Title
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Damping In Yb Nuclei

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Abstract. In a mixture of three Yb nuclei, we find the rotational damping widths vary from 180 keV at 1.1 MeV γ-ray energy to 290 keV at 1.5 MeV, and the *average* compound damping widths (or spreading widths) vary from 40 keV at 1.1 MeV γ-ray energy to 60 keV at 1.3 MeV. The simulations also suggest extensive motional narrowing.

INTRODUCTION

When one or two MeV of thermal energy is added to nuclei like those studied here, the level separations become very small and the levels mix due to small residual two-nucleon interactions that are ineffective near the ground state. This process is the damping of the nucleonic motion from ordered to chaotic. The same high level density that induces the mixing causes the emitted γ-ray spectra to consist of very many lines, currently unresolvable, making studies difficult. Nevertheless, there is a lot of information buried in this unresolved "continuum", having to do both with the order-to-chaos transition and with the very highest angular momenta in nuclei that can be studied using these γ-ray techniques. Matsuo et al. [1] have recently suggested that it may be possible to measure two kinds of damping that occur concurrently in these rotational nuclei. The first of these is the damping of the rotational motion, a well known process [2], and measurement of this damping width, Γ_{rot}, was the subject of our recent paper [3]. Matsuo has suggested that a second kind of damping, superimposed on this rotational damping, comes from the spreading width due to the mixing of the levels. This spreading width, also called the compound damping width, is labeled Γ_{μ}. Matsuo saw evidence for this width in his calculations and we give here preliminary measurements of it in some Yb nuclei.

EXPERIMENTAL

One way to study damping is to look at correlations in the spectrum in coincidence with a given γ-ray energy (the gate). Such spectra show the relative likelihood that γ rays are associated with the gating γ ray. An undamped rotational band has the property that the emitted γ rays are roughly proportional to the spin and therefore the decay of a high-spin state consists of a sequence of approximately equally spaced lines with monotonically decreasing energies (like a picket fence). A gate on one of these γ rays will be associated with all the others, but not with itself. This generates a strong negative correlation at the gate energy in the gated spectrum, called the "rotational" correlation, which has an area of exactly one transition, the missing gate. This property is the basis for most of our techniques to study the damping.

The correlation spectra, "CORs", are generated from the 2D $E_{\gamma} - E_{\gamma}$ matrix using the the COR procedure [4] which removes an uncorrelated background. This background assumes that every γ ray has equal probability to be in coincidence with every other γ ray and is the full-projection spectrum normalized to the area of the gated spectrum.

The data were taken using Gammasphere at the LBNL 88-Inch Cyclotron to record γ rays from the reaction of 215 MeV ^{48}Ca projectiles on a 1 mg/cm^2 target of ^{124}Sn. This reaction forms the fusion product, ^{172}Yb, which decays into the product nuclei, ^{168,167,166}Yb, with yields of roughly 20, 40, and 40%, respectively. Events were stored if 5-or-more clean (no hit in the Compton suppressor) γ rays were in coincidence. About 2x10^{9} such events were recorded and sorted into the 2D matrix.

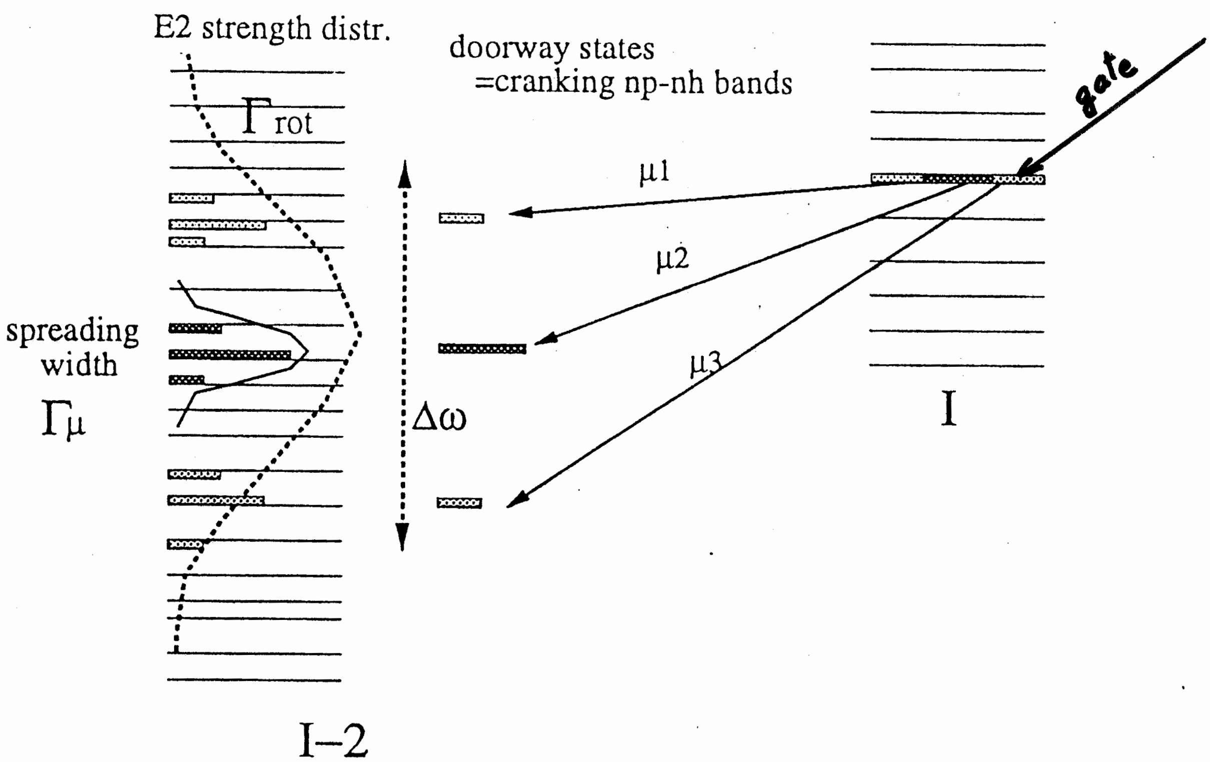

FIGURE 1. An illustrative sketch of the mixed levels and transitions involved in rotational and compound damping. A gate is shown populating one of the components of a level of spin, I. This figure is from Matsuo [1].

DAMPING

The relationship between rotational damping and compound damping is illustrated in Fig. 1. In the continuum region the levels are mixed and a level (of spin, I) with three components ($\mu 1, \mu 2, \mu 3$) is shown on the right side of Fig. 1. Each of these components has different rotational properties and thus emits rotational γ rays having different energies. The level can then emit γ rays having any of these energies. This generates a distribution of γ-ray energies called the E2 strength distribution, whose width is Γ_{rot}. This width depends only on the rotational properties of the admixed states. However, the new thing Matsuo noticed is that the wave function corresponding to each component will be spread over several levels in the daughter (I - 2) nucleus, as well. This is illustrated on the left side of Fig. 1, where each component is schematically spread over three levels. The width of this distribution is Γ_{μ} which is just the normal spreading width due to the residual interactions. This width has essentially nothing to do with the rotational properties. It is apparent that it would be difficult to separate Γ_{μ} from Γ_{rot} in the full spectrum.

However, in a gated spectrum the gate will come in via one of the three components as illustrated in Fig. 1. The level can then decay via any of the components, but if it decays by the same (entry) component, it will have the sharp energy correlation characteristic of that rotational band, spread only by the distribution of the final states, Γ_{μ}. If it decays via either of the other two components, the width will be the full Γ_{rot}. Thus, if the components have equal amplitudes, one third of the events will have a width, Γ_{μ}, while two thirds have a width, Γ_{rot}. In the limit of only one component in the parent and daughter this results in just a single band, a very familiar situation. In the limit of many components, say 100, the probability of entering and leaving via the same component is small, 1%, and only Γ_{rot} will be seen. We want to study the intermediate situation where both widths have appreciable intensity and I hope to convince you that we can measure both.

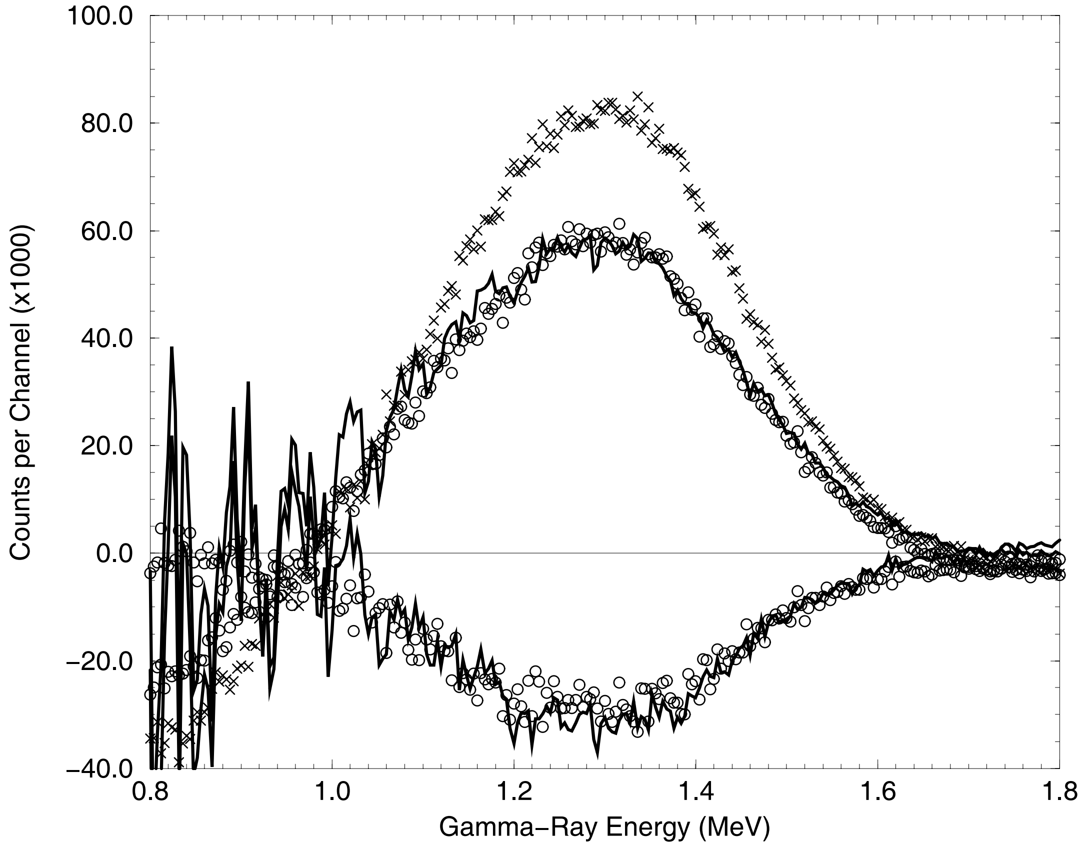

FIGURE 2. The upper line, circles and crosses are COR spectra for the data, simulation, and feeding simulation, respectively, for a gate energy of 1.4 MeV, all normalized to the same number of gates. The lower line and circles show the rotational correlations for the data and simulation, respectively.

ROTATIONAL DAMPING RESULTS

In the previous work [3] we have measured the rotational damping width, Γ_{rot}, in these Yb nuclei and this result will be summarized here. That work, as well as the present work, relies on comparisons of the data with realistic simulations. The COR spectra for the data (line) and the simulation (circles) are shown in Fig. 2 for a 20-keV wide gate of energy 1.4 MeV. This gate energy is above the region where there are significant compound damping effects, but is in a spin region where there is strong feeding from the fusion reaction. In that work we found that the feeding produces a strong positive correlation, which could be isolated in a modified simulation that allowed the gate transition to be in coincidence with itself (thereby removing the rotational correlation) while keeping everything else unchanged. We called this a feeding simulation and its COR is shown in Fig. 2 as the crosses. Subtracting the feeding COR from the data and simulation CORs leaves the negative rotational correlations also shown in Fig. 2. In this way we found Γ_{rot} values of about 300 keV for gate energies from 1.2 to 1.5 MeV. The difficulty in previous attempts to measure Γ_{rot} can be seen as due to its similarity to the width of the feeding correlation.

THE SIMULATION

In the present work we needed to incorporate the effects of compound damping into the simulation code. It is important that the simulation be realistic, so it must contain a competitive cascade to define the thermal excitation energy and spin for the emission of every γ ray. The following is a brief description of the new simulation.

The cascade starts from a spin randomly selected from the (slightly modified) measured distribution discussed in

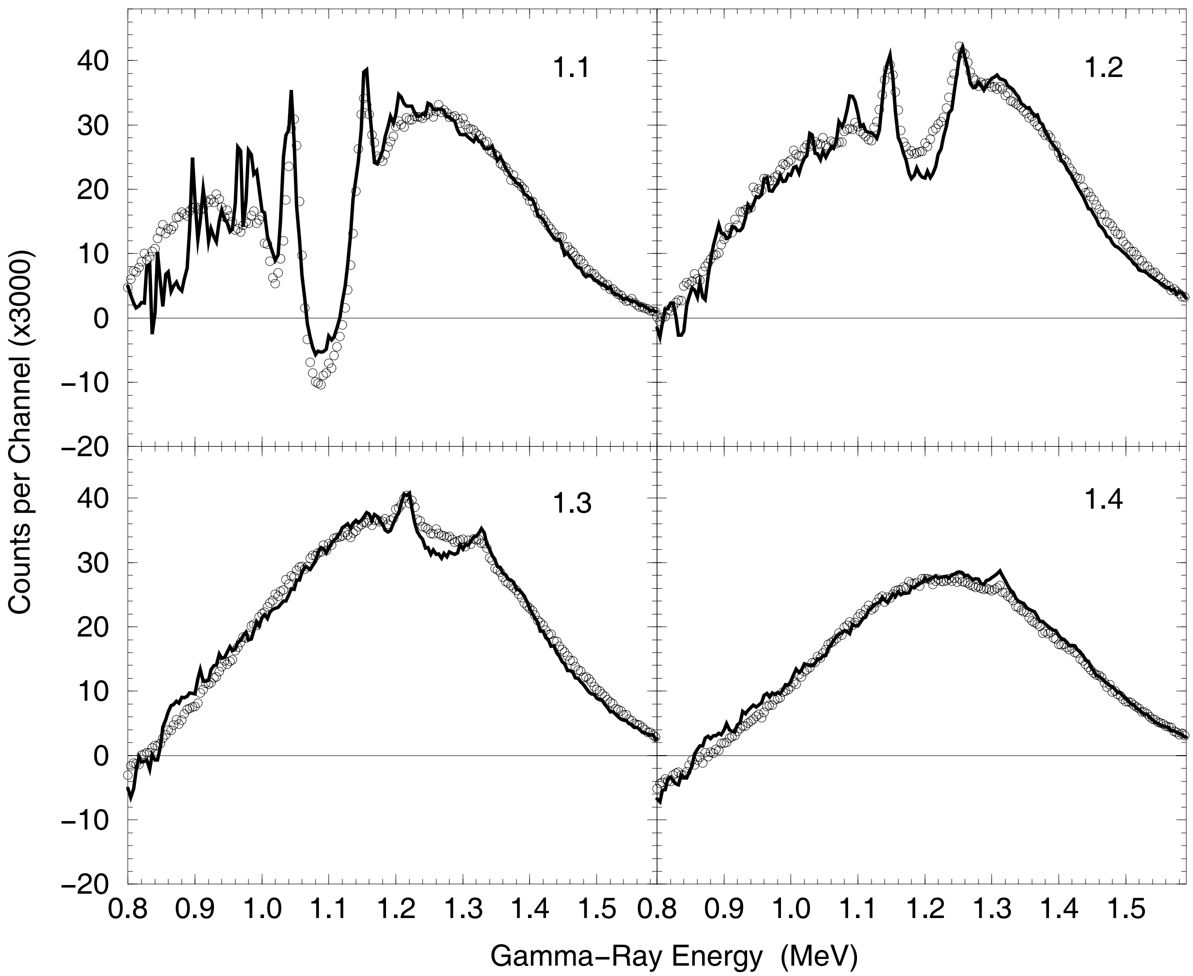

FIGURE 3. The lines and circles show the shift and add COR spectra at the indicated gate energies, for the data and simulation, respectively. For each gate energy the data and simulation are normalized to the same number of gates.

our previous work [3], and from a thermal excitation energy, E^*, randomly selected from a distribution determined by fitting the statistical γ-ray spectrum. This distribution included higher E^* values than we originally expected, which is an interesting story that I do not have time to tell here. The cascade was a competition between E1 statistical γ rays (whose energy and lifetimes were taken from standard estimates [5]) and rotational E2 γ rays (whose energy was taken from our previous paper and whose lifetime was determined from the average ground state Q_0 value for the Yb product nuclei). Values for Γ_{rot}, Γ_μ and the probability for Γ_μ (*i.e.* the probability for compound damping) were obtained from look-up tables as a function of spin, I, and E^*. The values for Γ_{rot} had the form, $\mathrm{aI}(E^*)^{1/4}$, where a was initially taken from Matsuo's calculations [6] and subsequently reduced by 10%. The values for Γ_μ had the form, $\mathrm{b}(E^*)^{3/2}$, where b had the standard value for the spreading width [2]. The probability for Γ_μ had the form, $(\rho\Gamma_\mu)^{-1}$, where ρ, the level density, had the standard form [2]. In these simulations we did not adjust Γ_μ nor its probability. The Γ_{rot} values required to fit the data varied from 180 keV at 1.1 MeV γ-ray energy to 290 keV at 1.5 MeV. These are about 15% lower than the values using the previous simulation, and we have not yet fully understood why this is the case.

COMPOUND DAMPING RESULTS

The data (line) and simulations (circles) from this work are shown in Fig. 3 for the four gate energies indicated to the upper right of each spectrum. These spectra are all CORs and are what we call "shift and add" spectra. The gates

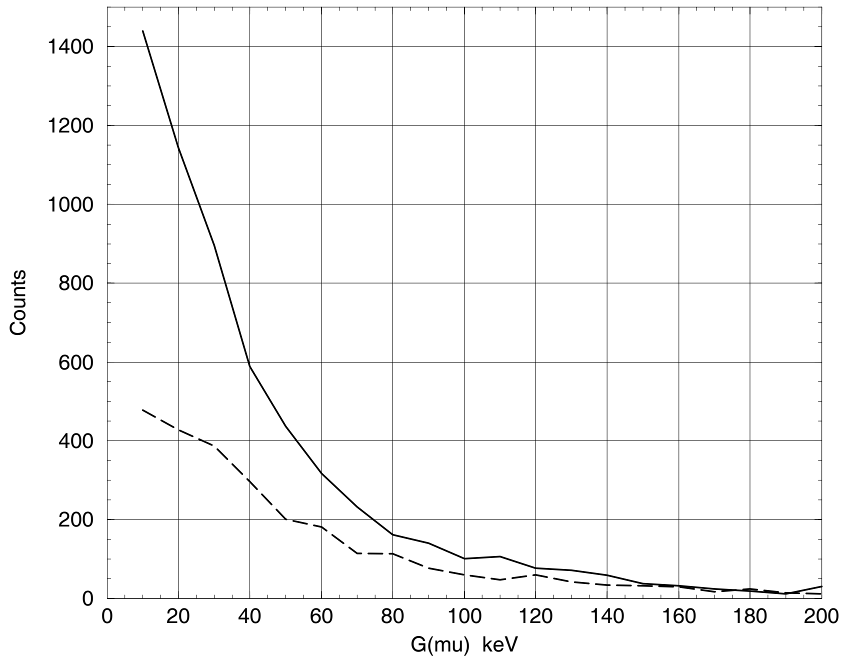

FIGURE 4. The solid and dashed lines show the distribution of Γ_μ values for the 1.1- and 1.2-MeV gates, respectively.

cover a 60-keV range consisting of 15 4-keV wide channels. As each gate channel moves up or down, we move the coincident spectrum up or down by exactly the same amount. Thus the gate always occurs at the same channel in the coincident spectra and we have 4-keV resolution for gate-related effects, whereas other effects are smeared out. This is exactly what we want.

In the lower right corner of Fig. 3 there is the 1.4 MeV gate we saw in Fig. 2 and again we see the broad peak that is a combination of the feeding and rotational correlations. This same broad peak appears in all the other gates without much change. However, in the lower gates a narrow valley and ridge structure appears and gets progressively larger as the gate energy decreases. This is exactly the region where compound damping effects should appear as it is between regions dominated by rotational damping (for higher gates) and discrete bands (for lower gates). The simulation fits both the size and shape of these structures amazingly well considering we have adjusted no parameters related to Γ_μ. In detail, the valley and ridge structures come in a little late (too small initially) and overshoot slightly for the lowest gate. This seems likely to require some small changes in Γ_μ and/or its probability. The first ridges are fit reasonably well, but not the second ridges. If the second ridges are systematically as large as they seem to be in these data, then some significant changes in the simulation parameters may be required. The possible third ridges in the 1.1- and 1.2-MeV gates are likely to be due to discrete lines in the spectrum rather than to systematic behavior. In any case, it is clear that the intensity of the second and higher ridges decreases rather quickly and this is a clear indication that the population does not stay in a particular band for very long. This suggests that we are, indeed, in a region where compound damping should be present. Now we will look at what the simulation implies about this.

For the compound-damped transitions, the *average* damping width ranged from 40 to 60 keV for the 1.1- to 1.3-MeV gates. This is exactly what would be expected [2], however the *distribution* of damping widths for the gates was surprising. These distributions are shown for the 1.1- and 1.2-MeV gates in Fig. 4, where it can be seen that they decrease monotonically as Γ_μ increases. While this very broad distribution surprised us, it does explain an otherwise puzzling result: the average Γ_μ for the 1.1-MeV gate is about 40 keV, whereas the width of the ridges for both the data and the simulation is about 20 keV. Unfortunately, however, this says that the ridge width is not a very good measure of Γ_μ.

To understand this situation better we show in Fig. 5 the results of some additional simulations. The data and

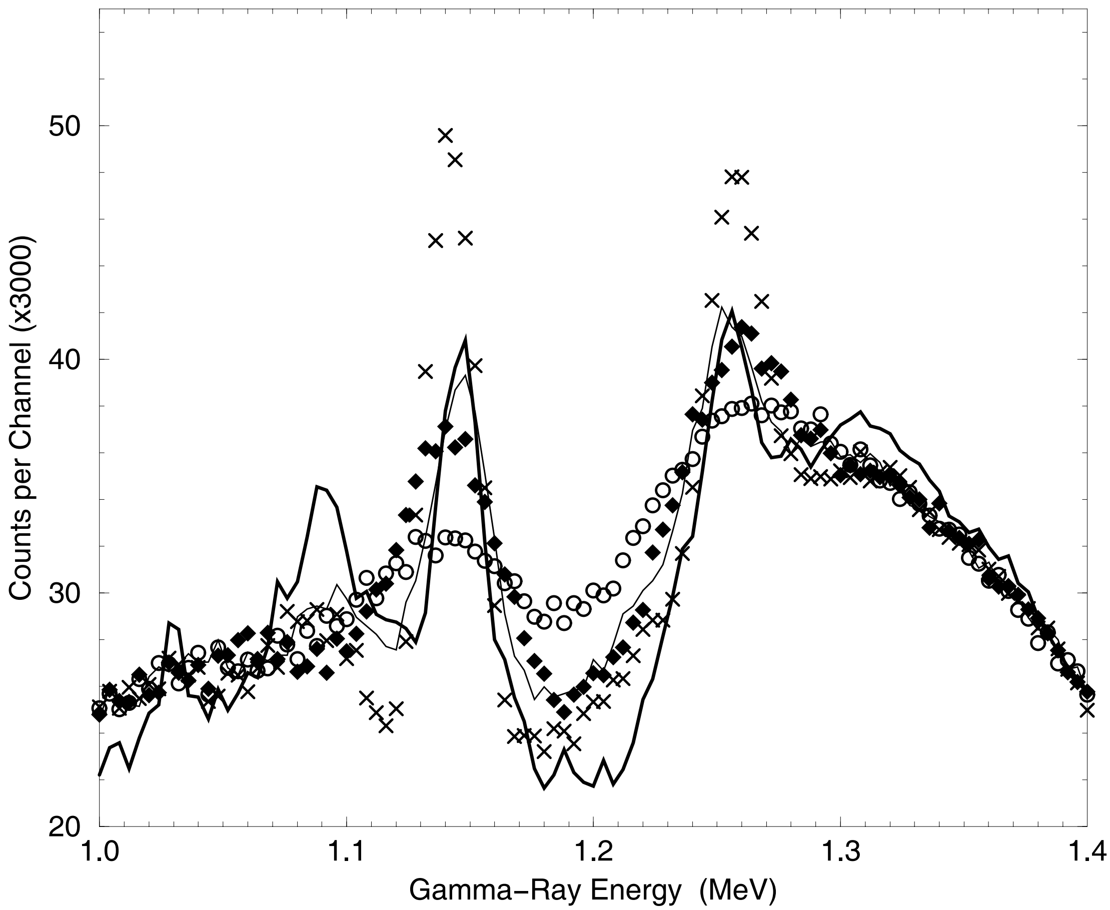

FIGURE 5. The heavy and light lines show the shift and add COR spectra from the 1.2 MeV gate for the data and simulation, respectively (as shown in fig. 3). The circles, diamonds, and crosses are similar spectra having fixed Γ_μ values of 75, 45, and 15 keV, respectively. All the spectra are normalized to the same number of gates.

simulation for the 1.2-MeV gate are shown in heavy and light lines, respectively, (as in Fig. 3) together with three test simulations that had Γ_μ fixed (rather than a function of E^*). This is to give a feeling for what kind of effects a given value for Γ_μ will produce. The circle, diamond, and cross curves have Γ_μ fixed at 75, 45, and 15 keV, respectively. We observe that: 75 keV washes out the ridge completely and half of the valley as well; 45 keV leaves some ridge, but it is clearly too wide; and 15 keV has a reasonable width but is two times too high. This seems to say that there must be some values of Γ_μ near, or larger than, 45 keV in order to reduce the ridge. There is no other obvious way to do that, because a distribution of normal bands with a spread of moments of inertia large enough to do it (about 100%) seems unreasonable. On the other hand, there must also be a lot of small damping widths to give the narrow observed width. The simulation with Γ_μ a function of E^* gives exactly that.

There are some discrete lines (strong enough population to be seen in the spectrum) in the 1.1-MeV gate region and a few very weak discrete lines in the 1.2-MeV gate region. These are largely smeared out by our shift-and-add method of generating spectra; however, we estimate they: could cause the third ridges seen in the data; are unlikely to cause the second ridges; and cannot affect significantly the valleys or first ridges. Our simulation includes very small values of Γ_μ that would emulate discrete bands, but does not yet account for the accumulation of population into just a few such bands. Though it seems unlikely to affect results in this gate-energy region, we plan to incorporate fully discrete bands in future simulations and extend our studies to lower gate energies.

Overall we believe that these results give strong evidence for compound damping as the predominant cause of the valley and ridge structures seen in these gates from 1.1 to 1.3 MeV. The height of the ridge is probably the most sensitive indicator of Γ_μ, as the ridge width is strongly affected by the large distributions of Γ_μ values. We have not yet determined the uncertainties that should be associated with our Γ_μ values.

CONCLUSIONS

Rather than summarize these results I want to make only a couple of comments here. Although it is early in these studies, we believe that both Γ_{rot} and Γ_μ can be measured. This is because, in the way that each is populated in the spectra, they differ in width by a factor of about five, which is enough to make their effects resolvable and that made the present analysis possible. The only other work on this subject that I know about is that presented here by Matsuo et al. [7] and other studies by this Copenhagen, Italian and Japanese collaboration [8, 9]. Although there are no widths for comparison with those given here, all the data are generally consistent with Matsuo's picture and with the present results in so far as I am aware.

Finally, I am sorry I did not have time to tell you about motional narrowing: it is a very interesting process [2]. Our simulations indicate there should be extensive motional narrowing present in these data. It should be exciting to try to find direct evidence for this.

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