Damping of Nuclear Rotational Motion at Modest Temperatures

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There is mounting evidence that the nuclear rotational motion is damped at modest ($\sim$0.5 MeV) temperatures, which reduces correlations between the energies of γ rays emitted in a rotational cascade. We observe such reduction to be strongest at the highest spins and to be larger than previously thought. Preliminary calculation shows that shape fluctuations are most likely responsible for the increased size.

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Rotational bands are well known in nuclei. In some rare-earth nuclei beautiful examples are seen that extend up to spins around $40\hbar$ and decay by emission of a sequence of γ rays that is highly correlated in time, energy, and direction. Such bands are thus normally easy to recognize. However, above about $40\hbar$ in these nuclei individual bands are not resolvable (at present) because of the very many different pathways followed, and the resulting spectra have some puzzling properties. On the one hand, they seem to be rotational—they are composed mostly of stretched $E2$ transitions ($I \rightarrow I-2$); their energies are roughly correlated with the spin (a rotor has $E_\gamma \propto I$); and, in the few measured cases, their transition probabilities are strongly enhanced over the single-particle values. On the other hand, the E_γ-E_γ correlations expected in (even unresolved) rotational bands were found to be very weak or absent. An exciting explanation of these properties was recently proposed, which involves the mixing or "damping" of rotational bands occurring at modest temperatures, where the level density is high.

The rotational damping causes each rotational state to emit, rather than the usual single γ-ray energy, one from a distribution ("spread") of energies, whose full width at half-maximum is called $\Gamma_{\rm rot}$. Two recent measurements[1,2] in rare-earth nuclei have given values for $\Gamma_{\rm rot}$ ($\sim$50–125 keV) in good agreement with those estimated[3] for the damping. However, in one of the measurements[1] a second broader spread in γ-ray energies (> 125 keV) was found to be necessary. We suggest here that this broader spread is very likely a damping effect, whereas the previously measured "narrower widths" may not be. At the same time new calculations[4] indicate that there are contributions to $\Gamma_{\rm rot}$ due to shape fluctuations (and perhaps other effects) that were not included in the previous calculation. The question of damping in these rotational bands is surely one of the most open and interesting problems in high-spin physics.

The highest-spin states in nuclei are generally populated in heavy-ion fusion reactions and studied through their γ-ray decay. The γ-ray spectrum following such a reaction has both resolved and unresolved components. The unresolved component arises at higher temperatures (1 MeV < E^* < 10 MeV; 0.2 MeV < T < 0.7 MeV) where the population is spread out over very many pathways. Such temperatures are associated with the higher-energy rotational-type transitions because their transition probabilities ($\propto E_\gamma^5$) allow them to compete against the statistical-type transitions that otherwise cool the nucleus. Many studies[5] have shown that the energy of rotational-type transitions increases with spin, which, together with the above conclusions, implies higher average emission temperatures for higher spins. The resolved component comes when the population condenses into just a "few" ($\lesssim$10, with present technology) pathways at lower temperatures. The lower-energy (lower-spin) rotational-type transitions do not compete well against the statistical transitions and the nucleus cools quickly, resulting in mostly low-temperature emissions. In a typical rare-earth nucleus the resolved lines generally are close to 100% of the population below spin 10, and decrease to $\sim$50% at spin 20 ($E_\gamma \sim$0.6 MeV) and $\sim$1% at spin 40 ($E_\gamma \sim$1 MeV), about the present limit of detection. These numbers vary considerably in different cases, but leave no doubt that lower-spin transitions occur, on average, at lower temperatures.

We study the γ-ray energy correlations in coincidence spectra. One step is to evaluate the effect on the coincident γ-ray spectrum of the requirement of a gate having a particular energy and width. There is always one transition, the gate, that must be missing from this (coincident) spectrum. In the case of a single undamped cascade, one sharp transition (the gate) is indeed missing, but with a γ-ray spread the missing transition is distributed over an energy related to the width of this spread. In a full spectrum, the undamped situation produces a rather rectangular "dip," which is smoothed and eventually washed out as a γ-ray spread of increasing size is introduced. An example of such a dip is shown in Fig. 1. Two gated spectra are shown in this figure—the lighter one is the full projection of the coincidence matrix from (mainly) ^{159}Er and ^{160}Er, and the darker spectrum is coincident with a narrow gate (24 keV width) at 1.1 MeV. The dip, resulting from the narrow gate, is ob-

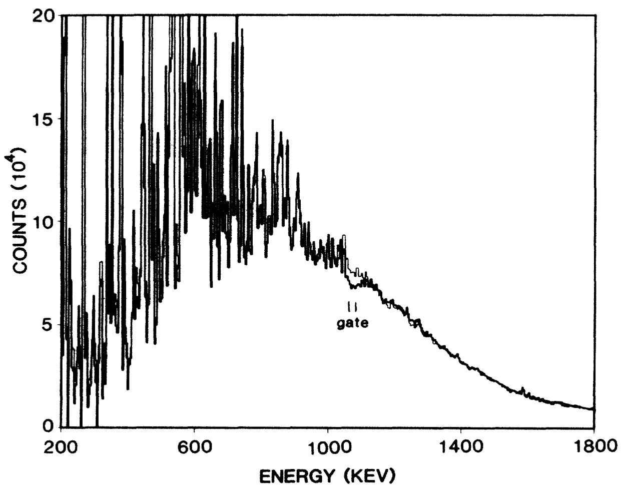

FIG. 1. Spectra from two 0.5-mg/cm^2 ^{124}Sn targets bombarded by 180-MeV ^{40}Ar ions producing mainly ^{159}Er and ^{160}Er. The lighter line is the full projection of all coincidences, whereas the darker one is coincident with the narrow gate indicated. The two-dimensional matrix from which these spectra were taken has been unfolded. The beam was provided by the Lawrence Berkeley Laboratory's 88-in. cyclotron, and the data ($\sim 1.4\times 10^9$ double coincidences) taken with the HERA array of 21 Compton-suppressed γ-ray detectors.

vious. For gates above γ-ray energies of 1.3 MeV, this dip disappears completely. However, it can be reasonably well identified between 0.8 and 1.3 MeV where its width is $\sim$90 keV and its area drops from $\sim$30% to $\sim$5% of one transition with increasing E_γ. (Note that the full coincident spectrum represents 20–25 transitions, and the area of the dip is *a priori* expected to be one transition.) The intensity pattern of this dip is very much like that of the resolved lines, which, in this spectrum, also become too weak to be observed somewhere between 1.2 and 1.3 MeV. This is a strong suggestion that the observed dip is a rather "cold" effect. Cool (undamped) bands, having moments of inertia around the rigid-body value, would produce widths around $8\hbar^2\mathcal{J}_{\text{rig}}^{-1}\approx 100$ keV, in reasonable accord with the 90 keV observed. We are at present studying the detailed shape of this dip, and currently believe that it also is consistent with being a rather cold effect that involves little damping.

On the other hand, this observed dip is a weak feature ($\sim$30% of one transition) already at γ-ray energies around $\sim$0.8 MeV [spins $(25\text{–}30)\hbar$], and to explain the spectra, the bulk of the populations must have the dip washed out. It is completely washed out above $\sim$1.3 MeV (spin $\sim 50\hbar$). This requires that the dip have a very "broad width" for these higher-energy γ rays, which are normally associated with higher temperatures (as discussed above). Both earlier studies involved a broad width directly or indirectly. In Ref. 1 it was found that most of the population at higher spins had such a broad width, which was interesting and not understood, but the authors concentrated on the measurement of the narrower width of the observed dip. In Ref. 2 a broad width was generated indirectly in their cascade model by variation of the moment of inertia and alignment during band changes associated with statistical transitions. Such individual band character implies undamped behavior, and it is not very clear at present how large an effect this had on their fits. In addition, the authors of Ref. 2 superposed a damping width Γ_{rot} on the bands. The value of this Γ_{rot} was adjusted to fit the observed dip. Thus both of these references associated the damping effects mainly with the width of the observed dip, while any broad width was either unexplained[1] or implicitly ascribed to undamped effects.[2]

We are proposing here that the main damping effects are associated with the broad width, while the observed dip is mostly an undamped feature. Our view is that Γ_{rot} is essentially zero at low temperatures, rises rather sharply near some critical temperature where the damping sets in, and then has a rather large value over a broad range of higher temperatures. A dip ($\sim$100 keV wide) will certainly be produced in the low-temperature region ($\Gamma_{\text{rot}}\sim 0$), and a smoothed dip will be generated in the region around the critical temperature, where Γ_{rot} is comparable to $8\hbar^2\mathcal{J}^{-1}$ ($\sim$100 keV). It is not yet clear whether this critical region is large enough for this smoothed dip to be observable. At the higher temperatures the rather large Γ_{rot} value is the source of the broad width which has been observed, and which makes the dip so wide and shallow as to be virtually invisible. The size of this broad width (leading to values of Γ_{rot}) would be a most interesting quantity to measure, and we have tried to do that.

Limits on this broad width have been known for some time. It must be greater than 100 keV in order to produce a dip too broad to be observed in Fig. 1. On the other hand, sum-energy gates and multiplicity gates *do* show correlations of $\bar{E}_\gamma$ with I, which require this width to be less than $\sim$400 keV. There are two methods by which we try to measure this width. To understand these, assume first that all moments of inertia are equal and constant so that E_γ is strictly proportional to spin. A gate at energy E_γ then corresponds to a particular spin, I, and can occur only if the initial population (feeding) had spin values of I or higher (with subsequent decay through I). The spectrum coincident with this gate will be constant up to E_γ (no feeding at spins below I) and then fall as the reduced feeding makes higher spin values less likely. If this spectrum continues to rise below E_γ, then E_γ is not strictly proportional to spin, and we will assume that, in this region of E_γ [1.0–1.5 MeV; $\sim(40\text{–}60)\hbar$], the main cause is a spread in the γ-ray energies emitted by each rotational state (e.g., a Γ_{rot}). Then the energy range below E_γ (the gate) over which the spectrum continues to rise is a rough measure of the width of this spread in energies. Figure 2(a) shows such a spectrum with the gate energy (1.4 MeV) indicated. The distance from the gate to the intersection of the lines in Fig. 2(a) is 350 keV, which we take to be the FWHM of the broad width (as would be the case for a triangle). From this we estimate that the FWHM of the γ-ray spread from each rotational state is around $350/\sqrt{2}=250$ keV, since the spread is involved twice: $E_\gamma \rightarrow I \rightarrow E_\gamma$. Between 1.0 and 1.5 MeV, there seems to be an increase in this spread from ~ 160 to ~ 280 keV, but this is not very clear.

Another way to evaluate the width involves a second *lower* gate, at E'_γ. If there is no γ-ray spread, all the feeding above E_γ should contribute equally to both gates.

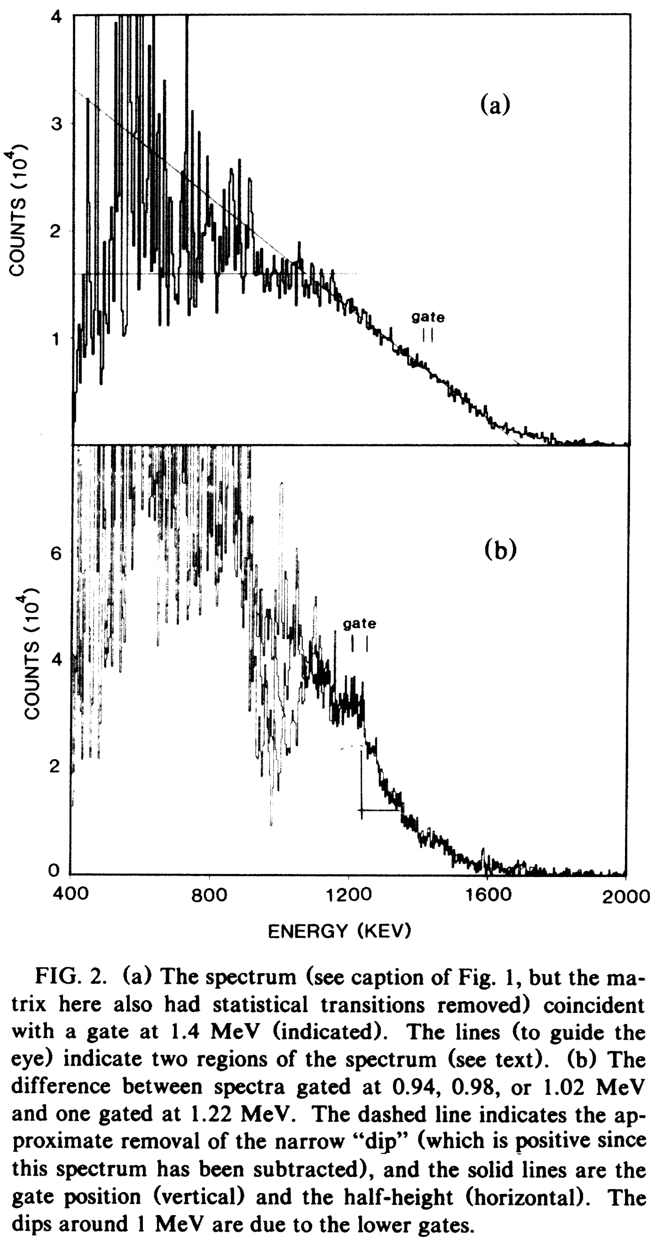

FIG. 2. (a) The spectrum (see caption of Fig. 1, but the matrix here also had statistical transitions removed) coincident with a gate at 1.4 MeV (indicated). The lines (to guide the eye) indicate two regions of the spectrum (see text). (b) The difference between spectra gated at 0.94, 0.98, or 1.02 MeV and one gated at 1.22 MeV. The dashed line indicates the approximate removal of the narrow "dip" (which is positive since this spectrum has been subtracted), and the solid lines are the gate position (vertical) and the half-height (horizontal). The dips around 1 MeV are due to the lower gates.

Thus a subtraction of the spectra should be zero above E_γ. The data for $E_\gamma=1.22$ and E'_γ values of 0.94, 0.98, and 1.02 MeV (gate widths 44 keV) are shown in Fig. 2(b). The indicated half-width at half maximum is 125 keV, from which we estimate the FWHM of the spread to be $250/\sqrt{2}=180$ keV at 1.22 MeV, reasonably consistent with the above values. Neither of these methods is very reliable. The experimental difficulties are least serious and 15–20% uncertainties in the quantities measured are reasonable. The interpretation depends on feeding patterns and moment-of-inertia variations which we do not know very well. We estimate overall uncertainties at 30%–40%. If we associated this broad width with a Γ_{rot}, then the present indications are that between $40\hbar$ and $60\hbar$ it is in the range 150–300 keV, probably increasing with E_γ(spin).

The damping mixes together states of equal spin over some interval. Below the energies where motional narrowing is important,[3] the resulting mixing bands can emit γ-ray energies characteristic of the range of admixed moments of inertia. Thus the problem of the calculation of Γ_{rot} becomes mainly that of estimation of the spread in moments of inertia over the damping interval. Moments of inertia can vary as a result of fluctuations in alignment, shape, pairing correlations, and probably other quantities. The previous calculations[3] took account only of alignment fluctuations, and reproduced rather well the narrow width then thought to be Γ_{rot}. We believe that the shape fluctuations are likely to contribute at least as much to Γ_{rot} as the alignments. These have been evaluated with use of a microscopic model described in more detail elsewhere.[4] For a given temperature T and angular momentum I, the free-energy surface, $F(\beta,\gamma)=E(\beta,\gamma)-\omega(\beta,\gamma)I-TS(\beta,\gamma)$, was explored in the Hartree-Fock approximation, where $E(\beta,\gamma)$ is the thermal expectation value of a Nilsson-type Hamiltonian, $\omega(\beta,\gamma)$ is the cranking velocity adjusted at each β,γ point to give the right angular momentum, and $S(\beta,\gamma)$ is the entropy. The minimum of this surface corresponds to the self-consistent solution of the finite-temperature Hartree-Fock equations. In this minimum for ^{160}Er, Γ_{rot} was found to vary up to ~ 100 keV. However, at the higher temperature, a broader width arose because of shape fluctuations. These were evaluated by an averaging over the β-γ surface with the Boltzmann weights. The contribution from shape fluctuations gave maximum values between 150 and 200 keV. These do not include dynamic effects that may reduce it (motional narrowing) but, on the other hand, only two shells were included in this calculation, which are obviously insufficient to give the full range of shapes. Thus we feel that the combined width is certainly in the correct range to explain the experimental data.

The situation regarding damping effects in these nuclei seems to be getting somewhat clearer. The broad width at the highest spin and temperatures seems very likely to be a damping effect, as would be expected in this region, with 150 keV $< \Gamma_{rot} <$ 300 keV. While irregular undamped cascades (e.g., due to triaxial shapes) could account for the behavior in this region, they would, in general, make the cascades slower, whereas, in the few cases measured, they are observed to be fast—as fast as in the good (low-lying) rotational bands. The simplest explanation of the observed dip is that it is mainly a cold effect. But we do expect damping to affect this dip, as was discussed, and to what extent it does is an open question. If the narrow dip turns out to be strongly affected, it could be understood as either due to a low-temperature shoulder of Γ_{rot} values around 100 keV (caused perhaps by alignment contributions coming at lower temperatures than those due to shape fluctuations), or due to structure in Γ_{rot} (at all temperatures), as might arise in the "halo" effect in Ref. 3. More work is clearly needed to resolve these questions.

It is apparent that we do not yet understand the damping of rotational bands in nuclei at modest temperatures. But we are progressing—and it is an interesting problem. Because of the high level density at modest temperatures, the rotational bands mix, and thereby start mixing internal degrees of freedom into the (external) rotation. This is the first small step in the transition from order (the deformed nucleus rotating collectively) to chaos (a hot nuclear gas) or, equivalently, in the restoration of rotational invariance to the deformed nuclei, whose intrinsic shapes break this symmetry. It is not often in nuclei that this first step can be so well isolated and studied.

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