Correlation Properties of Unresolved Gamma Rays from High-Spin States

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There is evidence that the highest-spin states observed in nuclei are basically rotational, but that each state emits a distribution of γ-ray energies rather than a single energy. We have measured the width of this distribution and the fraction of the population that emits it, for several (unresolved) γ-ray energy regions in ^{160}Er. These widths may be related to a damping of the rotational states at the high level densities through which these cascades flow.

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Evidence is accumlating that the rotational behavior of nuclei at the highest spins differs significantly from that which is familiar for lower-spin states. It has been known for some time that the γ-ray spectra following heavy-ion fusion reactions consist of both resolved and unresolved parts. The resolved lines have been intensively studied and are emitted after the population has condensed into the lowest few (cold) states of each spin. In the rare-earth nuclei, such lines are seen from states having spins as high as about $45\hbar$, and carry most of the population below spins of $(20\text{–}30)\hbar$. The rest of the spectrum is composed of unresolved lines which are thought to be emitted while the population is spread over very many states prior to condensing into the lowest few. Thus it presumably occurs at nonzero temperatures where the level density is high. It is possible to study the general properties of these unresolved γ rays, and the evidence is rather convincing that most of them are rotational-type transitions.[1] On the other hand, there should be strong correlations among the γ-ray energies in rotational bands, and these are found to be either much weaker or absent in the unresolved spectra. An important objective of high-spin physics is to learn more about the correlations remaining and to determine whether the modified rotational behavior is due to the high level density in which the bands are thought to be located, or, if not, what causes it.

The present experiments are aimed at better defining the nature of the rotational correlations in the unresolved spectra. These are displayed in plots of coincident γ-ray energies, $E_{\gamma 1}$ vs $E_{\gamma 2}$, called correlation plots.[2] The main characteristics are a valley along the diagonal of the plot ($E_{\gamma 1} = E_{\gamma 2}$) and ridges that sometimes occur on either side of this valley. These "rotational correlations" result from the properties of a "good" rotational band, $E_\gamma \approx 2I\hbar^2/\mathscr{I}$, where the difference ΔE_γ between $E_\gamma(I+2 \to I)$ and $E_\gamma(I \to I-2)$ is a constant (giving the ridges) related to the moment of inertia, $\mathscr{I}$, and no two γ rays ever have the same energy (giving the valley). Attenuation of these correlations implies that the transition energies within any particular band are not so regular as those in a "good" rotor. The effect of such irregularities is first to wash out the ridges and, as they increase further, to broaden and fill in the valley. The extent of the irregularities can be expressed as a width σ_γ of a Gaussian probability distribution for the γ-ray energies emitted by each rotational state. The normal sharp rotational energies result when σ_γ is equal to zero. To determine σ_γ, we have devised an experimental method to measure independently the width and depth of the valley at any particular γ-ray energy. The width is closely related to σ_γ, and the depth to both σ_γ and the fraction of cascades having such properties. Results have been obtained[3] for several γ-ray energy regions in ^{160}Er.

The reaction was ^{124}Sn(^{40}Ar, $4n$)^{160}Er using 185-MeV ^{40}Ar ions from the Lawrence Berkeley Laboratory 88-in. cyclotron. Eight 12.7×15.2-cm NaI detectors were placed at 1 m from the target which was nearly surrounded by the two halves of a NaI sum-energy spectrometer, each 33×20 cm thick, located above and below the plane of the other detectors. A Ge(Li) detector identified the reaction products. The adding-back[4] method of combining sum-spectrometer pulses and NaI-detector pulses was used to achieve a true NaI spectrum corresponding to a selected sum energy. A sum energy larger than ~ 10 MeV was required as a trigger for the eight NaI detectors.

To measure the valley width, we vary a gate width on the spectrum of one NaI detector and look for a change in the coincident spectrum on a second NaI detector when these two widths become comparable. To assess the detailed shape of the coincident spectrum, it is compared with a very similar spectrum, namely that in coincidence with a contiguous gate of the same width. The present analysis involves coincident spectra from pairs of contiguous gates having various widths between 20 and 200 keV and median energies of 720, 840, 960, 1080, and 1200 keV. In order to visualize our method, consider two gates, W_1 and W_2, on an idealized spectrum, Fig. 1(a), consisting of a horizontal part which would arise if the moment of inertia were constant and the population did not change, and a linearly falling part over the feeding region, i.e., the region of γ-ray energies (proportional to spin) over which the population is decreasing. The two (idealized) coincident spectra, shown in Fig. 1(b), are horizontal up to the gate location and are normalized to the same height in this region, as shown. There are "dips," corresponding to the valley, located at the gate energies, and, of course, both spectra end at the (common) upper limit of the feeding. For easy comparison we take the difference of these spectra, Fig. 1(c), which has positive values in the lower-gate and feeding regions, and more or less negative values in the upper-gate region. For quantitative evaluation, we define a height H as the difference between the most positive and most negative (or least positive) values in the vicinity of the gates. This H is then divided by the gate width W to remove the trivial effect that wider gates generate larger H values. Then H/W will increase (linearly at first) with W so long as W is less than the valley width, and thereafter it will decrease slowly. Figure 2(a) shows a real coincidence spectrum analogous to one of those in Fig. 1(b), and Fig. 2(b) is the corresponding real difference spectrum.

For each pair of contiguous gates, H/W is measured for several values of W, and σ_γ is then determined by fitting these data points with the output of a computer code simulating the cascade. For a particular sequence of γ-rays (family), the computer generates a grid of regularly spaced $\bar{E}_\gamma(I)$ values at the spin interval $\Delta I = 2$. When a state I in the family is populated, we assume that a Gaussian distribution of γ rays of width σ_γ centered at $\bar{E}_\gamma(I)$ depopulates the state. If the gate catches a gamma from I, the spectrum available to the other NaI detectors is a series of Gaussians centered at each of the other $\bar{E}_\gamma(i \neq I)$ values of the grid, but with the Gaussian at I missing. An essentially continuous spread of families is created, so that the γ-ray spectrum is essentially continuous and horizontal apart from the feeding (discussed later); however, all families have the same $\Delta\bar{E}_\gamma$, 60 keV, to which the results are relatively insensitive. A fraction δ of all the cascades is assumed to have this behavior. The remaining fraction, $1-\delta$, of the cascade have Gaussians that are wide compared to $\Delta\bar{E}_\gamma$, so that they only contribute a smooth base under the dip. The part of the difference spectrum at energies higher than both gates is most sensitive to the feeding. We assume a feeding pattern that gives rise to a linearly falling spectrum across the gate regions, and the slope of this falloff is adjusted to fit the experimental difference spectrum beyond the gate regions. The results are not very sensitive to variations of this slope around the optimum value. For particular values of σ_γ, δ, and the feeding slope, coincident spectra are generated for each pair of gates, and subtracted, as for the experimental data. A curve of H/W vs W is generated, and the best fit to the data is found by iteration.

The above method has been applied to five

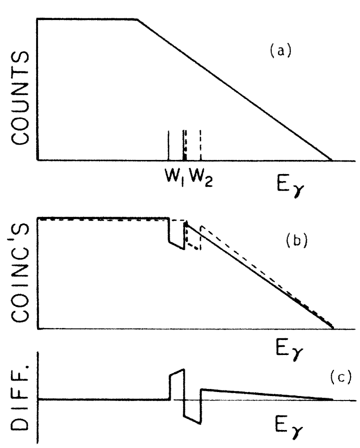

FIG. 1. (a) Idealized γ-ray spectrum with two contiguous gates, W_1 and W_2, indicated. (b) Idealized spectra in coincidence with gates W_1 and W_2. (c) Difference of the two spectra in (b).

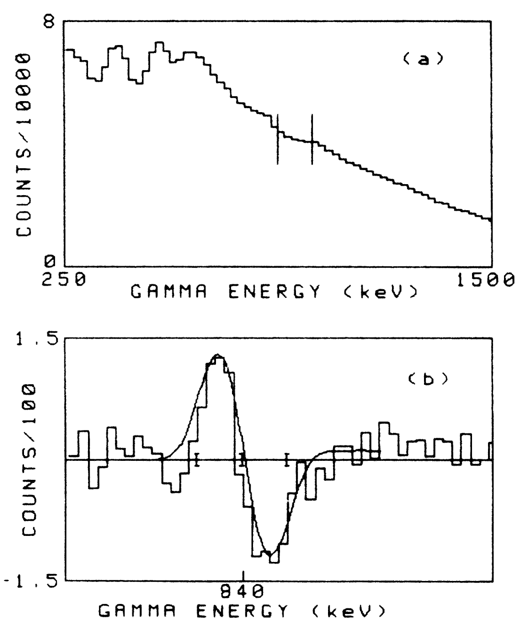

FIG. 2. (a) Coincidence spectrum for 840–940-keV gate (vertical lines). (b) Difference spectrum for gates 840–940 and 740–840 keV, indicated, with use of spectrum (a). The smooth curve is a calculated result and uses the width deduced from Fig. 3 and listed in Table I. Experimental spectra in (a) and (b) are raw data at 20 keV/channel.

contiguous-gate regions of a spectrum which contains mainly γ rays from ^{160}Er. It was found that the shape of the H/W vs W curve depends only on σ_γ, and that δ just renormalizes the vertical (H/W) scale. Thus, in practice, we first normalize the heights of these curves to 1, and determine σ_γ. This is done on raw data, since the unfolding causes more statistical variation in the spectrum, and does not affect the shape of the dip, but only the amount of smooth spectrum under it. Then the spectrum is unfolded, and δ is determined. The experimental points and best-fit curves for two contiguous-gate regions (840 and 1200 keV) are shown in Fig. 3, together with a dashed curve that shows an uncertainty limit. Also the appropriate calculated difference curve is shown in Fig. 2(b).

The experimental results (the FWHM rather than σ_γ is given) are shown in Table I. The fits represented in Fig. 3 are good, which indicates that there is a single dominant γ-ray spread (σ_γ) causing the observed dips. Below about 900 keV the widths are small and comparable to the NaI resolutions (whose effect has been removed from all values in Table I), and thus only a limit is given; however, the accuracy of the higher-energy points is rather good. Surprisingly, only 10%–20% of the population contributes to this dip. At the lower energies there could be a significant contribution from known resolved lines, but at the higher energies these are much too weak to affect appreciably the observed dip. Since this is the first experiment to evaluate σ_γ and δ simultaneously, it is the first indication of more than a single γ-ray spreading width. The measured width has a possible interpretation, as will be discussed; however, the broad spreading of most of the population (80%–90%) is still a puzzle.

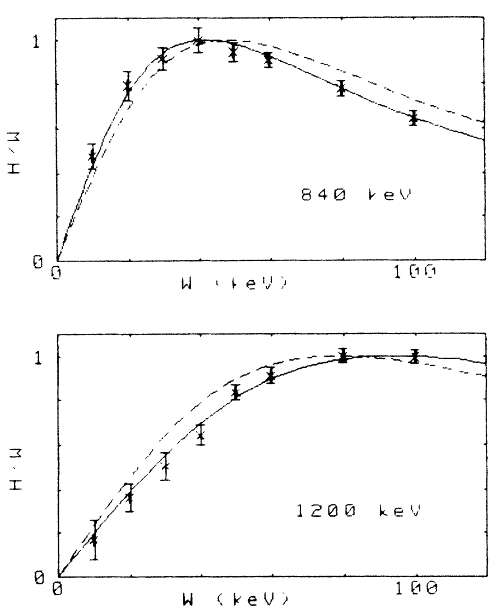

FIG. 3. Examples of the experimental points for H/W and the best fits for two median energies. The dashed curves correspond to uncertainty limits given in Table I.

An interpretation for such γ-ray spreads has been given recently. As mentioned, the high-spin γ-ray spectra are thought to occur at nonzero temperatures, where the density of background states is high. Some implications of this were considered by Leander,[5] and recently developed by Døssing *et al.*[6] It is well known that a given shell-model state in a region of high level density will be mixed (by residual interactions) into the other states over a region called the damping (or spreading) width, which increases with level density. If there were no changes in the internal nuclear structure as a function of spin, such a damping would *not* lead to a γ-ray spread for rotational nuclei. This is because, with no changes in internal structure, whatever complicated mixtures occur at spin I will also occur at spin $I+2$, and fully collective $E2$ rotational transitions will connect these related states.[7] However there *are* changes in the internal structure—the leading-order (expected) effects being due to the Coriolis interaction which tends to produce rotationally aligned particle motion. For a given spin this gives rise to a spread in particle alignments—i.e., a distribution of moments of inertia. On the other hand, in the absence of a damping width this distribution of moments of inertia would produce a superposition of sharp ridges, which would broaden the observed composite ridge, but never fill the valley inside a limit given by the largest moment of inertia—nothing like the experimental observation. However, as soon as a given level has damped so that it has components with the different moments of inertia, it no longer emits a single γ-ray energy (characterized by its moment of inertia), but emits one of a distribution of γ-ray energies corresponding to the admixed distribution of moments of inertia. The result of this mixing produces a distribution of γ-ray energies from a given state like that set up by our simulation codes, and one that probably can explain the measured experimental values of σ_γ. A characteristic size of the γ-ray spreads in this picture should be given by the spread in the moments of inertia, which is just

TABLE I. Experimental results.

Common gate border (keV)	δ	FWHM γ
720	0.09 ± 0.02	< 40
840	0.09 ± 0.02	< 40
960	0.14 ± 0.03	90 ± 15
1080	0.12 ± 0.03	70 ± 15
1200	0.17 ± 0.03	125 ± 20

equivalent to the spread in alignments. Since these total alignments vary because certain individual-particle alignments are present in some states and not in others, the scale of the variation should be given by the largest individual alignment near the Fermi level ($\sim 6\hbar$ around ^{160}Er) compared with the total spin of $(50-60)\hbar$, i.e., around 10%. This compares well with the measured γ-ray spread of 125 keV at a γ-ray energy of 1200 keV. The decrease in γ-ray spreads with decreasing γ-ray energy is also in general accord with this explanation. Thus the possibility exists that these results will give us not only information about nuclei at the very highest spins, but also about the damping of shell-model states at high level densities.

That the γ-ray spreads are caused by damping is a very interesting possibility, but it should be emphasized that this subject is still quite young and there may be other explanations. Along this line, it should be remembered that the bulk of the population (80%–90%) has a wider spread, as yet unmeasured. It is not at all clear that the Døssing *et al.* picture[6] can account for this, since it predicts decreasing γ-ray spreads at very high excitation energies (large damping widths). It will be quite interesting to characterize better both the unresolved γ-ray properties and the origin of these properties.

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