Search for Motional Narrowing Effects in Nuclear γ-Ray Spectra

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At moderate temperatures in nuclei ($\simeq 0.5$ MeV), there is evidence for damping effects in the rotational behavior. Instead of normal rotational bands, each state can emit any one of a distribution of γ-ray energies whose FWHM is called the damping width. At higher temperatures, there are expected to be motional narrowing effects, where the damping widths decrease with further increases in temperature. We do not find such a narrowing in the experimental damping widths.

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With increasing temperature, the nucleons in a nucleus make an important change from the reasonably ordered motion of the low-lying states toward a completely disordered or chaotic motion. There are very interesting questions as to just when and how this change takes place, and what identifiable landmarks might occur along the way. One such landmark is expected at excitation energies around 2 MeV (excitation energies E^* are measured from the "yrast" line, i.e., from the lowest state of each spin), where the average separation between states becomes comparable to the residual interaction between those states. At this point, the "simple" states that occur at low energies (e.g., approximate shell-model eigenstates in reasonably stable potentials) mix heavily over a spreading width $\Gamma_\mu(E^*)$, producing complicated eigenstates that no longer correspond to any simply motion. This transition has similarities to a solid-liquid phase transition, in that the low-temperature states have a (reasonably) fixed internal structure defined by, for example, an appropriate shell-model wave function; but the higher-temperature states contain pieces of many such simple states, and thus can be thought to represent a complicated "randomlike" motion, more characteristic of a liquid.[1] Although this change presumably corresponds to a "melting" of shell structure, it is certainly not the full shell structure that is destroyed (that occurs at considerably higher temperatures), but probably a large part of the structure within the individual major shells. Where this transition occurs and how sharp it is under various conditions are questions that have recently become accessible to study through the damping of rotational motion.

In a normal (undamped) rotational band, the internal structure is reasonably well fixed, and the decay occurs through a particular set of states (a band); $I \rightarrow I-2 \rightarrow I-4 \ldots$. At the point described above ($E^* \simeq 2$ MeV), these bands will become mixed, and calculations[2] suggest that a given initial state of spin I will no longer decay to a particular final state of spin $I-2$, but rather to a distribution of spin $I-2$ states, with a strength function whose width $\Gamma_{\rm rot}$ is (at least initially) related to the spread in moments of inertia of the admixed bands. A surprising feature of these calculations[3] is that at the higher excitation energies, where Γ_μ becomes large compared with the damping width $\Gamma_{\rm rot}$, then $\Gamma_{\rm rot}$ will begin to decrease. This occurs because $1/\Gamma_\mu$, the lifetime of one of the "simple" component states, becomes short compared with $1/\Gamma_{\rm rot}$, the time needed to "resolve" a variation in the moment of inertia, $\mathcal{J}$ (or, for a constant I, to resolve a frequency variation, $\Delta\omega$) and thus the system can no longer "feel" the full variation.[4] This situation, known as motional narrowing, is well known in some other systems—particularly in the decreasing linewidth observed with increasing temperature in nuclear-magnetic-resonance absorption lines. There is already reasonable evidence in the nuclear spectra for the damping behavior proposed above, and the present work represents a search for the expected motional narrowing effects.

The higher-energy γ rays emitted following heavy-ion reactions are mostly (or entirely) unresolved, but their bulk properties can be studied. They are known[5] to be basically rotational-like γ rays; however, the strong correlations expected between the energies of such γ rays should produce "dips" in coincidence spectra at the energy of the gate, and these have been shown[6,7] to be reduced or absent. Currently, the leading explanation for this reduced correlation is the rotational damping described above. It was first thought[6,7] that the damping would gradually alter the shape of the dip, and that $\Gamma_{\rm rot}$ could be determined from the observed shape. Later work[8,9] suggests rather that the observed dip comes from a "cool" region (not far above the yrast line), where the damping is small or absent, and its reduced size is caused by the presence of other γ rays in the spectrum coming from "warm" regions, where the damping is large and the dip is completely washed out. This large damping seems inconsistent with the expected motional narrowing, and in order to test this, we simulate the deexcitation cascades with and without the effects of the motional narrowing.

Codes to simulate the γ-ray decay following particle evaporation in heavy-ion reactions can be quite complex;

however, the only really important feature for the present problem is to define the average decay pathway and its variations. In our code that is done in the following way. The initial spin is chosen randomly from a triangular distribution (as is expected following fusion reactions) having a maximum angular momentum (l_{max}) estimated from the reaction characteristics, and a rounding at l_{max} with a Fermi function with a width of $\simeq 3\hbar$. The excitation energy above the yrast line (following particle evaporation) is usually chosen from a Gaussian distribution centered at 7 MeV with a FWHM of 5 MeV.

The γ-ray cascade is a competition between rotational ($E2$) and statistical (mainly $E1$) γ rays. The rotational γ rays have an energy proportional to the spin, and a transition probability proportional to the fifth power of the energy. In undamped regions these γ rays follow bands whose moments of inertia are chosen from Gaussian distributions centered at the rigid-rotor value and having widths of 25%–30%. The moment of inertia is rechosen (only) following statistical transitions. In damped regions each transition energy is chosen from a Gaussian distribution centered at the rigid-rotor value with a FWHM equal to Γ_{rot}, and the transition probability depends only on the average γ-ray energy.

The statistical γ-ray energies are chosen from a distribution having the form $P(E_{stat}) = (E_{stat})^n \exp(-E_{stat}/T)$. This distribution results from an exponential level density and individual statistical transition probabilities proportional to the nth power of the transition energy. The total transition probability for the emission of statistical γ rays from a given state is proportional to the $(n+1)$th power of the average γ-ray energy, or to $T^{(n+1)}$. For dipole transitions, one would expect n to be 3; however, we found that to reproduce transition probabilities resulting from the tail of the giant dipole resonance, a value of 4 is much better. We have run the code for n values of 2, 4, and 6, with very little difference in the γ-ray spectrum above $\simeq 0.8$ MeV.

Rather than making absolute estimates of the transition probabilities, we choose to take the functional form for each type of transition probability (as given above) and then fix the relative rates with one adjustable constant, such that the experimentally observed feeding along the yrast line is given correctly. The criterion we have generally used to fix the adjustable constant is that 1% of the population must reach the yrast line at spin 40

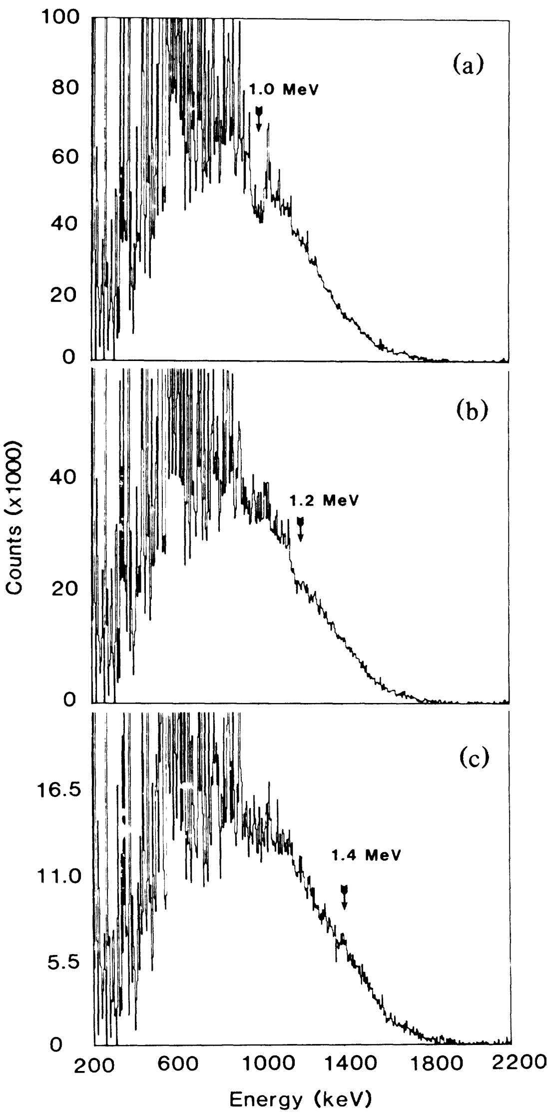

FIG. 1. γ-ray spectra following the reaction ^{40}Ar(180 MeV) + ^{124}Sn, where (20 keV wide) gates were set at (a) 1.0 MeV, (b) 1.2 MeV, and (c) 1.4 MeV.

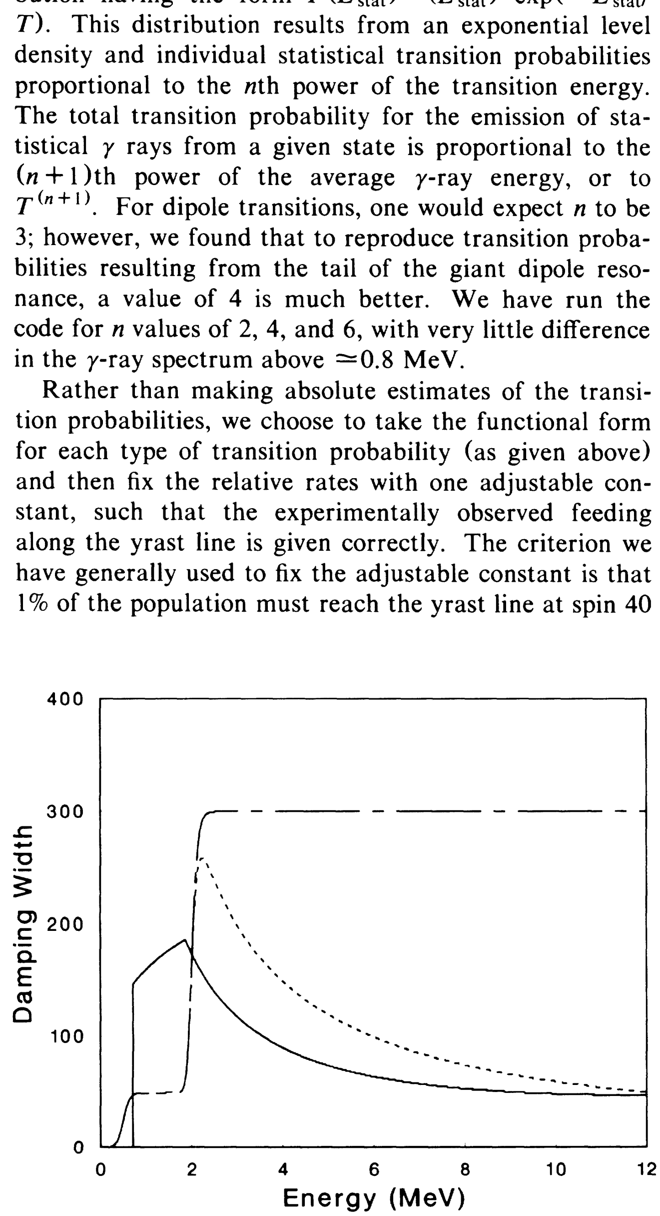

FIG. 2. Damping widths (in kiloelectronvolts) as a function of excitation energy: solid line, calculation of Ref. 2; broken line, simulation of the data [Figs. 3(a)–3(c)]; and dashed line, data simulation with motional narrowing effects added [Figs. 3(e)–3(g)].

(above the spin range of our pairing gap).

The data were taken on the Hadron Electric Ring Accelerator (HERA) array of 21 Compton-suppressed HPGe detectors. The principal reaction studied was ^{40}Ar(180 MeV) + ^{124}Sn, leading to the main product, ^{160}Er. Threefold and higherfold events were stored on magnetic tape in event mode. These events were later broken down into $\simeq 2\times 10^{9}$ independent double coincidences, which were unfolded and from which the statistical transitions were subtracted two dimensionally. Gates (20 keV wide) were placed on the resulting symmetrized matrix at energies of 1.0, 1.2, and 1.4 MeV, and the coincident spectra are shown in Fig. 1.

Qualitative fits to these data have been made with the code described above. These had a narrow (50 keV) damping width at excitation energies between 0.5 and 2 MeV, and a broad width (300 keV) above 2 MeV (see Fig. 2). This shape is not well determined; however, the 2-MeV boundary gives the correct size of the dip, the 50-keV width reduces the ridges on either side of the dip, and 300 keV represents a minimum width to wash out the dip at high temperatures. We are only interested in the region above 2 MeV in the present case. The resulting calculated spectra are shown on the left-hand side of Fig. 3, and they resemble rather closely the data in Fig. 1. We can simulate the effects of motional narrowing[2] by having the damping width fall off like $1/E$ above energies of 2 MeV. The spectra calculated with this damping width are shown on the right-hand side of Fig. 3. These damping-width curves are shown in Fig. 2, with

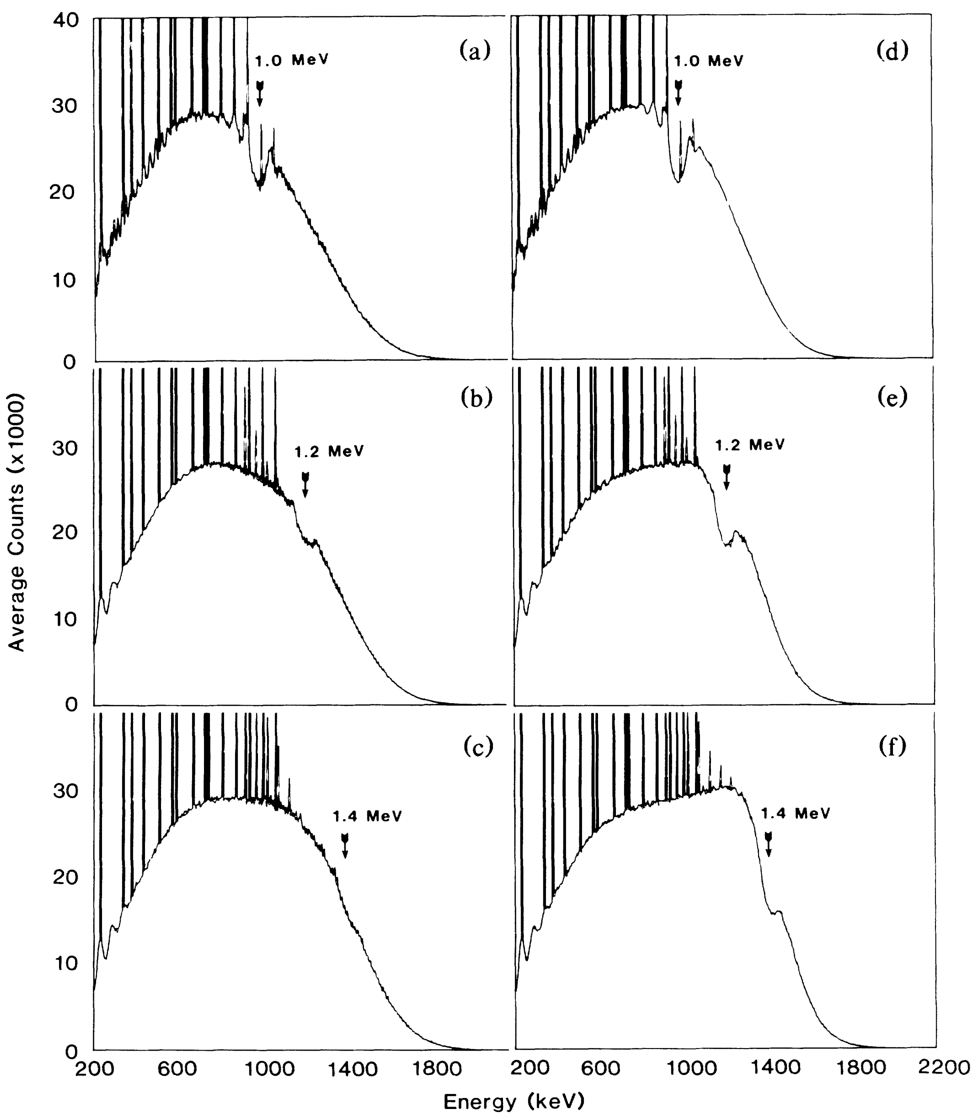

FIG. 3. Monte Carlo–generated spectra [(a)–(c)] to simulate those in Fig. 1; and with motional narrowing effects added [(e)–(g)] as shown in Fig. 2. The resolved lines are less complex in the simulation, since only one resolved band is included.

the theoretical curve of Ref. 2.

It is obvious that the dip associated with the motional narrowing in Fig. 3(f) is not present in the data [Fig. 1(c)]. A second difference is that the smaller average damping widths used in the generation of Fig. 3(f) give a much steeper falloff of intensity with energy than is observed in the data of Fig. 1(c). In Ref. 8, this slope was used to estimate the damping width and gave values around 300 keV. Thus the data exclude damping widths as small as those given by the dashed line in Fig. 2, which are already considerably larger than those calculated in Ref. 2.

Wide variations in the functional form of the statistical γ-ray strength function or in the initial excitation energy used in the simulation code do not change this conclusion. In fact, the $\simeq$300-keV damping width is needed most at the highest observed γ-ray energies ($\sim$1.4 MeV) which very likely come from the highest excitation energies. Two other systems studied, ^{40}Ar(180 MeV) + ^{100}Mo and ^{48}Ti(215 MeV) + ^{124}Sn, behave in the same way. Thus, unless there is something fundamentally wrong with our ideas of how these nuclei deexcite, there is no evidence for any narrowing of the damping width, and certainly anything like that predicted in Ref. 2 can be ruled out.

This leaves us with some interesting possibilities. One is that some basic process is wrongly understood; either damping is not responsible for the reduced correlations, or the decay does not go as we think it does. There is, however, a considerable amount of experimental evidence consistent with the damping interpretation and with the simulated decay path. It is also possible that the motional narrowing is much reduced or absent—as could be the case, for example, if the matrix elements mixing the states were reasonably strong functions of the spin.[2] This would certainly be an interesting and unexpected result that could give us some new insight into processes occurring at higher temperatures than those we are familiar with. Finally, and perhaps most likely, the initial damping widths may be considerably larger than predicted in Ref. 2, where, for example, the contribution from shape fluctuations was not included. If this contribution were large, as has been suggested,[8] then the combination of much larger initial damping widths, together with the expected motional narrowing, could be consistent with the data. Whatever the explanation, the observed absence of the large motional narrowing predicted in Ref. 2 is an interesting problem, whose solution may teach us something new about the processes occurring at these temperatures in nuclei. What we find may contribute toward the understanding of the onset of chaos in quantal systems.

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