Shell Effects at High Angular Momentum

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Major-shell effects are seen in the unresolved γ-ray spectra coming from high-spin states in the transition region: ^{154}Er to ^{160}Er. The angular momentum alignments in the valence shell, which are spread in frequency in the heavier nuclei, are compressed into the low-frequency region in the lighter nuclei and separate almost completely from the angular momentum contributions due to the next higher major (proton) shell.

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It now appears that the behavior of nuclei at high spins can be largely understood as an interplay between collective and single-particle motion. At spins up to $40\hbar$ where the γ-ray spectra are resolved, the collective and single-particle contributions to the angular momentum can be rather easily separated. Collective rotational motion is characterized by a smooth increase in rotational frequency with spin. The rotational frequency is proportional to the collective $E2$ transition energy (E_γ), and thus in rotational nuclei there is a strong correlation between the observed γ-ray energies and spins ($E_\gamma \approx 2I\hbar^2/\mathscr{I}$). Angular momentum can also be built from single-particle motion by aligning the single-particle spins along a common axis, and there is then very little or no resulting correlation between γ-ray energy and spin. This latter behavior is generally observed in nuclei near closed shells, but alignments may occur in rotational nuclei, producing local irregularities in the γ-ray energies as a function of spin (backbends). Above spin $40\hbar$, individual sequences can no longer be seen in the decay of compound nuclei, and it becomes necessary to analyze the unresolved (continuum) γ-ray spectra. This is generally done by measuring average moments of inertia[1] and γ-ray energy correlations (E_γ vs I or E_γ vs E_γ). In favorable cases these can also lead to a separation between the single-particle and the collective contributions to the angular momentum of the system.

Whether the nucleus behaves collectively or not depends very much on shell effects. Near closed shells the shape tends to be spherical, and alignment of single-particle angular momentum is favored. Between closed shells deformations tend to build up, favoring rotational behavior. However, in a single nucleus these tendencies will both occur as a function of spin or rotational frequency. Some frequency regions will be favorable for alignments and others for rotations. It can also happen that a nucleus is so located in N and Z that the large alignments of the major shells tend to be bunched together in frequency. This will produce large effects in the γ-ray spectrum. We believe that such effects occur in the light Er nuclei, where the large alignments of the valence shell are bunched together at low frequency and those from the next higher shell produce a broad peak at higher frequencies. To see these effects, we have compared the continuum spectra of erbium nuclei in the mass region 154 to 160.

The experimental spectra come from the deexcitation of high-spin states in the product nuclei after a compound-nucleus reaction. The experiments were performed at the 88-in. cyclotron of the Lawrence Berkeley Laboratory with a 185-MeV ^{40}Ar beam on lead-backed targets of ^{124,122,120,118}Sn. These reactions each produce two or three final-product Er nuclei, but for the highest spins considered here there is essentially only one product (as shown by GeLi spectra taken simultaneously), namely, ^{160,158,156,154}Er, respectively. The continuum γ-ray spectra were detected in seven (12.7×15.2 cm) NaI scintillators placed at various angles, 1 m away from the target, and in coincidence with a sum spectrometer.[1] The latter gives a signal approximately proportional to the total γ-ray energy for an event. The γ-ray spectra, in coincidence with different slices of the total energy, sample the decay from different initial populations of states. The γ-ray spectra are unfolded, normalized to their multiplicity, and then combined to give an "isotropic" spectrum. A statistical component of the form $E_\gamma^3 \exp(-E_\gamma/T)$ normalized to the exponential tail of the spectrum is then subtracted. Figure 1 shows the γ-ray spectra so treated, which correspond to a total energy slice of 25 to 27.5 MeV

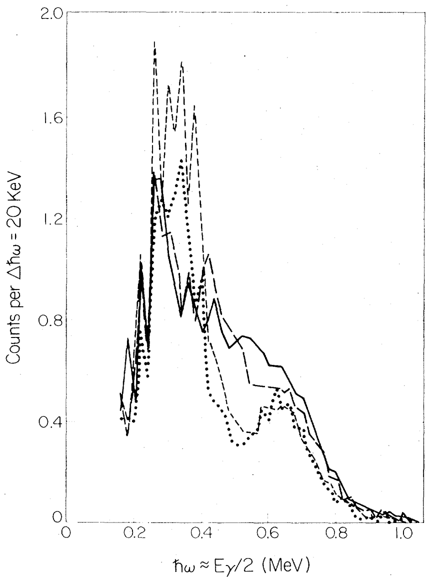

FIG. 1. The γ-ray "isotropic" spectra (after subtraction of a statistical background) as a function of frequency for the following systems: ^{124}Sn + ^{40}Ar (solid line), ^{122}Sn + ^{40}Ar (long-dashed line), ^{120}Sn + ^{40}Ar (short-dashed line), and ^{118}Sn + ^{40}Ar (dotted line).

in the sum spectrometer for all the systems studied.

The nucleus ^{160}Er (full line in Fig. 1) has already been extensively discussed.[1,2] The two peaks at ~0.2 MeV are partially resolved known discrete lines, and at somewhat higher frequency three more peaks can be distinguished. The large one (lowest energy) corresponds to the well-known first backbend in ^{160}Er, where the additional aligned angular momentum produces extra γ rays in this frequency region. The blocked first backbend shows up as the narrow second peak, and the third peak at a frequency about 0.45 MeV is very probably the second backbend in ^{160}Er. The height of the γ-ray spectrum falls off above frequencies around $\hbar\omega \approx 0.6$ MeV, as a result of the incomplete feeding of that frequency (spin) region.

In ^{158}Er (long-dashed line), the spectrum looks very much like the previous one, but one sees much more clearly the second backbend[3] around 0.4 MeV. The shoulder around 0.5 MeV very probably indicates the third backbend in this nucleus.[3] Some intensity missing at ~0.6 MeV seems to have been redistributed to lower frequencies, mainly into the second backbend. This suggests that the valence-shell angular momentum is more easily generated in ^{158}Er than in ^{160}Er. This is reasonable, both because the neutron Fermi level becomes lower, approaching the beginning of the $i_{13/2}$ and particularly the $h_{9/2}$ neutron subshells, and because the deformation decreases. Thus, the neutrons in these orbitals align more easily. At the same time, the nucleus becomes softer[4,5] and can move more easily towards triaxial shapes, which also favors alignment. This trend, to see the valence alignments (backbends) at lower frequency, is expected to continue in lighter erbium nuclei.

The effect is indeed clearer in ^{156}Er (short-dashed line). Above about 0.6 MeV the spectrum does not change very much, but the low-energy bump becomes taller and narrower, corresponding to a "compression" of the three valence backbend frequencies (the two neutron ones mentioned above plus the $h_{11/2}$ protons). In fact, Dudek's[6] calculations suggest that the second backbend in ^{156}Er is due to $h_{9/2}$ neutron alignment rather than $h_{11/2}$ proton alignment as was the case in ^{158}Er. This is consistent with a compression of the neutron alignment frequencies. The other important feature is the "dip" at 0.5 MeV between the low-energy bump and the high-energy bump; the transitions seem to be removed from the 0.5-MeV region to accumulate at lower frequency where the three valence backbends very probably occur. This indicates that around 0.5 MeV, the nucleus cannot easily generate additonal aligned angular momentum, so that essentially only the collective contributions remain.

The ^{154}Er spectrum (Fig. 1, dotted line) is very similar to that of ^{156}Er, although the low-energy bump has a very different character. It is smaller, since some transitions are lost as a result of a 40-ns isomer, but it also contains a much bigger proportion of stretched dipole transitions as indicated by angular distributions. Figure 2 is a plot of the percentage of stretched quadrupole transition deduced from the ratio of spectra at 25° and 90° based on (1) the assumption of only stretched dipole and stretched quadrupole transitions, and (2) the use of only the $P_2(\cos\theta)$ term in the angular distribution. Above frequencies of ~0.55 MeV, all the systems are similar and are consistent with pure stretched quadrupole transitions. Below ~0.55 MeV the ^{156,158,160}Er systems still show a strong predominance of stretched quadrupole transitions, whereas the ^{154}Er system drops to ~60% quadrupoles. It is interesting that the high-energy bump in the ^{154}Er system remains unchanged despite the large change in the low-energy bump.

We concentrate now on the properties of the

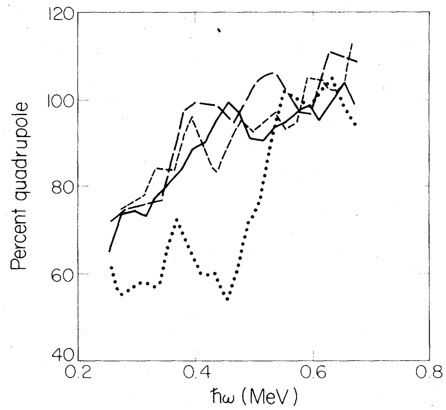

FIG. 2. Percentage of stretched quadrupole transitions as a function of frequency for the spectra of Fig. 1. The systems are represented by the same symbols as in Fig. 1.

high-energy bump. The similarity of the γ-ray spectra above $\hbar\omega \sim 0.5$ MeV for all the Er nuclei studied suggests a similar behavior of these nuclei at high frequencies. The spectrum of ^{156}Er is the most suggestive of the mechanism through which the angular momentum in that region is built. As described above, there are probably three valence-shell backbends in ^{156}Er concentrated in the narrow low-energy bump. The dip in the spectrum at 0.5 MeV suggests that the generation of angular momentum after these large alignments is much slower. The occurrence of a bump at still higher frequencies indicates that a new source is contributing additional angular momentum. The only plausible new source is from the higher shells, though that could come either as alignments with little shape change or as part of the larger moment of inertia associated with larger deformation.

To generate the rather large amounts of angular momentum observed in the 0.6-MeV frequency range by a shape change alone would require quite sizable deformations—probably involving the "superdeformations" that may occur at the highest spins. For the heavier Er nuclei, these are not expected to occur until still higher frequencies; however, the lighter Er nuclei are expected to be significantly softer than the heavy ones, and there may be considerably larger shape changes in those cases. A heavy population through states with much larger deformation does not seem so likely since this should give strong rotational transitions that have not yet been observed in γ-γ correlation experiments. The other extreme is that we are seeing alignments in orbitals originating from the next shell, which are brought down to the Fermi level at these higher frequencies without much change in deformation. An earlier, more quantitative analysis of the continuum γ-ray spectra[1] in ^{160}Er and ^{166,162}Yb in terms of $\mathcal{G}_{\text{eff}}$, with use of a feeding correction, showed the probable occurrence of $h_{9/2}$ and $i_{13/2}$ proton alignments at frequencies around 0.6 MeV in these nuclei. A persistence of these alignments in the lighter nuclei could cause their observed high-energy bumps. This latter possibility seems somewhat more likely to us, though we emphasize that the higher shells are involved in either case.

Thus, the effects of the valence shell and of the next higher shell are directly seen as two separate bumps in the ^{156}Er spectrum. The same two shells are also seen in ^{154}Er, but the lower bump (valence-shell region) has a noncollective character. In ^{158,160}Er, the neutron Fermi level is higher and the prolate deformation is more stable.[4] In those cases, the neutron alignments are less easy and therefore generated over a wider frequency range than in the lighter erbiums. As a consequence, there is no longer a pronounced separation between the two shells. This kind of two-bump structure has been known for some time to exist in several nuclei in this region,[7-10] but has not been interpreted in this way.

It is not clear yet whether this evolution of the spectra as a function of neutron number is due to a change in nuclear structure or to a change in population flow or both. We know that resolved γ-ray lines are seen from higher-spin states in the lighter nuclei, suggesting that there might be a lower average temperature in the decay paths for these nuclei. Although the γ-ray spectra of interest here come from higher spins, there still might be temperature effects in these spectra. The shell effects we have described could therefore be partly caused by a change in temperature (different deexcitation pathway).

Our main point here has to do with the source of the angular momentum in the two frequency ranges. Below $\hbar\omega \sim 0.5$ MeV it is the valence shell, and this does not change when the structure becomes mainly noncollective in ^{154}Er rather than mainly collective in the heavier Er nuclei. Above $\hbar\omega \sim 0.5$, the size of the bump indicates a generation of angular momentum (i.e., a moment of inertia) which is larger than the valence shell alone is likely to produce (after it has already produced $\sim 40\hbar$), and thus other shells must also be involved here. Whether the appearance of the higher shells is accompanied by appreciable shape and/or temperature changes is not yet clear and may differ in different nuclei. Such major-shell effects in the unresolved γ-ray spectrum are also likely to occur in other regions of nuclei, and can provide some important tests of present cranked-shell-model calculations.

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