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SPECTROSCOPY OF THE HIGHEST-SPIN STATES

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SPECTROSCOPY OF THE HIGHEST-SPIN STATES*

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ABSTRACT

The reasons for constructing large arrays of Compton-suppressed germanium detectors are discussed and a description is given of the Berkeley array, presently under construction. Preliminary results from the Berkeley system are given for the nucleus ^{156}Er. A transition is seen, around spin 30, from collective rotational behavior to non-collective single-particle behavior. The transition depends on configuration, as well as spin.

1. INTRODUCTION

In this paper I would like first to discuss some of the recent developments in γ-ray spectroscopy and then give some preliminary results from our partly completed Berkeley detector array. The data I will present were taken with nine Compton-suppressed Ge detectors, part of a planned array of twenty-one.

2. TECHNIQUE

2A. Compton suppression.

Germanium semiconductor detectors offer a unique combination of energy resolution and efficiency for γ-ray spectroscpic studies. However, they cannot yet be made very large, so there is a high probability that a Compton-scattered γ ray will escape from the crystal, leaving a partial energy. This results in a poor ratio of peak events (full energy)

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to total events (P/T ratio), which is only about 0.16 for a 1.33 MeV γ ray in a moderately large Ge detector. (The size implied here is about 2" diameter by 2" thick, and is called "20%", where the 20% is relative to the peak efficiency of a 3" x 3" NaI detector for γ rays of 1.33 MeV.) This means that in a γ-γ coincidence spectrum only ~2.5% of the events are full energy—full energy (P^2), and in a γ-γ-γ triple event (of particular interest in this paper) only ~0.4% of the events are useful (P^3). The remaining 97.5% of double or 99.6% of triple events carry no information, and simply fill up the storage systems with data that obscure the interesting events. A partial solution to this problem has been known for some time, and is to surround the Ge detector with a scintillating material, so that the γ rays scattered out of the Ge detector can be detected in the scintillator and used to anti the partial-energy pulse left in the Ge detector. With this technique one can reasonably easily get a P/T of ~0.5 ; i.e., a P^2/T of 0.25 in the double events, and a P^3/T of 0.13 in the triple events. These are improvements of ~3, 10, and 30, respectively, which are extremely important, especially in the last two situations. Compton-suppression techniques have been pioneered at Daresbury and Copenhagen [1], giving very impressive results with which I am sure you are all familiar. In the Berkeley array [2] we use bismuth germanate (BGO) as the surrounding scintillator instead of NaI as was used previously. The approximately 2.5 times greater efficiency of BGO (a combination of density and higher atomic number) means that the volume of such a shield is ~15 times smaller—a very signficant reduction. The Berkeley shields are cylindrical and about 13 cm long and 13 cm in diameter.

2B. Rates.

The new feature we wanted to add in the Berkeley array was the capability to go to very high rates and especially to be able to use triple coincidences. There are two principal factors that determine the rate of coincidence events. These are, the distance from source to the detectors, and the number of detectors (the size of Ge detectors is not really variable over much range, and furthermore is related to distance). The minimum desirable distance is given by the point where summing in the crystal (simultaneous arrival of two coincident γ rays in the same detector) becomes excessive (~10% is the maximum summing tolerable). For

average multiplicities around 20, this gives an upper limit for the efficiency of ~0.5%, or a minimum distance for a 20% Ge detector of ~13 cm. It is important not to go much farther away than this, since the rate for triple coincidences falls off as the sixth power of the average distance. The Berkeley detectors will be ~14 cm from the source, or about half the distance of the Daresbury array, giving an improvement of $\sim 2^6 = 64$ for the triples rate.

Another obvious way to improve the rate is to increase the number of detectors, and the small size of the Berkeley BGO suppressors allows 21 detectors to fit rather easily around a source at 14 cm distance. The rate for triples goes roughly as the cube of the number of detectors so that the Berkeley array gains another factor of ~50 over the Daresbury array (6 detectors), for a total gain in triples rate of about 3000. A real study of triple Ge events will be possible for the first time using the Berkeley array.

The reason we are so interested in triple coincidences has to do with the effective resolution. For a single detector the energy resolution is defined as the reciprocal of the number of resolvable points below a given peak. For a 1 MeV peak with 2 keV resolution, this becomes $\sim 1/500 = 2 \times 10^{-3}$. For a two dimensional matrix the number of resolvable points will be $(500)^2$, for an "effective" resolution of 4×10^{-6}. One can appreciate this higher resolution by realizing that two γ rays of essentially identical energy (unresolved in one dimension) will, in general, have completely different coincident relationships, and thus be easily resolved in the two-dimensional coincidence matrix. For triple coincidences the effective resolution becomes much higher—8×10^{-9} To illustrate this resolution, consider a model, where one has N unbranched rotational bands, each with 25 γ rays spread over ~1 MeV. This gives $\sim N(25)^3$ possible γ-ray triplets (G). Since there are $\sim(500)^3$ resolvable triplets (R), we have:

$$G/R = N/(20)^3 \sim N \times 10^{-4} \qquad (1)$$

One thousand bands leaves this matrix 90% empty—a situation which would result from only two bands in the one-dimensional γ-ray spectrum. It is this enormous resolving power that interests us in triple coincidences.

2C. The Berkeley Array.

A sketch of half of the Berkeley array is shown in Fig. 1. The 21 Compton-suppressed Ge detectors are arranged in three rings of 7 each around a central ~4π BGO ball. The ball consists of ~44 BGO elements

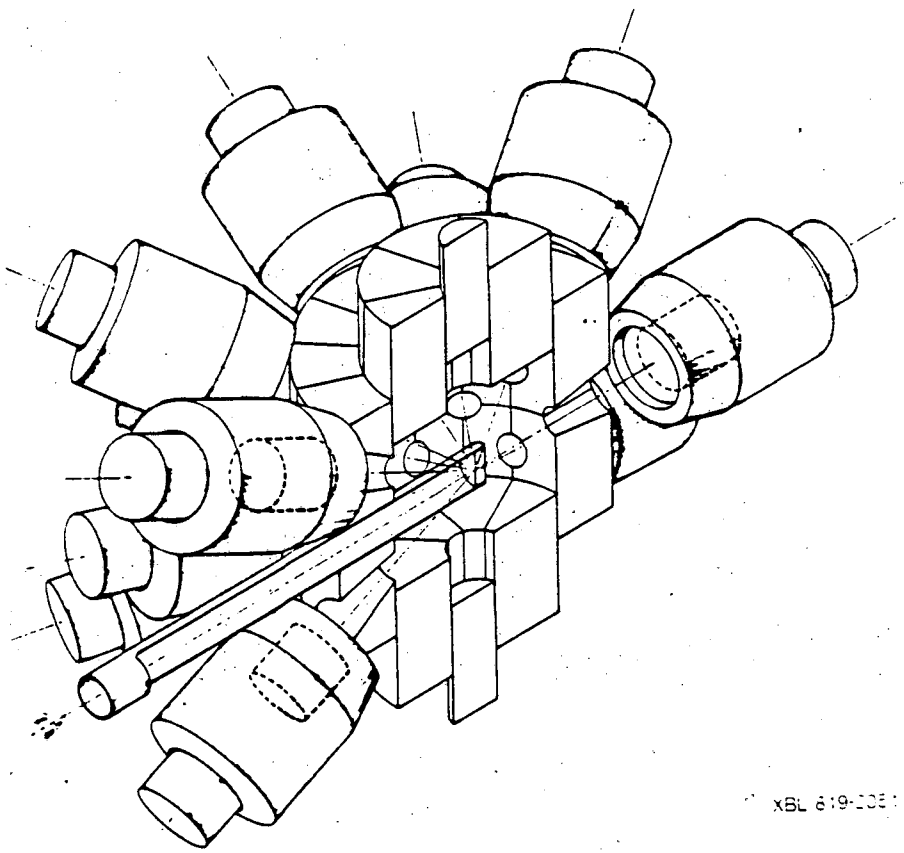

Fig. 1. Cutaway sketch of the Berkeley array. Phototubes which would attach to each element at the top and bottom of the central BGO ball are not shown. the Compton-suppressed Ge detectors are arranged in three rings of seven each. The beam entrance tube is shown from the left.

arranged in three concentric cylinders, with holes through which the Ge detectors view the target. It serves to measure the number, angular distribution and total energy of the γ rays emitted (as well as individual γ-ray energies, if desired). This information can identify, or help to identify, the product nucleus, its temperature and spin prior to γ-ray emission, and the spin orientation. One can estimate, using a simple model, which I won't take the time to describe here, that this system will enable us to resolve about ten times more levels than is now possible following a typical heavy-ion fusion reaction. The first results, which I will report now, come from nine detector systems and no central ball, but already give double events of unprecedented quantity and quality, and a

first glimpse of triple events.

3. RESULTS

3A. Region of study.

A problem with high-resolution in-beam γ-ray spectroscopy has to do with Doppler broadening of the peaks. An approximate expression for this width is:

$$\frac{\Delta E_0}{E_0} \approx \frac{v}{c} \sin\theta \sin\phi \quad , \tag{2}$$

where v is the velocity of the emitting nucleus, θ is the angle between the recoil velocity and the γ-ray emission, and φ is the opening angle of the γ-ray detector. In the worst case ($\theta = 90^\circ$, $\phi \sim 20^\circ$) for a typical $v/c \sim 2.5\%$ (for projectiles like ^{40}Ar), one finds: $\Delta E_0/E_0 \sim 1\%$, or $\Delta E_0 \sim 10$ keV at 1 MeV, which is about five times the Ge resolution of 2 keV. This is a serious loss, which, however, it is possible to avoid in certain cases. A product nucleus recoiling into lead (or other high-

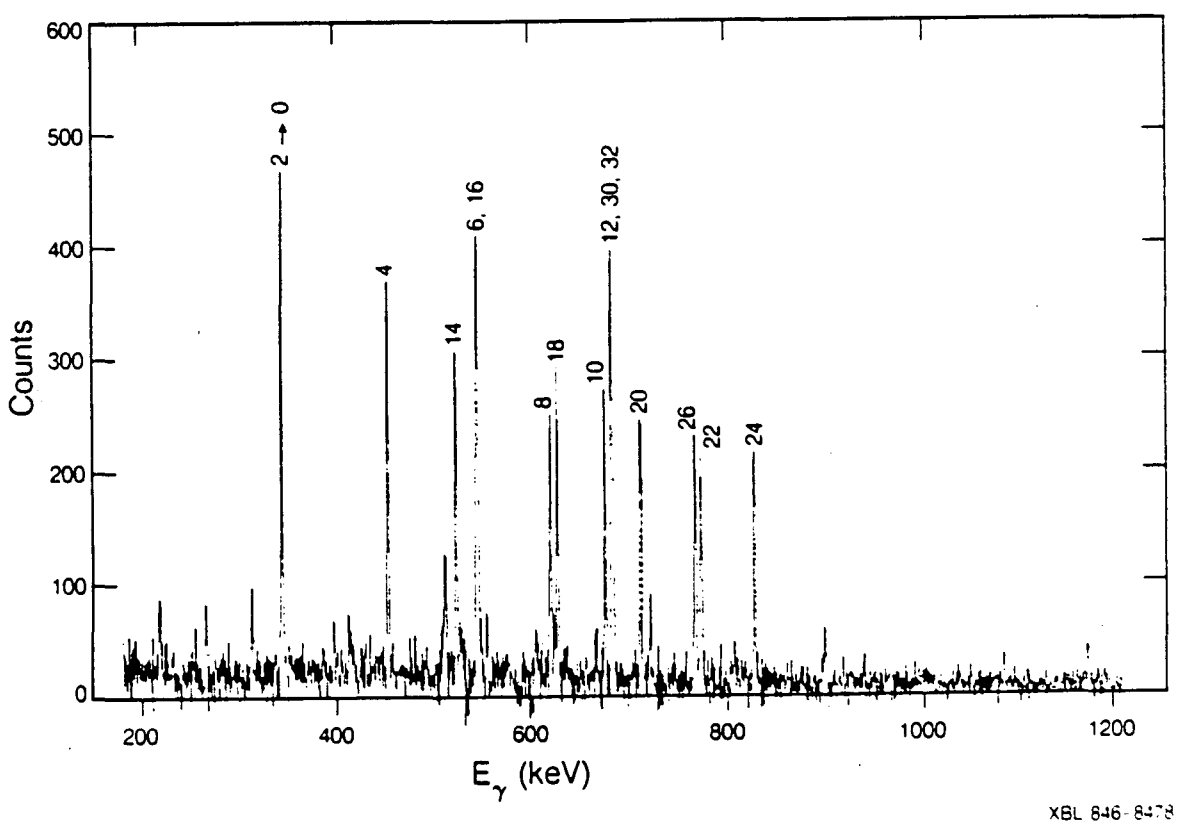

Fig. 2. Spectrum in coincidence with the 884 keV (28 → 26) transition.

density material) stops in about 1 psec. If the γ rays are emitted after this time, they have no Doppler broadening. There is a class of nuclei, those near closed shells, which have long been known to have deexcitation times long compared to 1 psec. In a preliminary survey of nuclei just above the Z = 64, N = 82 double closed shell, we have found essentially all the discrete γ rays to be emitted after stopping in Pb. The resolution is thus determined by the Ge detector to be ~2 keV at 1 MeV. The nuclei in the survey were: $^{144,146,148,150}Gd$, $^{148,150,152,154}Dy$ and $^{152,154,156,158}Er$, from which we are currently studying ^{146}Gd, $^{148,150}Dy$ and ^{156}Er. I will show you some of the results on ^{156}Er.

3B. Results on ^{156}Er.

The ^{156}Er data consist of about 1.5×10^8 double and $\sim 10^7$ triple events. It was taken with nine detector systems over a period of about two days. The quality of the doubles data is shown in Fig. 2 for one of the spin 28-26 transitions (884 keV), whose intensity is ~3%. One

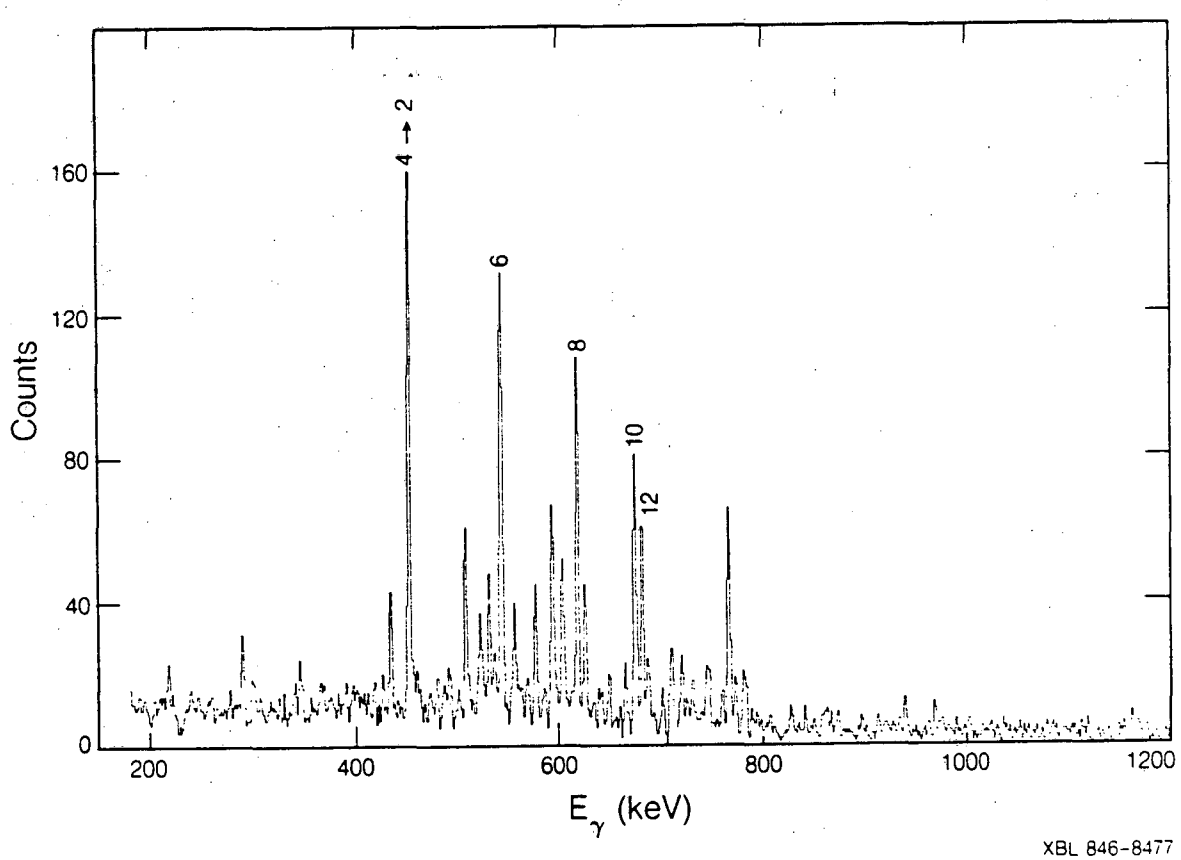

Fig. 3. Triple coincidence spectrum with a gate set on two 344 keV transitions. The spectrum has been smoothed using a simple three-channel algorithm.

sees a rather clean decay down to the ground state, and no continuation of the band above the gating transition energy. An example of a triple spectrum is shown in Fig. 3. The 2 → 0 transition (344 keV) is weakly coincident with a transition of the same energy. The spectrum in Fig. 3 results from requiring two transitions of energy 344 keV as a gate. It contains a number of interesting features, especially the transitions in the energy range 550-600 keV, which are very weak in the full spectrum. Nevertheless, it has not yet been possible to place this second 344 keV transition in the level scheme, and we estimate that an order of magnitude more events are needed to make full use of the higher resolution in such spectra. The full array of 21 detectors will take triple events about ten times faster.

The preliminary level scheme for ^{156}Er is shown in Fig. 4. The

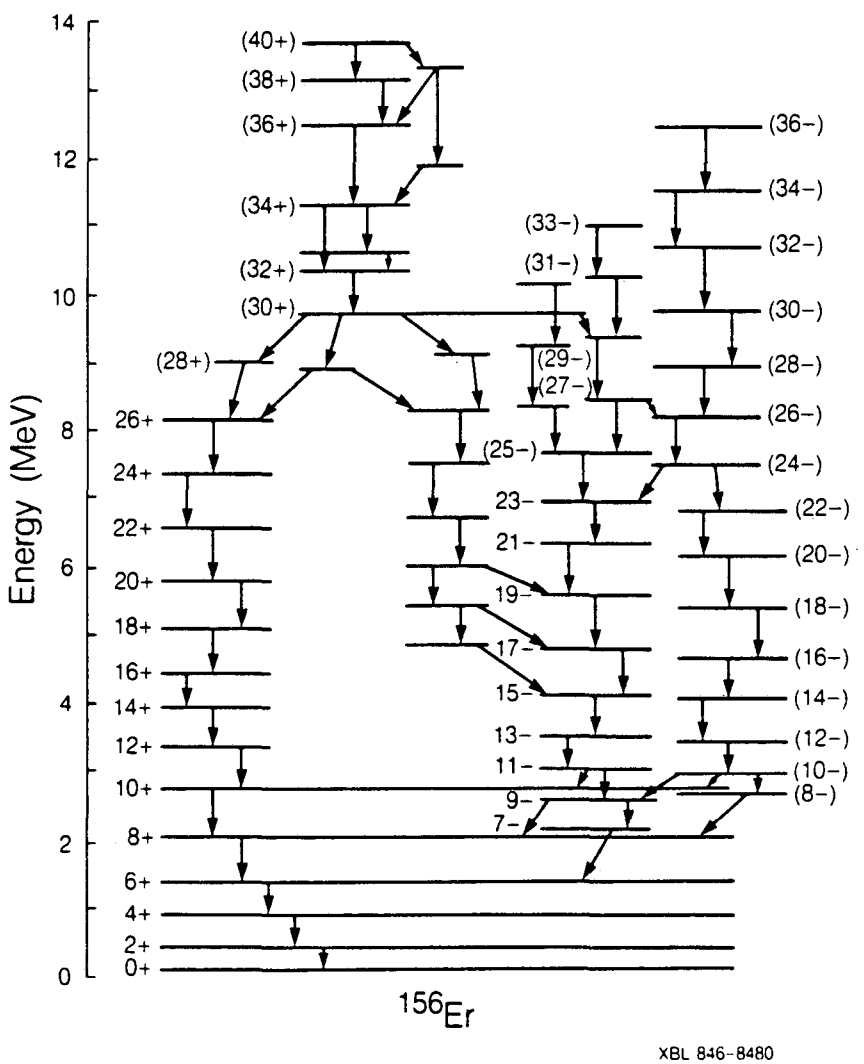

Fig. 4. Preliminary level scheme of ^{156}Er.

spins above about 20 are tentative and based on angular distribution data only. The spin and parities of the right-most band differ from those proposed for the lower part by Sunyar et al. [3], and are all tenatative, pending conversion electron data. The interesting features of the scheme are: (1) the change in character (to non-collective) of the left-most (even parity) band at spin 30 (or perhaps even 26); (2) the splitting of the center band above spin 25 into two apparently very similar branches; and (3) the apparent rather smooth continuation of the right-most band above both of the previously mentioned disruptions. Although the results are preliminary, some analysis to support these conclusions will be presented.

A plot of energy versus I(I + 1) is shown in Fig. 5. The lines are only to guide the eye, and can, in general, be rather misleading. However, in this case the data do seem to divide rather clearly into three regions with different slopes consisting of: (1) the ground band below spin ~10 (0 quasiparticles); (2) all bands between spins ~10 and ~25 (2

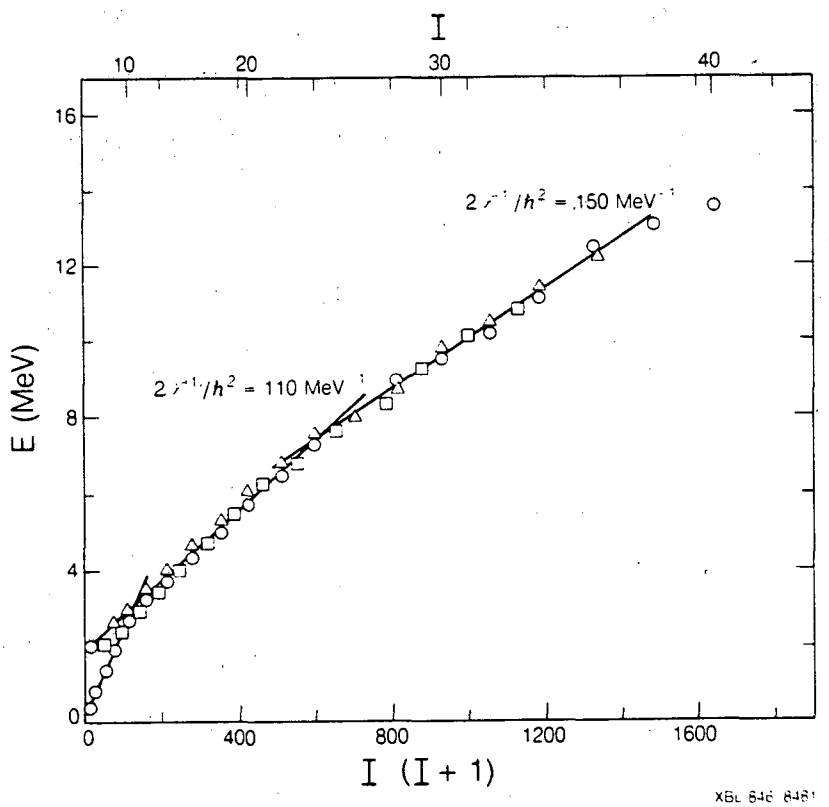

Fig. 5. Plot of energy vs. I (I + 1) for the three main bands of ^{156}Er. The symbols are: circles, left-most (even-parity) sequence, including the non-collective region at the highest spins; triangles, the right-most (π, σ = −, 0) sequence; and squares, the center sequence (π, σ = −, 1).

quasiparticles); and (3) all bands above spin ~25 (4 or more quasiparticles). This is probably just a result of decreasing pairing as the number of quasiparticles increases, but it is interesting that the bands follow one another so closely in this respect, and that the slope above spin ~25 corresponds to nearly the rigid-body moment of inertia.

A spin versus frequency plot is shown in Fig. 6. The ground band undergoes a rather sharp backbend around $\hbar\omega \sim 0.3$, with an alignment of

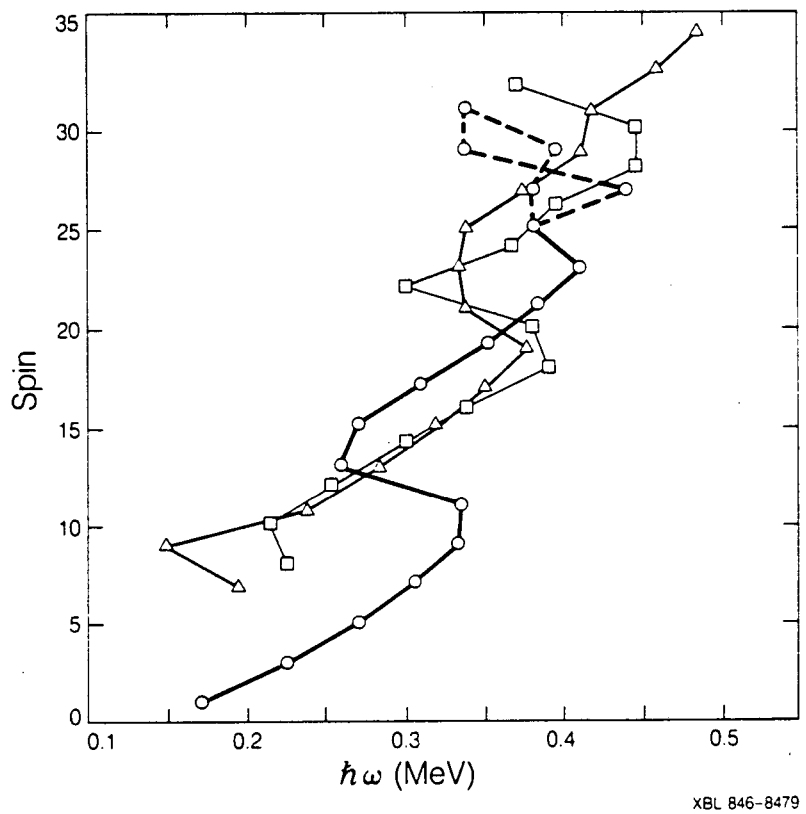

Fig. 6. Plot of spin vs. $\hbar\omega$. The bands have the same symbols as in Fig. 5.

nearly 10 ħ. This is rather typical for the first $i_{13/2}$ alignment (AB) in this region. During the second backbend (or upbend) in this sequence (around $\hbar\omega = 0.4$) the smooth (collective) character ends. Whether this represents a termination of the sequence in a $\gamma \sim 60^\circ$ configuration, or whether this just means a shift in population to a different (non-collective) sequence is not clear at present.

The other two bands have similar alignments of 7 or 8 ħ at the lower frequencies ($\hbar\omega \sim 0.22$—0.37). This would be consistent with the lowest configurations expected in the cranked shell model, AE and AF.The odd-spin (signature 1) band (AE) lies lower, as expected. The backbends in both of

these bands at $\hbar\omega \approx 0.35$ have alignments around 7 or 8 $\hbar$ and would be consistent with the blocked $i_{13/2}$ backbend (BC). Above this frequency the situation is not very clear, except that neither of these bands becomes obviously non-collective, like the even-parity sequence.

Perhaps the best way to compare the ^{156}Er data with the cranked shell model (CSM) calculations is shown in Fig. 7. Here the level energies have a smooth rotational energy (roughly rigid body) subtracted, and are plotted against spin. Fig. 7a shows the data, and Fig. 7b gives the CSM calculation by Dudek and Nazarewicz [4]. This agreement is quite striking, particularly the predicted onset of non-collective behavior.

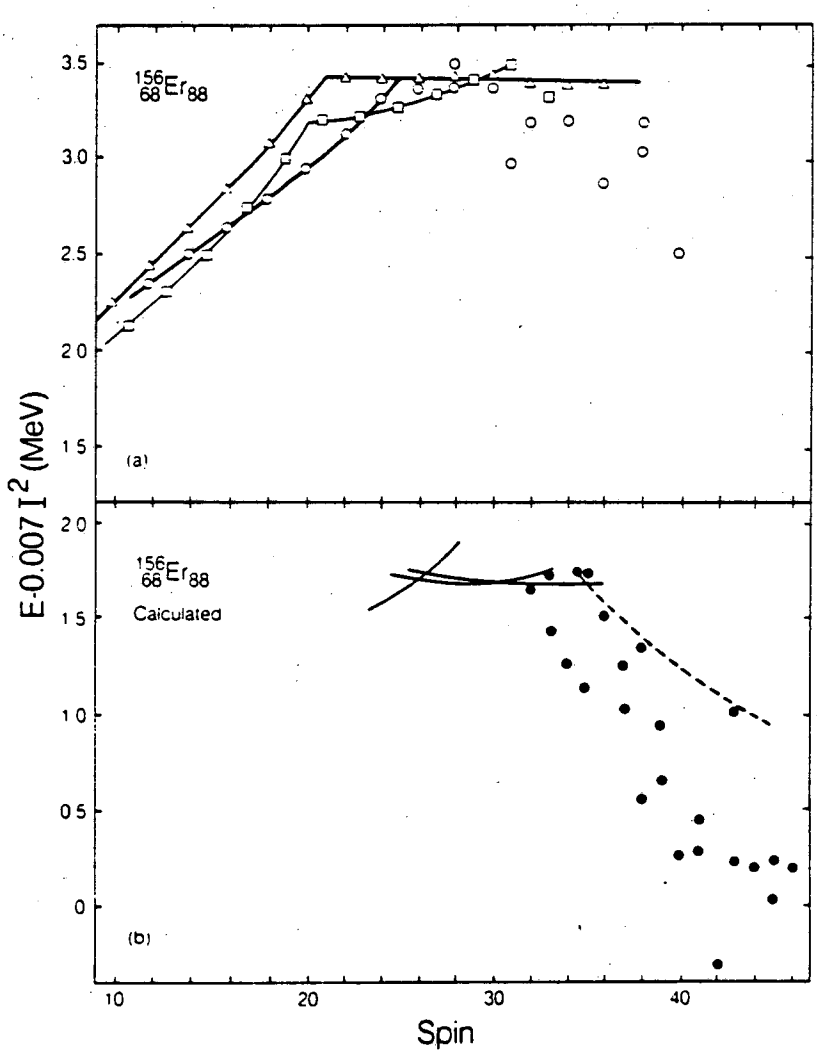

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Fig. 7. Plot of energy (minus a smooth rotational energy--0.007 I^2) vs. spin. The top plot, a, is for the experimental bands, with the same symbols as in Fig. 5. The lower plot, b, is for the calculated results of Dudek and Nazarewicz, where the lines indicate collective bands and the points indicate particle-hole (non collective) states. The dashed line represents a band with large triaxial deformation.

The very low-lying calculated state at I = 42 is interesting. The discrete lines observed run up to ~40 ħ, and it seems possible that they all result from population collected into this I = 42 state. Even the lifetime observed (>1 psec) could arise from the decay of this state. Its configuration (not included in the information from Dudek and Nazarewicz) relative to the N = 82, Z = 64 closed shell is very probably: π, $(h_{11/2})^4$; ν, $(i_{13/2})^2(h_{9/2})^2(f_{7/2})^2$. Thus far the state has not been observed experimentally.

The present data on ^{156}Er are still preliminary, and the interpretation should probably not be pushed further at present. It will be interesting to study in some detail the transition to non-collective behavior (presumably $\gamma \approx 60°$) as a function of spin and configuration. A similar transition occurs in some of the other nuclei of this region (especially those with fewer neutrons), but has been difficult to study in much detail due to the complexity of the level schemes. Also in these cases the transition occurs at lower spin and the rotational structure of the initial bands is not so well developed as in ^{156}Er.

4. CONCLUSION

Large arrays of Compton-suppressed germanium detectors are extremely powerful tools for γ-ray spectroscopy. In connection with studies of ^{156}Er, the coincidence spectrum of a peak with 3% intensity was shown in Fig. 2. This is an intensity level where a few years ago the peak itself could barely have been identified. The quality of the present coincidence spectrum is due to a combination of Compton-suppression and very good statistics. We have chosen to use the partially completed Berkeley array first in the region just above N = 82 and Z = 64. The reasons for this are: (1) the γ-ray lines from lead-backed targets are not Doppler broadened, due to the long feeding times; (2) the level schemes are complex and thus represent a challenge; and (3) the physics of the region is interesting, involving many shape changes and the (theoretical) promise of superdeformed shapes at rather low spins. We hope to be able to extend our knowledge of high spin states in nuclei of this type in the way the Daresbury array has extended our understanding of deformed nuclei.

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