Fragment Spin Orientation in Deep-Inelastic Reactions from Anisotropy Measurements of Continuum γ Rays

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The in-plane and out-of-plane anisotropy has been measured for γ rays in coincidence with deep-inelastic products from the 1064-MeV ^{136}Xe + ^{197}Au reaction. The γ-ray energy spectra exhibit a bump corresponding to a dominantly stretched-$E2$ cascade, but only a small out-of-plane anisotropy, indicating a misalignment of the fragment spins. A simple model is used to extract a rms misalignment angle of 34° ± 7°.

Simple friction models suggest that during deep-inelastic (DI) reactions the angular momentum transferred into fragment spin should be normal to the plane of the reaction. This spin alignment should yield a strong anisotropy in the out-of-plane to in-plane intensity ratio for the γ rays emitted by the fragments if most of the spin is carried off by stretched quadrupole ($E2$) transitions. Large anisotropies are indeed observed[1] for discrete γ rays from light systems such as ^{16}O + ^{27}Al. Similarly, a strong anisotropy is also expected and has been observed in out-of-plane α-particle[2] and sequential-fission fragment[3-5] angular distributions. In contrast, measurements[6-9] of continuum γ rays have yielded relatively small anisotropies.

To account for this behavior, two not mutually exclusive explanations have been put forth. On the one hand, the small continuum γ-ray anisotropy could be due to a depolarization mechanism[4,6,7] similar to that which occurs in the fission process, namely, the excitation of collective modes carrying angular momentum (e.g., bending modes.) On the other hand, even if the fragment spins are aligned, a small anisotropy would result if there is a substantial admixture[8] of quadrupole and dipole transitions in the γ-ray cascades. The latter explanation may be more proper for light nuclei where the proportion of dipole transitions present in the continuum γ-ray spectra can be large. Thus, it is important to investigate more favorable systems where the γ-ray cascade multipolarity is relatively pure and is known, and where large amounts of angular momentum can be transferred into fragment spin.

For this purpose, we have studied the 1064-MeV ^{136}Xe + ^{197}Au reaction. The symmetric DI products from this reaction are rare-earth nuclei of mass ~160 which are known to be good rotors and have been shown[10] via (HI, xn) reactions to decay mainly by stretched-$E2$ transitions when formed with large spins. The continuum γ-ray energy spectra from such nuclei consist of a prominent (80% ± 10%) $E2$ bump[10] from 0.6 to 1.5 MeV followed by a higher energy statistical tail.

In our experiment, both the projectilelike and targetlike nuclei were detected in coincidence by two X-Y position-sensitive parallel-plate avalanche detectors.[11] These 12 × 12-cm^2 detectors have an intrinsic time resolution of 0.4 ns, and were located at 57° and −37° with respect to the beam axis and at a distance of 30 cm from the target. The γ rays were detected in four 7.6-cm × 7.6-cm NaI detectors 52 cm from the target. These detectors had an intrinsic time resolution of 1.5 ns; thus, particle-neutron events could be separated from the particle-γ events of interest in the time spectra. Self-supporting 185-μg/cm^2 ^{197}Au targets were placed in a low-mass target holder which was tilted in such a way that all detectors had an unobstructed view of the target.

In order to verify[10] the amount of $E2$ component in the γ-ray spectra and its expected anisotropy for the "symmetric products" produced in the Xe + Au reaction, we studied $^{154-156}$Dy nuclei produced in the 617-MeV ^{136}Xe + Mg compound-nucleus reaction. Representative energy spectra of γ rays detected in coincidence with the Ge(Li) detector at −150° are shown in Fig. 1(a). Both the 150° and the 90° raw NaI spectra are characterized by a "bump" of intensity below 1.2 MeV and above that by a lower intensity "statistical" tail. This bump in the γ-energy (E_γ) spectra is evidence that these Dy nuclei deexcite primarily by rotational transitions.[10] Confirmation of the $E2$ multipolarity of the transitions in this region comes from measurement of the in-plane γ-anisotropy. Figure 1(b) shows the ratios $W(150°\text{ in})/W(90°\text{ in})$ and $W(90°\text{ out})/W(90°\text{ in})$ extracted from the unfolded NaI spectra after Doppler-shift and aberration (solid angle) corrections[12] were made. (The raw data and the unfolded spectra gave the same ra-

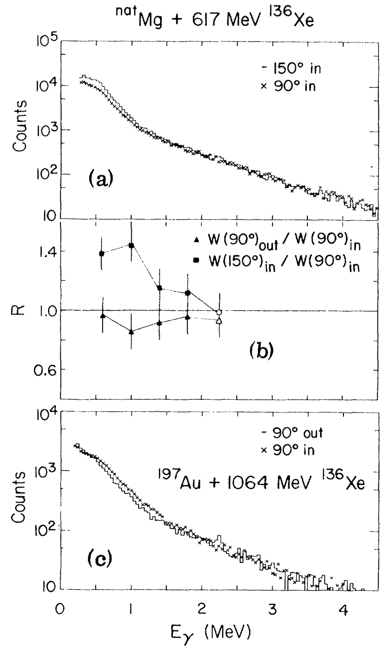

FIG. 1. (a) γ-ray pulse-height spectra of the two in-plane NaI detectors gated by the Ge(Li) detector (see text). The anisotropy of the γ-ray in-plane distribution is evident in the "bump" region (0.6–1.2 MeV) in these data. (b) The ratios $R = W(150°\text{ in})/W(90°\text{ in})$ (squares) and $W(90°\text{ out})/W(90°\text{ in})$ (triangles) as a function of E_γ. The solid symbols represent a 400–keV bin in the unfolded γ-ray spectra, whereas the open symbols represent a bin from 2 to 10 MeV. (c) γ-ray pulse-height spectra emitted by symmetric products ($152 \leq A \leq 172$) from the 1064-MeV ^{136}Xe + ^{197}Au reaction detected in the 90° in-plane and 90° out-of-plane NaI counters.

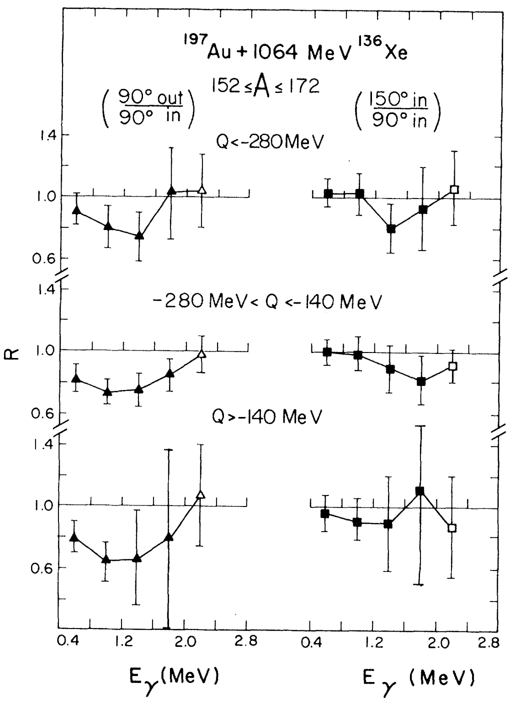

FIG. 2. The ratios $R = W(90°\text{ out})/W(90°\text{ in})$ (triangles) and $W(150°\text{ in})/W(90\text{ in})$ (squares) as a function of E_γ for the product mass range $152 \leq A \leq 172$ at three different Q-value bins.

tios to within 5%.) The observed ratios, $W(150°\text{ in})/W(90°\text{ in})$, of ~1.4 and ~1.0 for E_γ below 1.0 MeV and above 2.0 MeV, respectively, are consistent with previous measurements[10] yielding for these nuclei an ~80% stretched-$E2$ composition for the γ rays in the bump region. The ratio of $W(90°\text{ out})/W(90°\text{ in})$ does not show any marked anisotropy, which is also consistent with the above conclusions.

In the main part of this experiment, we produced DI products from the ^{136}Xe + ^{197}Au reaction. Those corresponding to a symmetric division should have masses, and a percentage of $E2$ transitions, similar to the Dy nuclei. When triple coincidences were detected for both deep-inelastic fragments and a γ ray in one of the NaI counters, the positions of the particles, their time-of-flight difference, E_γ, and the particle-γ time-to-amplitude convertor (TAC) signal were recorded on magnetic tape. Assuming a binary reaction mechanism, we extracted the Q value and the masses of both reaction products. From elastic scattering, the mass resolution was determined to be 16 amu full width at half maximum (FWHM). To define the reaction plane, the coplanarity of both fragments was restricted to be within ±6°.

In Fig. 1(c) E_γ spectra from the symmetric DI products ($152 \leq A \leq 172$) and for Q values between −140 and −280 MeV are shown for the 90°-out and 90°-in NaI counters. Both γ-ray spectra show the yrast $E2$ bump at the same position as observed in the Xe + Mg compound-nucleus reaction. This similarity indicates a rotational spectrum with predominantly stretched-$E2$ γ-ray transitions in the bump region. For this range of masses, and for the three Q-value bins ≥ -140 MeV, −140 to −280 MeV and < -280 MeV, the average γ-ray multiplicity, $\bar{M}_\gamma$, was measured to be 30, 38, and 42, respectively, assuming that five γ rays lie below the 360-keV threshold set off-line to cut out the backscatter region. These values indicate a transfer to each fragment of a large amount of angular momentum [$(24–36)\hbar$, assuming six dipole transitions], though somewhat less than that estimated ($44\hbar$) from the sticking or rolling limit for symmetric fragments and for an l_{max} of $460\hbar$.

To extract the γ anisotropy, the E_γ spectra were unfolded, and corrected for Doppler shift and aberration effects. Since one does not know which of the two similar fragments emitted the γ ray, these last two corrections were made in an average way. In Fig. 2, the out-of-plane and in-plane intensity ratios are plotted as functions of E_γ for $152 \leq A \leq 172$ and for three Q-value bins. The error bars reflect the uncertainties due to statistics, the above corrections, and the unfolding procedure. The ratio $W(90^\circ \text{ out})/W(90^\circ \text{ in})$ equals 0.75 ± 0.1 for E_γ between 0.8 and 1.6 MeV (the "bump" region), possibly decreasing slightly with decreasing Q value. For all values of E_γ, the ratio $W(150^\circ \text{ in})/W(90^\circ \text{ in})$ is near unity and independent of Q value.

The small out-of-plane anisotropy for the bump region (~80% $E2$) implies a substantial misalignment of the fragment angular momenta. The magnitude of this spin misalignment has been estimated by assuming that the probability function for misalignment is Gaussian [$P \propto \exp(-\theta^2/2\sigma^2)$] in the polar angle, peaked at $\gamma = 0^\circ$. The angular distributions for dipole and quadrupole γ rays emitted by the depolarized source was then obtained by folding the theoretical angular distributions[13] with this function, weighting by the solid angle, and integrating over all space. For 80% $E2$ transitions it was found that a standard deviation, σ, of $34^\circ \pm 7^\circ$ would reproduce the anisotropy data. If the admixture is 70% stretched $E2$'s then $\sigma = 30^\circ$. Although a possibly larger misalignment has been determined from continuum γ rays for the Ne + Cu system[9] and a smaller one from discrete γ rays for the $^{16}O + ^{27}Al$ system,[1] these differences could be explained by (1) a Q-value effect; (2) the narrower l window available for DI reactions in light systems; and (3) the larger background of dipole transitions for the $^{20}Ne + ^{63}Cu$ system or the absence of such a background for the $^{16}O + ^{27}Al$ system.[1]

Sequential-fission fragment out-of-plane distributions show comparable angular widths (25–35°).[3-5] While part of this width arises from the fission process itself, it is also true that sequential fission should select out the highest angular momenta which will tend to reduce the width. In view of this, there is no serious discrepancy between the sequential-fission data and the present experiment.

Recently Moretto and Schmitt[14] have considered the equilibrium statistical excitation of bending, twisting, tilting, and wriggling modes which are presumably responsible for the spin depolarization. Utilizing a two-sphere model, they have derived expressions for the angular momentum associated with each of these modes. The bending and twisting modes are degenerate in this model and lead to a random angular momentum I_R whose mean square value is $\bar{I}_R = (3\mathscr{I}T/2)^{1/2}$, where $\mathscr{I}$ is the moment of inertia of one of the fragments and T is the temperature. The wriggling and tilting motions also produce angular momentum components along all three coordinate axes. In this case, the angular momentum I_k is not completely random, but is nearly so and its rms value is $\bar{I}_k = (14\mathscr{I}T/5)^{1/2}$. The rms misalignment for these two modes is given by the following expression:

$$\sigma_R \simeq \tan^{-1}(\langle I_R^2\rangle/S^2)^{1/2}$$

and

$$\sigma_k \simeq \sin^{-1}(\langle I_k^2\rangle/4S^2)^{1/2},$$

where S is the spin of one of the fragments. Since the modes considered above are independent, the total misalignment can be obtained by adding the two standard deviations in quadrature. Using the experimental values of Q and $\bar{M}_\gamma$, and assuming rigid moments of inertia to calculate S and T, one obtains a misalignment, σ, of ~35°. Although the experimental uncertainties are large and the model unsophisticated, the good agreement between the experimental and theoretical values indicates that the observed γ-ray anisotropies are consistent with the thermal excitation of collective modes which depolarize the fragment spins.

In summary, we have established that for symmetric ($A \simeq 160$) DI products from the $^{136}Xe + ^{197}Au$ reaction, the E_γ spectra exhibit an $E2$ bump and a large $\bar{M}_\gamma$, but a small out-of-plane anisotropy. This provides clear evidence of a depolarization of the fragment angular momentum during the deep-inelastic process. The extracted misalignment is interpreted in terms of a statistical excitation of various depolarizing modes.

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Orbiting in the $^{12}C + ^{20}Ne$ System

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An experimental study of the $^{20}Ne + ^{12}C$ systems reveals a large cross section for inelastic scattering with large negative Q values at backward angles. The differential cross section is proportional to $1/\sin\theta_{c.m.} > 100°$ and has characteristics consistent with the decay of an orbiting $^{20}Ne + ^{12}C$ dinuclear system.

The elastic scattering of heavy ions at large angles has received much attention since the measurements of Braun-Munzinger *et al.*[1] first revealed an enhanced cross section for scattering of $^{16}O + ^{28}Si$ at center-of-mass angles larger than 100°.[2] The backward-angle enhancement seems to be a general feature for projectiles and targets in this mass region, although the size of the enhancement can vary markedly from system to system. A number of explanations have been offered for this phenomenon, such as Regge poles,[3] resonances,[4] parity-dependent potentials,[5] diffraction,[6] and particle exchange.[7] The regular broad structures appearing in the excitation functions could also be explained by orbiting in the mutual potential.[8] It would be desirable to have additional experimental data which might help in distinguishing among these various pictures. Since the interpretation of backward-angle enhancement in terms of the orbiting of projectile and target should have general consequences for inelastic scattering as well,[9] we have investigated the gross features of the inelastic scattering at backward angles. Experimental data of this type are reported here for the first time. We find both for the system $^{12}C + ^{20}Ne$, on which we report here, and for other systems as well,[10] a strong enhancement of the cross section for inelastic scattering with large negative Q values at backward angles. The gross features we observe for the inelastic scattering find a natural interpretation in terms of orbiting and support this mechanism as the origin of backward-angle enhancement of elastic scattering as well.

A natural carbon target was bombarded with beams of 50- to 80-MeV $^{20}Ne^{4+}$ from the Oak Ridge isochronous cyclotron. The reaction products with $Z > 3$ were identified with a position-sensitive ΔE-E counter[11] which spanned an angular range of 9° in 1° steps. Angular distributions

