

### Three-Photon Correlations in Rotational Nuclei

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We have studied the correlations among energies of three  $\gamma$ -rays emitted by high-spin nuclear states. The correlation features (ridges and dip) in coincidence with two  $\gamma$  rays of a given energy are found to be the same, within our statistics, as those in coincidence with a single  $\gamma$  ray of that energy. We believe that this implies that the full  $\gamma$ -ray spectrum is a mixture of some essentially undamped rotational cascades and some rather strongly damped ones.

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Collective rotational motion is very well established in nuclei—bands exist that follow the  $I(I+1)$  energy relationship within a few percent over ranges of spin as large as  $\sim 40\hbar$ , with intraband transition probabilities up to several hundred times that expected for noncollective motion. These are seen when the nuclei are cold with respect to other degrees of freedom. One of the questions that has very recently come under study has to do with what happens to the rotational motion when other degrees of freedom are present; i.e., in “hot” nuclei—or in nomenclature in better context with other types of current nuclear studies, slightly “warm” nuclei. Evidence has been presented<sup>1-6</sup> that the rotation persists but becomes mixed with the other degrees of freedom (especially single-particle ones); that is, it is damped. The damping of various types of nuclear motion plays an important role at high temperature in nuclei, but has been virtually impossible to study in detail because of the complexity and the difficulty in controlling conditions. It appears that rotational motion, with its very characteristic decay pattern, offers a unique opportunity to study this process in the region where it initially sets in. In addition, we can hope to learn something about the underlying rotational properties of such nuclei.

Warm nuclei ( $0.2 < T < 0.7$  MeV) with high spins are produced following the evaporation of particles in heavy-ion fusion reactions. The subsequent  $\gamma$ -ray decay initially follows so many pathways that the spectrum cannot be resolved. However, the rotational behavior can still be studied through the average  $\gamma$ -ray properties. Thus, studies of the average lifetimes, directional correlations, and correlations of  $\gamma$ -ray energy ( $E_\gamma$ ) with spin have shown rather convincingly that the behavior is rotational. However, more detailed studies<sup>1,2</sup> found that the correlations between two  $\gamma$ -ray energies are much weaker than expected for good rotational behavior, leading to the suggestion of some damping.<sup>3</sup> More recently<sup>4,5</sup> attempts have begun to characterize the damping in greater detail. The present note represents an important step in this direction, where we examine the correlations between *three*  $\gamma$ -ray energies at high resolution. The first result seems to be a rather clear indication that

the main damping widths are larger than was first thought,<sup>1,2</sup> in better agreement with other types of recent studies.<sup>4,5</sup>

We have studied the reactions  $^{48}\text{Ti}(215 \text{ MeV}) + ^{124}\text{Sn} \rightarrow ^{168}\text{Hf} +$ ,  $^{40}\text{Ar}(180 \text{ MeV}) + ^{124}\text{Sn} \rightarrow ^{160}\text{Er} +$ , and  $^{40}\text{Ar}(176 \text{ MeV}) + ^{100}\text{Mo} \rightarrow ^{136}\text{Nd} +$ , using beams from the LBL 88-in. cyclotron. In each case the main ( $4n$ ) product is given, but there are two or three others (indicated by the +) made in sizable yield. The data were taken on HERA, our array of 21 Compton-suppressed germanium detectors, each of which subtends 0.75% of  $4\pi$  and has a peak-to-total ratio of about 0.5 for the  $^{60}\text{Co}$   $\gamma$  rays. Between  $3 \times 10^8$  and  $7 \times 10^8$  threefold and higherfold events were taken in each of the three cases. These were sorted into a symmetrized 250-channel three-dimensional matrix beginning at 200 keV with 8 keV per channel. This matrix was unfolded to correct for the response function of the germanium detectors and, in addition, statistical  $\gamma$  rays, which are essentially uncorrelated, were subtracted by means of a spectral shape,  $E_\gamma^3 \exp(-E_\gamma/T)$ , normalized to the high-energy part of each spectrum. The temperature,  $T$ , was obtained by a fit with the high-energy part of the total projection of the matrix. Thus single- and double-gated spectra from this matrix should not be influenced by either detector response or statistical  $\gamma$  rays.

Single-gated spectra were generated by our taking the full projection of the two-dimensional matrix (plane) in coincidence with a single (8-keV) channel of the third dimension. A number of full projections of consecutive planes were sometimes added, but only after shifting of their individual energy scales so that the gates were aligned. Thus, features correlated with the gate were preserved with no loss of resolution, whereas those not correlated with the gate were smeared out. To generate the double-gated spectra, we followed this same procedure except that, instead of the full projection of a plane, we used a three-channel (24-keV) projection in the plane, centered at the gating channel (energy) for that plane. Note that (prior to shifting and adding) each of these one-dimensional spectra has an 8-keV-wide gate defining the plane and a 24-keV-wide gate within the

plane. We shift and add the spectra from consecutive planes, thereby using information over a 200–400-keV-wide region (rather than 8 keV). This shift also corrects for the center of the gate within the plane (since it coincides with the gate defining the plane), and no further correction for gate width within the plane is possible. Thus, as a compromise between better statistics and too much smearing of the spectra, a 24-keV-wide gate within the plane was chosen. The lower limit of the region for shifting and adding was determined by the size of the resolved-line effects, and the upper limit by the absence of any significant structure. The single- and double-gated spectra are normalized to the same number of counts and shown superposed in Fig. 1 for the three reaction systems.

A good rotational band has  $\gamma$ -ray energies proportional to spin, and thus decays by a sequence of equally spaced  $\gamma$  rays. The spectrum coincident with one of these will contain all the others, but have one missing at the position of the gating transition. A superposition of  $\gamma$  rays from many good (undamped) rotational bands (that have different moments of inertia, alignments, etc.) will still have this property, where the area missing at the gate position corresponds to one transition, the width of the missing area is given by the average moment of inertia, and the coincident spectrum drops to zero in the gate region. Essentially all the experimental evidence for damping at present is that, whereas other data indicate that the higher-energy  $\gamma$  rays (from the higher-spin states) are rotational, there is not one full transition missing at the gate position. Instead, the coincident spectra have only a small “dip” at this position, whose area varies from 30% to 40% of one transition at  $\gamma$ -ray energies somewhat less than 1 MeV (for our reactions), down to zero above  $\sim 1.5$  MeV. A large damping width will wash out this ( $E_\gamma$ - $E_\gamma$  correlation) dip, since each rotational state will be able to emit any one of a variety of  $\gamma$ -ray energies instead of the usual single energy that generates the dip.

To learn more about the process occurring, we place a second narrow gate at the position of the first gate. In a superposition of  $\gamma$  rays from good rotational bands, there would be no counts in the coincident spectrum, since the dip, after just one gate, would go to zero, leaving nothing to provide a second gate. Experimentally, however, the dip is never large, so that there are counts in this double-gated spectrum as shown in Fig. 1. To understand what the damping will do to such a spectrum, we have written a computer code to simulate the cascade.

Only the most general features of the simulation code will be discussed here; some additional information is available in Ref. 5. The relevant results are not at all sensitive to the details of this code. An initial spin and excitation energy are chosen at random from reasonable distributions. Then a cascade of rotational- and statistical-type transitions deexcites the nucleus. At each step

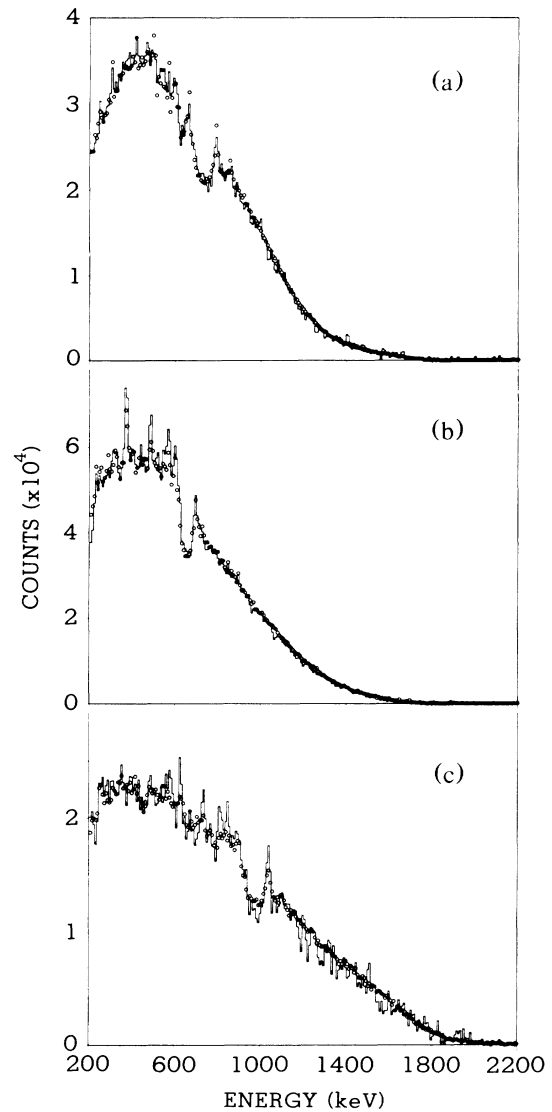


FIG. 1.  $\gamma$ -ray spectra in coincidence with a single gate (circles) and a double gate (solid line), for the (a)  $^{168}\text{Hf}$ , (b)  $^{160}\text{Er}$ , and (c)  $^{136}\text{Nd}$  data. The energy regions covered by the gates (see text) are (a) 0.68–1.00 MeV, (b) 0.60–1.00 MeV, and (c) 0.92–1.16 MeV, and they are shifted to centers (a) 0.72 MeV, (b) 0.64 MeV, and (c) 0.96 MeV.

of this cascade, the transition type is chosen at random from the two possibilities, weighted by the expected transition probabilities. The rotational properties are the most important and at low temperature, these are good rotational bands whose properties (moments of inertia and alignment) are chosen (initially, and following each statistical transition) at random from reasonable distributions. Above some critical temperature, where the damping is supposed to set in, this type of rotational behavior ends and every rotational transition energy is chosen at random from a Gaussian distribution whose

FWHM ("damping width" or  $\Gamma_{\text{rot}}$ ) is a particular chosen value. It is essential to realize that at low temperatures band properties are chosen at random, but then the cascade typically stays in that band for several transitions (producing the  $E_\gamma$ - $E_\gamma$  correlations), whereas at high temperatures every rotational transition energy is chosen at random within an energy range determined by  $\Gamma_{\text{rot}}$ .

Since the dips in Fig. 1 all have a FWHM around 100 keV, a first trial in the simulation is simply  $\Gamma_{\text{rot}}=100$  keV for all temperatures. The average moment of inertia is taken to be  $60 \text{ MeV}^{-1}$ , and the gates are always 8 keV wide and placed at 1.2 MeV. Figure 2(a) shows the result of this calculation, which can be easily understood. Both dips have roughly the FWHM of  $\Gamma_{\text{rot}}$ , and areas of one and two transitions, respectively, for the single- and double-gated spectra. Also, the area of the calculated dips is too large. One can make the calculation somewhat more realistic by having good rotational behavior below an excitation energy of 2 MeV above the yrast line ( $T=0.3 \text{ MeV}$ ), and damped behavior about that, with  $\Gamma_{\text{rot}}$  still equal to 100 keV, as shown in Fig. 2(b). Some features are better here (e.g., the peaks beside the dip—which correspond to the diagonal ridges in the two-dimensional correlation spectra and are due to the low-temperature undamped bands—and the steeper side walls of the dip due to the innermost ridges whose separation is determined by the moment of inertia), but the factor of 2 difference in area between the single- and double-gated spectra is unchanged, as is the dip area, in striking disagreement with the data. Since there must be one and two transitions missing in the single- and double-gated spectra, respectively, the only solution we have found is to make the main damping width very large, so that the associated dip becomes quite wide and therefore difficult to see. Changing  $\Gamma_{\text{rot}}$  from 100 to 300 keV gives the spectra in Fig. 2(c), which now begin to look very much like the data, in both the absolute and the relative areas of the dips. The broad dip corresponding to the 300-keV  $\Gamma_{\text{rot}}$  can hardly be seen in these spectra, and the apparent dips come from the undamped cascades below  $T=0.3 \text{ MeV}$ . To understand this result, one should remember that one gate on an undamped  $\gamma$  ray excludes the second gate (at the same energy) catching an undamped  $\gamma$  ray (the dip in undamped cascades goes all the way to zero). Thus, the second gating  $\gamma$  ray must come from the broad damped distribution, which does not affect the dip very much. One could adjust a number of additional parameters in order to make detailed fits to the experimental data, but that will not be pursued here.

These data indicate the overall behavior rather clearly: an observed dip that is (nearly) undamped, together with a broad ( $\sim 300 \text{ keV}$ ) damping width at higher temperatures. [The present measurements only set a lower limit around 300 keV, but previous work (Refs. 1–4 and refer-

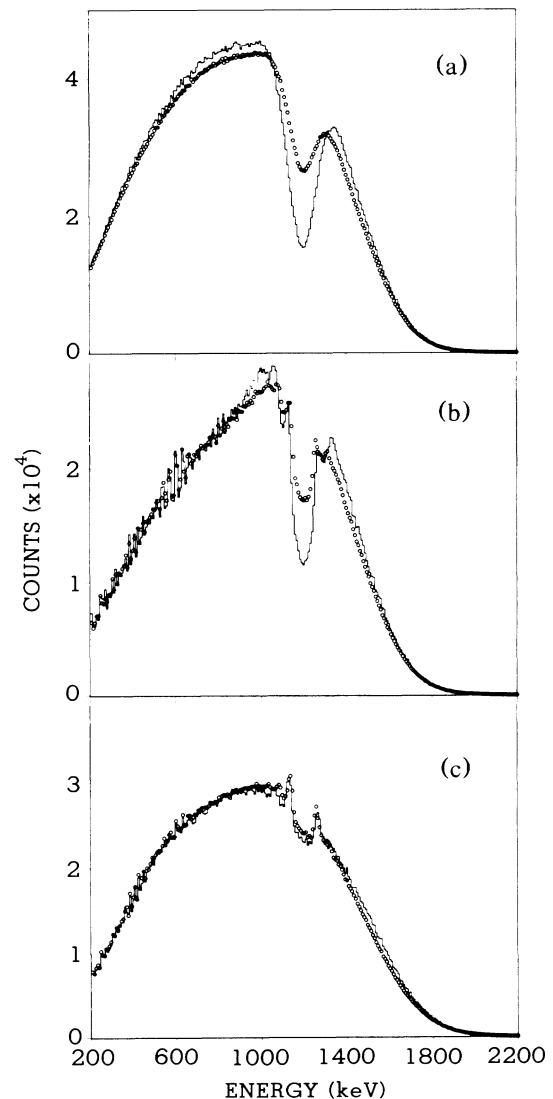


FIG. 2. Same as Fig. 1 except for simulated data with gates at 1.2 MeV (see text): (a) fully damped, width 100 keV; (b) undamped below  $T=0.3 \text{ MeV}$ , damped above (width 100 keV); (c) undamped below  $T=0.3 \text{ MeV}$ , damped above (width 300 keV). The resolved lines are suppressed in all these simulated spectra.

ences therein) shows that it cannot be much larger than this.] This type of behavior was previously suggested on the basis of the temperature dependence of the dip area<sup>4</sup> and the detailed shape of the dip.<sup>5</sup> However, the present threefold correlation data are by far the most direct indication of it. Nevertheless, this analysis represents only the first step in the extraction of information from threefold (and higherfold) data, which we feel hold great promise for giving us a much more detailed understanding of the damping process.

While the general behavior of these warm rotational

bands is becoming clearer, there remain many open questions. First, we would like to know the excitation energy or temperature at which the damping sets in, as this is the point where the average separation between levels of a given spin becomes comparable to the average matrix element connecting these levels. Whereas the dip area (in the simulation) is quite sensitive to this excitation energy, it is also strongly coupled to the cascade parameters, especially the rotational and statistical  $\gamma$ -ray transition probabilities. Thus, we need to be sure of the cascade parameters before this energy can be known reliably, but 2 MeV (as above) is in reasonable accord with theory. Second, we would like to know how suddenly the damping sets in. Since we see only essentially undamped and strongly damped behavior, a rather sudden onset of the damping is indicated (again as is expected by the theory), but more specific information would be interesting. Third, we would very much like to know if the damping is complete: i.e., whether there are types of states (like superdeformed or strongly triaxial ones) that have much smaller matrix elements connecting them with the bulk of the states, and therefore remain largely undamped over our populated temperature regions. In this connection, Egido<sup>6</sup> found that alignment variations may be damped before the normal shape variations. Finally, it would be nice to have more direct evidence that damping is indeed the process causing the observed effects. An onset of large irregularity in the rotational-band energies around 2 MeV (for example, as a result of more triaxial shapes) could explain the dip behavior, and is considered less likely than damping only because (1)

lifetime measurements suggest that the behavior is fully rotational, and (2) damping is expected to occur generally, whereas sources of irregular rotational energies (e.g., triaxiality) are not. We believe that understanding this (damping) behavior is one of the most open and interesting problems in high-spin physics.

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