reproduces both the shape and the magnitude of the data. To give a feeling for the importance of various contributions, the same calculation is shown with no correction for neutron evaporation (curve 2), assuming no statistical transitions (curve 3), and with no thermal effects (curve 4). This comparison shows that the most important effect is the thermally induced misalignment which is inherent to the deep-inelastic process itself. The contribution due to statistical \( \gamma \)-ray emission is negligible (\( \sigma^2 \sim 3N \)).

By gating on the 0.6-1.2-MeV region of the \( E_\gamma \) spectra, one both increases the fraction of \( E^2 \) transitions and biases the spin distribution to larger values \( (E_\gamma \approx I) \), which should yield larger anisotropies. In Fig. 3(b), measured (symbols) and calculated (solid line) anisotropies are shown for the 0.6-1.2-MeV \( \gamma \)-ray region. The data show the expected larger anisotropies, which the model calculations reproduce. For the alignment parameter \( P_{zz} = 3\langle I_z^2 \rangle / 2\langle I^2 \rangle - 1 \) before neutron emission, these model calculations yield a value of 0.74 for \( Q = -125 \text{ MeV} \) which decreases to 0.61 for \( Q = -400 \text{ MeV} \). This maximum value is comparable to that observed in sequential-fission studies.\(^{9,10}\)

The above \( \gamma \)-ray multiplicity and anisotropy data in conjunction with the model calculations give rise to the following picture of the reaction process. In the QE region, the transferred spin increases rapidly with \( Q \) value, whereas the thermally misaligned components increase more slowly \( (T \propto |Q|^{1/3}) \). Thus, the aligned component dominates and the transferred angular momentum is nearly perpendicular to the reaction plane, giving a large anisotropy. However, across the DI region the transferred angular momentum saturates while the thermal components increase to become an ever larger fraction of the total.
Evidence for Anomalous Nuclei among Relativistic Projectile Fragments from Heavy-Ion Collisions at 2 GeV/Nucleon

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Two independent emulsion experiments using Bevalac beams of $^{16}\text{O}$ and $^{56}\text{Fe}$ at $\approx 2$ GeV/nucleon find with $>99.7\%$ confidence that the reaction mean-free paths of projectile fragments, $3 \leq Z \leq 26$, are shorter for a few centimeters after their emission than at larger distances, or than predicted from experiments on beam nuclei. This effect, which is enhanced in later generations of fragments, can be interpreted by the relatively rare occurrence of fragments that interact with an unexpectedly large cross section.

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Evidence for anomalously short reaction mean free paths (mfp) of projectile fragments (PF) from high-energy heavy-ion collisions has been persistently reported in cosmic-ray studies since 1954; however, because of limited statistics, these results have not gained recognition. To overcome this limitation, we have performed two independent similar experiments with beams from the Lawrence Berkeley Laboratory Bevalac.

Our results, based upon 1460 events, can be summarized as follows: (a) Over the first few centimeters after emerging from a nuclear interaction ($\approx 10$ gm/cm$^2$ of matter traversed or $\approx 10^{-11}$ s proper time) the PF’s exhibit significantly shorter mfp’s than those derived from "normal" beams of the same charge $Z$; (b) at larger distances from the emission point, the mfp’s revert to "normality" in the above sense; (c) the data are incompatible with a homogeneous lowering of the mfp and require the presence among PF’s of at least one component with an unexpectedly high reaction cross section.

Two stacks of Ilford G5 nuclear research emulsion pellicles, 600 $\mu$m thick, were exposed to...