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From High-Spin States

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Abstract:

There is evidence that the highest spin states 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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In recent years techniques have improved for studying the unresolved part of the γ-ray spectra from the decay of collective states at high spin. Increasing interest has developed in the plots of coincident γ-ray energies, $E_{\gamma 1}$ vs. $E_{\gamma 2}$, called correlation plots.(1) 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" rotor, where the difference between $E_{\gamma}(I+2 \rightarrow I)$ and $E_{\gamma}(I \rightarrow I-2)$ is a constant (giving ridges) related to the moment of inertia, and no two γ rays ever have the same energy (giving the valley). Hjorth, et al.(2) experimentally studied $^{122}Sn(^{12}C,xn)$ at 106 MeV and concluded that at least half of all E2 transitions show no rotational correlation (valley) at all. They did not obtain information on the ridges, but concluded that they were distorted by the COR method(1) of removing background from the $E_{\gamma 1}$-$E_{\gamma 2}$ matrix. Love, et al.(3) found only a small ridge in ^{130}Ce, which they interpreted to mean that the probability to "stay in the band" is ~.20 for 1 MeV gammas, falling off at higher γ-ray energies. They got little information about the width of the ridge except to say that it is much larger than 15 keV, their definition of "staying in the band."

Absent or weak ridges indicate deviations from simple rotational motion, and this will tend (more slowly) to fill the valley as well. In order to determine the nature of these deviations, the most reliable quantities to measure are the width and the depth of the valley. The measured width depends a priori on the moment of inertia and the detector resolution, which are comparable in our case; about 60 keV at 1 MeV γ-ray energy. Thus any valley due only to the moment of inertia would be largely washed out for us by the NaI resolution, and therefore the moment of inertia does not play a strong role in our analysis. However, the lack of a strong valley in high-resolution Ge spectra implies in addition an irregularity or spread in the γ-ray energies within a given decay pathway (i.e. not just a spread in moments of inertia for different pathways). We call this the γ-ray spread, and it both fills in and broadens the valley. Above $E_\gamma \sim 1$ MeV this spread produces a valley that is wide enough to be measurable with NaI resolution. Over the last two years we have developed a method to measure independently the width and the depth of this valley. Using a simple model we can determine the γ-ray spread from the measured valley width. However, to explain the valley depth, we require a fraction of the γ-rays to show little or no correlation. Theoretical interest in the γ-ray spread has recently become quite high,(4) as it seems likely to be related to the damping width of the rotational states into the high density of background states at the non-zero temperatures of these cascades.

The reaction $^{124}Sn(^{40}Ar,4n)^{160}Er$ at 185 MeV from the LBL 88" cyclotron was used. Eight 12.7 cm diam x 15.2 cm NaI detectors were placed at 1 m from the target which was nearly surrounded by the two sum NaI's, each 33 cm diam x 20 cm. A GeLi detector identified the reaction products. The adding-back(5) method of combining sum pulses and NaI pulses was used to achieve a true NaI spectrum corresponding to a selected sum energy. All "sum" energies larger than ~10 MeV were accepted. Since the coincidence dips are only a few percent, the NaI spectra were not unfolded lest that introduce distortions in those dips. However, in order to assess the filling-in effect by the Comptons and the statistical gammas, the spectra were separately unfolded and corrected for statistical γ-rays extrapolated from the 2.4-4 MeV part of the spectra. Thus, effectively, we used unfolded spectra to determine the general features of the spectra, but not the detailed dip.

To measure the valley width, our general idea is to vary a gate width and look for a change in the coincident dip when these widths become comparable. The analysis involves the coincident spectra for pairs of contiguous gates of various widths 20-200 keV and of median locations 720, 840, 960, 1080 and 1200 keV. For such a pair in Fig.1a, d_2 is normalized to d_1, and the spectra are subtracted as in Fig.1b. We analyze first the shape (not the magnitude) of H vs. W. This gives the σ_γ of the assumed Gaussian γ-ray spread. Then the ratio H/d is analyzed to give, almost independently, the filling in of the valley due to other wider components of the spreading.

The principles of analysis follow. First consider that there is only one γ-ray spreading width σ_γ and a perfect detector of perfect energy resolution. For a particular sequence of γ-rays (family), there is a grid of regularly spaced $\overline{E_\gamma}(I)$'s at the spin interval $\Delta I = 2$. When a state I in the family is populated, we assume that a Gaussian spectrum of width σ_γ centered at $\overline{E_\gamma}(I)$ depopulates the state. If the gate catches a gamma from I, the spectrum available to the other NaI's is a series of Gaussians centered at each of the other $\overline{E_\gamma}(i \neq I)$ of the grid, but with the Gaussian at I missing. We consider a correlated strength function, S(I), located at $\overline{E_\gamma}(I)$, which is the sum of contributions at $\overline{E_\gamma}(I)$ from all (other) gate-caught γ rays.

$$S(I) = F(I) \sum_{i=I_{min}}^{I-2} g(i) + \sum_{i=I+2}^{I_{max}} F(i)g(i) \quad , \tag{1}$$

where I_{min} and I_{max} are the extreme spins that contribute γ rays into the gate, the sum indices step by two units of spin, F(i) is the feeding at state i, g(i) is the fraction (<1) of a Gaussian of unit area at $\overline{E_\gamma}(i)$ which is inside the gate of width W. S(I) can easily be calculated, and the final coincidence spectrum is the sum of Gaussians of width σ_γ and area $(1 - \delta)S(I)$ each centered at its $\overline{E_\gamma}(I)$, together with a wide Gaussian of area δ, where δ is the fraction of uncorrelated γ rays. The Gaussians associated with δ are wide compared to $\overline{E_\gamma}(I+2) - \overline{E_\gamma}(I)$, and only contribute a smooth base under the valley. In the calculation, Eq(1) is averaged over a continuous spread of families, all of the same $\overline{\Delta E_\gamma}$.

The fractional dip in the coincidence spectrum obtained from Eq(1) is approximately given by the fraction of all gate transitions that belong to the correlated Gaussian centered in the gate--i.e. $(1 - \delta)g_{cent}/g_{tot}$, where g_{cent} is the fraction inside the gate of the Gaussian centered in the gate and g_{tot} is the sum of all g(i)'s in a family. For the fully fed case, this is nearly exact. The primary effect of the feeding function F(I) in Eq(1) is to determine d_1/d_2 in Fig.1a, which in turn determines the relative magnitudes of the three peaks in Fig.1b. So we choose the slope of F(I) to give the best fit to the relative magnitudes of the three peaks in the experimental difference spectrum. The results are not very sensitive to variation of F(I) around this value.

Figure 2 shows the data for 100 keV gates with a common boundary at 840 keV. The top spectrum is for the higher gate; the bottom shows both the experimental and calculated difference spectra. The quantity most reliably obtainable from the data is the H shown in Fig.1b. In Fig.3 is plotted H/W vs. W/σ_{tot} for the best choice of σ_{tot}, F(I) and δ, which is found through iteration. The γ-ray spread under investigation is statistically independent from the Gaussian spread in pulse heights from a monoenergetic gamma ray in the NaI. For this reason it is σ_{tot} which is determined, from which we obtain the σ_γ of the γ-ray spread according to $\sigma_{tot} = (\sigma_\gamma^2 + \sigma_{NaI}^2)^{1/2}$. Thus Fig.3 determines σ_γ, almost independently of the value of δ. (The width of the Gaussian determined by σ_{tot} roughly corresponds to the gate width at the maximum of H/W.)

The experimental results are shown in Table 1. The fits represented in Fig.3 show that there is a dominant γ-ray spread (σ_γ) causing the observed valley. However, 80-90% (δ) of the population does not contribute to this valley. Since the other experiments have not addressed σ_γ and δ simultaneously, we feel that the present results are a substantial advance. We plan to use similar methods with high resolution detectors to determine more detailed features of the spreading widths.

The significance of the measured γ-ray spread has become much clearer since the time these experiments were begun. The high-spin γ-ray spectra are thought to be unresolved because they occur before the population "cools" to the yrast line--i.e. they occur at non-zero temperatures where the density of background states is high. Some implications of this were considered by Leander,[(6)] and recently developed by Døssing et al.[(4)] 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 spreading would <u>not</u> lead to a γ-ray spread for rotational nuclei. However there <u>are</u> changes in the internal structure--the leading order (expected) effects being due to the Coriolis interaction which tends to produce rotationally aligned particle motion that is quantized in the sense that a given state will contain certain aligned particles, but not others. For a given spin this gives rise to a spread in particle alignments or, in other words, a distribution of moments of inertia. In the absence of a damping width this distribution of moments of inertia would produce a superposition of sharp ridges, which would broaden the 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 can emit a distribution of γ-ray energies corresponding to the admixed distribution of moments of inertia. This is the situation our model represents, and one that can reproduce the experimental observations. Thus the possibility exists that our results will give us not only information about nuclei at the very highest spins, but also about the damping (spreading) of shell-model states at high level densities.

We have shown how the spread in γ-ray energies (σ_γ) emitted by a given high-spin state can be measured, and have given some results for ^{160}Er. These widths give information about nuclear behavior at both high spins and non-zero temperatures. One interpretation of them is that they result when different rotational bands having different moments of inertia are mixed together due to the high level density (damping). It should be emphasized, however, that this subject is still quite young, and the γ-ray spreads could be due to other processes. In addition, the relationship of the bulk of the population (80 to 90%) to the 10 to 20% producing these spreads is not at all clear. It will be quite interesting to characterize better both the unresolved γ-ray properties and the origin of such properties.

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Table 1

Experimental Results

Common gate border (kev)	exptl[a] H/d	δ[b]	FWHM γ[c]
720	.091 ± .014	.91 ± .02	<40
840	.089 ± .014	.91 ± .02	<35
960	.052 ± .010	.86 ± .03	90 ± 15
1080	.058 ± .015	.88 ± .03	70 ± 15
1200	.039 ± .012	.83 ± .03	125 ± 20

[a] gate width = 60 keV.
[b] δ = fraction of uncorrelated γ rays.
[c] full width at half maximum (keV) of dominant gamma ray distribution = 2.35 σ_γ.

Figure Captions

Fig.1 (a) Portions of coincidence spectra (schematic) for lower and upper contiguous gates of widths W. (b) Difference of spectra in (a) after normalizing d_2 to $d_1 \equiv d$. (c) Gaussian of unit area with $\sigma_{tot} = (\sigma_\gamma^2 + \sigma_{NaI}^2)^{1/2}$ centered at an $\overline{E_\gamma}(I)$. Its hatched area inside a gate is g(I).

Fig.2 (a) Coincidence spectrum for 840-940 keV gate (vertical lines). (b) Difference spectrum for gates 840-940 and 740-840 keV, indicated, using spectrum (a). The smooth curve is derived from Eq(1) and uses the width deduced from Fig.3 and listed in Table 1. Experimental spectra in (a) and (b) are raw data at 20 keV/channel.

Fig.3 Examples of fits of calculations to the experimental points in order to determine σ_{tot} for gates with the common energy shown. The maxima of both curves are normalized to unity. After iterations on σ_{tot}, the final fits are shown in this figure and the values derived are given in Table 1.

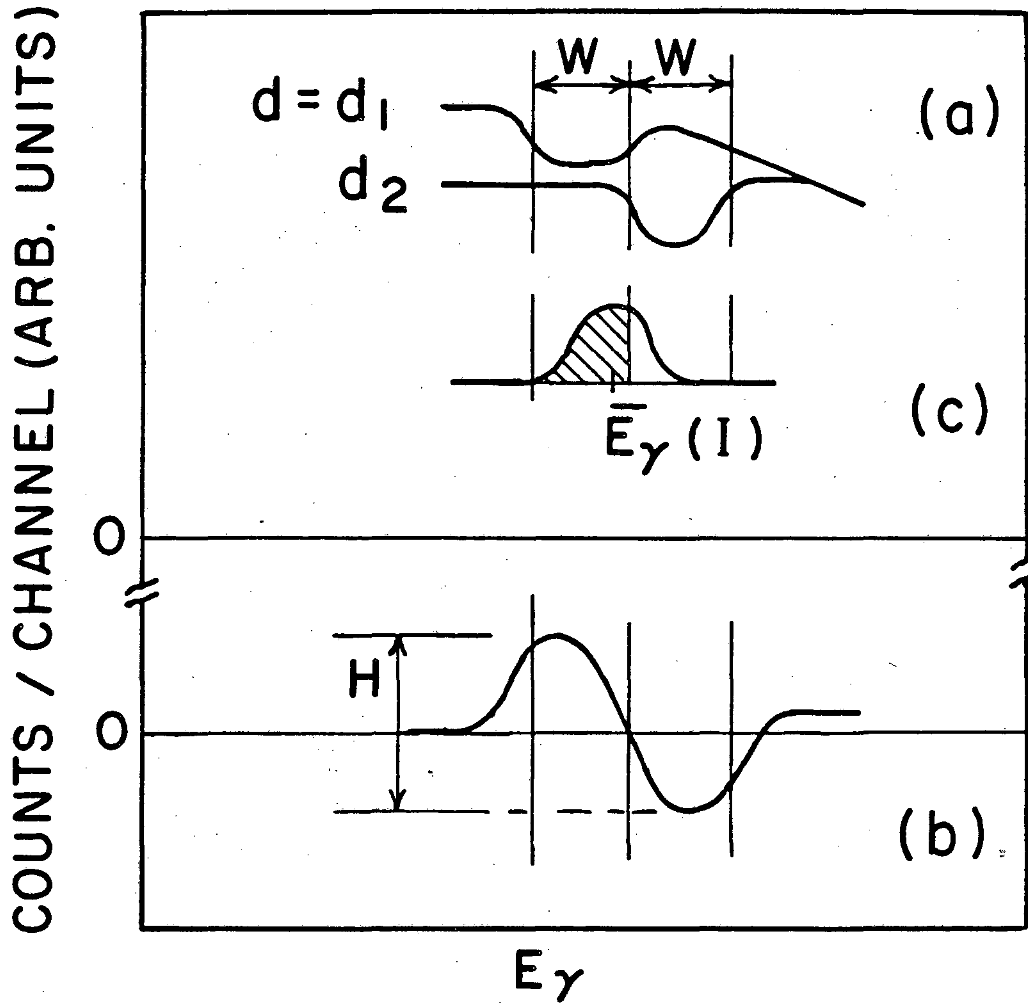

Fig. 1

XBL 857-3149

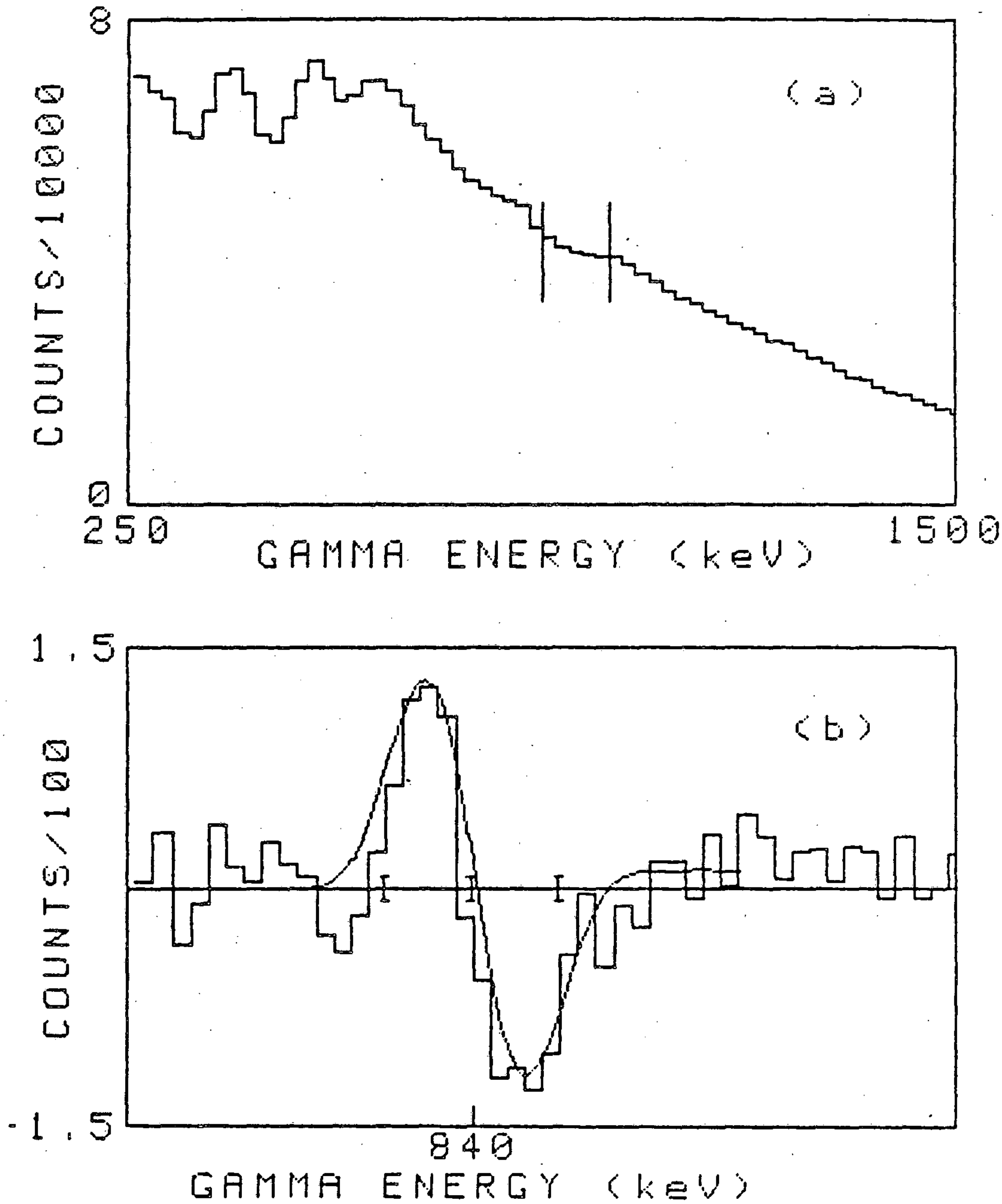

Fig. 2

XBL 857-3147

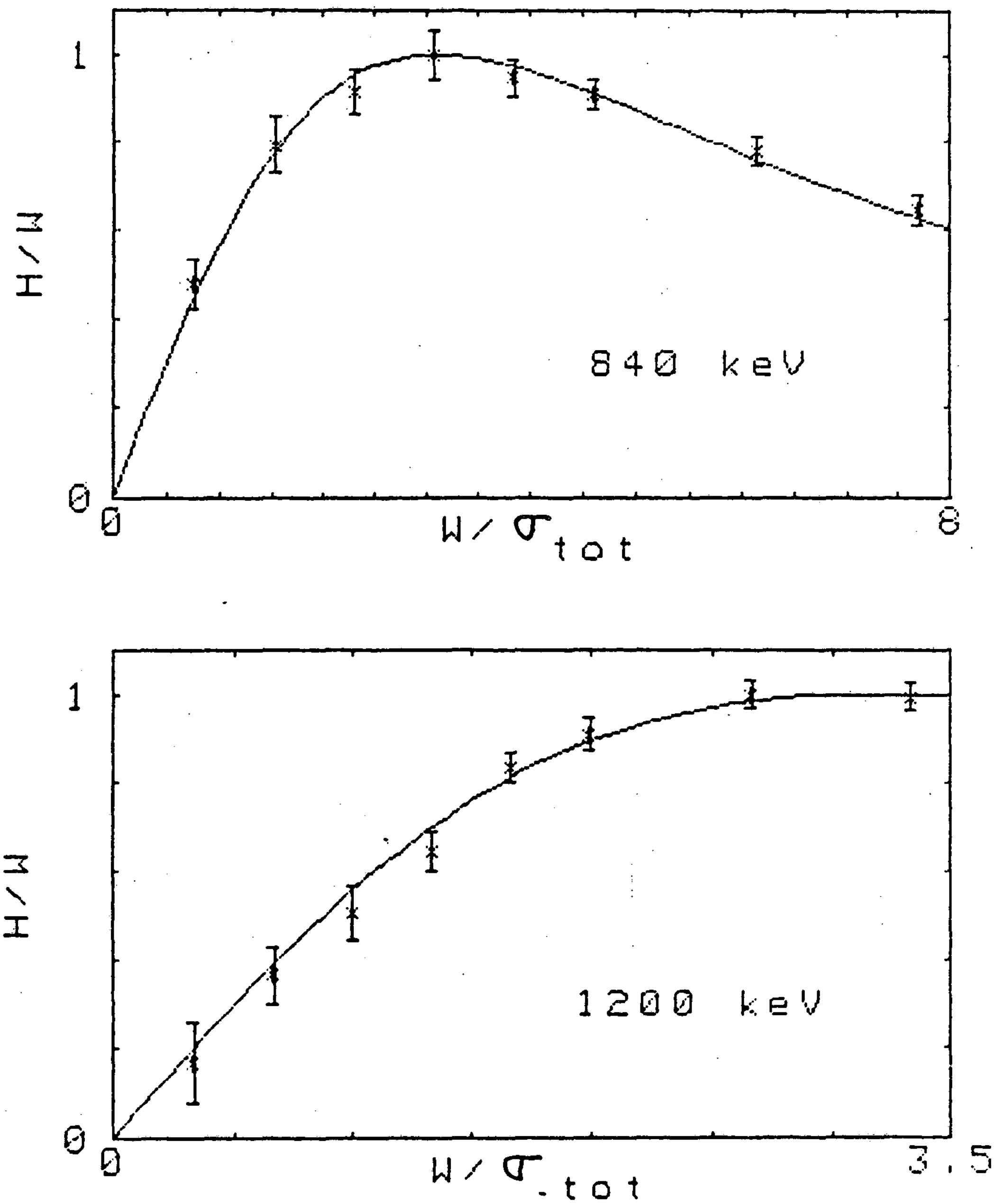

Fig. 3 XBL 857-3148

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