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THE BERKELEY HIGH-RESOLUTION BALL*

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Criteria for a high-resolution γ -ray system are discussed. Desirable properties are high resolution, good response function, and moderate solid angle so as to achieve not only double- but triple-coincidences with good statistics. The Berkeley High-Resolution Ball involved the first use of bismuth germanate (BGO) for anti-Compton shields for Ge detectors. The resulting compact shield permitted rather close packing of 21 detectors around a target. In addition, a small central BGO ball gives the total γ -ray energy and multiplicity, as well as the angular pattern of the γ rays. The 21-detector array is nearly complete, and the central ball has been designed, but not yet constructed. First results taken with 9 detector modules are shown for the nucleus ^{156}Er . The complex decay scheme indicates a transition from collective rotation (prolate shape) to single-particle states (possibly oblate) near spin $30 \hbar$, and has other interesting features.

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Four or more years ago Frank Stephens and I became interested in developing a high-resolution γ -ray system, both to extend discrete-line spectroscopy and to study continuum γ -rays. If it were possible to push discrete transition work 10-15 spin units higher, all the detailed studies possible at lower spins could be carried out and much more could be learned about how nuclei carry angular momentum and how they change with spin. Questions to be answered are how rapidly do the pairing correlations quench, do alignments and backbends continue to high spin, and what are the changes in shape and in collective motion with increase in spin? To achieve this goal appeared to require both the "looking down" technique of the NaI balls then being constructed, namely, to select a limited population of initial states by cuts on the fold distribution and on the total-energy response of the ball, and a "looking up" scheme in which a gate is set on a discrete line of moderately high spin and the transitions above it are looked for in coincidence. But the highest spin lines observed might represent at most a few percent of the total population at that spin, and to learn about the majority of the states and their properties, one would also have to study the continuum spectrum. We had already observed, by comparing NaI and Ge γ - γ correlation spectra, that there were structures in the continuum region that required 5-10 KeV resolution to be seen. This is better than can be done, with NaI detectors, but, as explained below, a good response function is also very important in coincidence studies and Ge detectors are poor in that regard.

So at that time we were able to convince C. Gruhn to undertake a feasibility study of liquid Xe detectors as modules for a 4 π high-resolution ball. In theory such a

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system would have an intrinsic resolution only a factor of two worse than solid-state Ge detectors, and it has a number of attractive properties including a much better response function. But this undertaking proved to be an ongoing developmental problem, principally because of very low-level (ppb) impurities, and appeared that it might take years to bring to fruition. So after a year we decided to base our multidetector system on already existing Ge detectors. However, you have already heard at this Conference from Dr. Lindblad¹ on the progress they have made in Stockholm during the last three years with liquid Ar and Xe counters, including the operation of a liquid Xe detector with about 8 KeV resolution for ~1 MeV γ rays. So such counters still may live up to their theoretical promise.

TABLE I Criteria for optimum γ -ray system.

-
1.	High energy resolution
2.	Good response function
3.	Good efficiency
4.	Total-energy spectrometer
5.	Multiplicity filter
6.	Prompt initial timing signal
-

In Table I are listed three primary criteria important for a high-resolution array, and three secondary features we wanted. As mentioned, Ge detectors provide the highest resolution possible today with reasonable efficiency for γ -ray energies in the range of 50 KeV to a few MeV (~2 KeV resolution at 1 MeV). Can we do better? With a single detector, no. In this case the average resolution can be defined as the reciprocal of the number of resolvable points in the energy range of interest. Consider a range

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FIGURE 1 The overlapping lines in the singles spectrum, $E_{\gamma 1}$, are resolvable in the doubles spectrum by their different cascade partners.

of 0-1 MeV and a constant resolution of 2 KeV; this gives 500 resolvable points. If two γ rays fall on the same point, they cannot be resolved. But the γ rays we are interested in are usually not single events but members of a cascade and are correlated with the other members. If two (or more) detectors are used, the coincidence relationships between the two overlapping γ rays and the other members of their individual cascades may serve to resolve them, as illustrated in Fig. 1. The 500 resolvable points

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of the single detector have become 500^2 points in the two-dimensional array of the two coincident detectors, and it is much less probable that the two pairs of γ rays coincide than the original single lines. Still higher order coincidences give still higher effective resolution for coincident cascades of γ rays by enormously increasing the number of possible resolvable points; a triple coincidence would have 500^3 possible resolvable points. Thus, a desirable feature for our array is to have as many detectors as close as is reasonably possible (see below) to the target, in order to favor high-order coincidences.

A second criterion is to have a good response function, i.e., every γ ray that strikes the detector should result in a voltage pulse proportional to the original γ -ray energy. A Ge counter does not fulfill this requirement very well. It is a relatively low Z, moderately dense material that interacts with γ rays in the energy range of interest principally by Compton scattering. With a 5 x 5 cm Ge detector (approximately 20% the efficiency of a 7.6 x 7.6 cm NaI detector for 1.33 MeV γ rays) a 1.33 MeV γ ray has an absorption probability of $\sim 3/4$ and a peak to total (P/T) ratio of 15-20%. This means that $\sim 1/4$ of such γ rays do not interact at all with the detector, and that of those that do, only 15-20% give useful full-energy peaks. In a doubles coincidence measurement, only 2-4% of the events obtained are good peak-peak values; the remaining 96-98% are unwanted garbage. This is a very undesirable situation, and the solution has been known for some time; put Compton-suppression shields around the Ge detectors. The preceding talk by Dr. Twin on TESSA illustrated how this was done at Daresbury²; large 20 x 25 cm NaI shields were placed on six Ge detectors arranged around the target,

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giving a markedly improved peak/total ratio and resulting in the beautiful spectra you have just seen. Not having such NaI shields on hand, we decided to try for bismuth germanate (BGO) shields, for, if successful, they offered a great advantage. The material is considerably denser than NaI (7.13 to 3.67 g/cm^3) and of higher average Z , so that it has a γ -ray absorption length $2\text{--}1/2$ times smaller than NaI. This means more compact shields, so that more Compton-suppressed detectors can be placed near the target to give the higher order coincidences discussed in the previous paragraph. But bismuth germanate also has a serious handicap; the light output is only $10\text{--}15\%$ that of NaI. In addition, at that time (1981) the companies that marketed it had not made BGO crystals large enough to serve this purpose, as shields of the order of 13 cm or more in diameter and length were needed.

It took a year to obtain a prototype version of the BGO shield. The unit was not quite large enough, and it had broken in two during machining and had been cemented back together. Indeed it looked as if it might be a long, hard period before single crystals of BGO of sufficient size could be processed into suitable shields. But upon testing the broken prototype, the cemented fracture did not seem to cause any problem, and the taper at the front of the shield appeared to reflect light so well that the phototubes at the back gave a bigger signal when the source was placed on the front piece (whose light had to pass through the fracture) than when it was put on the back piece. So the problem was solved by making the shield in six longitudinal pieces that were put together to form the detector shell of suitable size. I believe that all of the Compton suppression shields that have been made from BGO

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FIGURE 2 Outline of BGO Compton-suppression shield showing 5 x 5 cm Ge detector inside, two of six photomultiplier tubes on back surface, and NaI "cap" on front taper.

have been produced in this way. In our design a 1-1/2" photomultiplier tube was placed on the back of each of the six sections to gather the light as efficiently as possible. A schematic drawing of our BGO shield showing two of the tubes is given in Fig. 2. It is a coaxial design, so that there is no shield material at the front opening where the γ rays come in to the Ge detector, nor at the rear where the snout of the Ge detector enters. Lack of coverage at the latter position means that Compton-scattered γ rays in the angular range of 0° - 25° (multiple Compton scattering in the Ge crystal and primary interactions throughout the whole volume of the Ge smear these angles out) will not be caught by the shield, leaving the complementary non-full-energy transition in the resulting

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spectrum. We do not believe these low-energy transitions pose a serious problem, although there are attempts being made to reduce its magnitude by reducing the snout behind the Ge detector to a minimum diameter and then surrounding it with additional shield material. (Of course the transverse shields do not have this hole, but they have one at the side instead.) But the opening at the front is more disturbing, as the (low energy) γ rays Compton-scattered through about 135° – 180° correspond to leaving in the spectrum the Compton edges just below the full energy peaks. The edges appear just where we are interested in having a clean, low-background region. Figure 3 shows two spectra of ^{60}Co taken with one of our Ge detectors, a Compton-suppressed one taken with the BGO shield and an unsuppressed one normalized to the same full-energy peak heights. (In the former, the Compton-edge peaks just mentioned can be clearly seen.) The peak/total ratio for ^{60}Co above a 300 KeV threshold improves from ~20% to 50%. But for coincidence experiments there is the even more marked improvement shown in Table II. Note, for example, that with bare Ge detectors full-energy triple

TABLE II Ge detector 20% (counts above 300 KeV).

	Ge ¹	Ge ²	Ge ³	Ge ⁴
Peak/Total	0.2	0.04	0.008	0.0016
Compton-suppressed Peak/Total	0.5	0.25	0.13	0.06
Improvement Factor	2.5	6	16	39

coincidences are only 0.8% of the events, so that triple coincidences have not been used in in-beam spectroscopy. But with a 50% P/T ratio, 12.5% are good events making them

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FIGURE 3 Spectra of ^{60}Co taken with bare 20% Ge detector and with Compton-suppressed detector (no NaI cap).

quite useable. And still higher ratios are possible. By the addition of a NaI "cap" to the front of the BGO shield, as shown schematically in Fig. 2, we have obtained a P/T ratio of 55% for the ^{60}Co peaks (300 KeV threshold) and,

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most importantly, have almost completely wiped out the Compton-edge peaks. Other designs using larger BGO shields can give P/T ratios of 60-65% for ^{60}Co , so tremendous improvement in the Ge response function is possible.

The system efficiency involves the questions of how many Ge detectors at what distance from the target. With the design shown in Fig. 2 involving 13.5 x 13.5 cm shields, some units will touch at their tapered cones when 13-14 cm from the target. If we take 15 cm as the distance from the target to the face of the 5 x 5 cm Ge detector inside the BGO shield, we find we can place 21 detectors at this distance and still leave the top and bottom above the target clear. This will be necessary to accommodate the photomultiplier tubes for a small, central BGO ball between the target and the Ge modules. Of course, the number of detectors is a matter of choice and depends somewhat on the geometrical arrangement selected. Too small a number hurts the higher order coincidences and the statistics; too large a number is costly, and after a moderately large number one does not gain very rapidly, as additional detectors require an expansion in the radial distance from the target. Another consideration on the distance from the target involves the amount of summing to be tolerated in an individual detector. At 15 cm from the target, the geometric solid angle of our detectors, diminished by the Ge transparency, is $\sim 5 \times 10^{-3}$. Sixty percent (or more) of such γ rays interacting with the Ge detector are rejected by the shield (plus NaI cap) so the overall efficiency is $\leq 2 \times 10^{-3}$. If the γ -ray cascades have an average multiplicity of 20, this gives $\sim 4\%$ summing, on average. This is probably O.K. for most purposes; if not the geometric efficiency must be reduced.

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Lastly, but not least, Doppler effects must be considered. The usual method of producing nuclei in high-spin states is with (H.I.,xn) reactions. In a typical case, ~180 MeV ^{40}Ar on ^{124}Sn , the recoiling compound nucleus has a velocity ~2.5% that of light. The Doppler shift for a γ ray emitted by such a moving source is

$$\frac{E - E_0}{E_0} = \frac{v}{c} \cos \theta \quad (1)$$

where θ is the angle between the detector and the recoiling nucleus. So near 0° or 180° the Doppler shift is quite large, ~25 KeV for a 1 MeV γ ray. But the broadening due to the finite opening-half-angle ϕ of the detector

$$\frac{\Delta E}{E_0} \approx 2 \frac{v}{c} \sin \theta \sin \phi \quad (2)$$

is quite small, $\leq 1/2$ KeV for θ near 0° or 180° and $\phi = 9.5^\circ$. By using a thin target or multiple thin targets, the full Doppler shift is obtained, but since this corresponds to a change in gain it can be corrected for in the amplifier or ADC or in the analysis program with no loss in resolution. On the other hand, for angles of θ near 90° , the Doppler shift becomes small, but the broadening becomes a maximum. For the 180 MeV $^{40}\text{Ar} + ^{124}\text{Sn}$ example, $\Delta E/E_0 \approx 0.8\%$ or 8 KeV broadening for a 1 MeV transition. Such a smearing of the energy ruins the resolution of the detector, but can be reduced or avoided altogether under certain conditions. For example, if such a product nucleus recoils out of the target into a lead or gold backing, it will stop in the order of picoseconds. If the transitions are emitted after stopping, there will be no Doppler shift or broadening. Thus, nuclei that do not have fast, col-

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FIGURE 4 Vertical cut through the High-Resolution Ball system, showing one Ge detector in each ring. Not shown are photomultiplier tubes and NaI caps on BGO shields.

lective transitions in their de-excitation cascades can, and do, take picoseconds to de-excite and do not present a problem. But if the γ rays are fast, something has to be done to alleviate the Doppler broadening; the detectors must be pulled back further or collimated or both in order to decrease the detector opening angle, and thus the broadening.

With these considerations in mind we have designed³ the High-Resolution Ball to consist of 21 BGO-shielded Ge detectors arranged (in three rings of seven detectors) around a small, central "ball" or "castle" of 40 BGO sectors. Some of the latter have holes through which the Ge detectors see the target, and the 40 together form a sum spectrometer and multiplicity filter around the target, as well as giving the angular pattern of the γ rays emitted. A sideview of the arrangement is given in Fig. 4, which shows one detector from each ring. Not shown are the NaI caps on the BGO shields, nor are the photomultiplier tubes drawn in on either the shields or the central ball sectors. For the BGO sectors in the upper half of the central

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FIGURE 5 Perspective view of $\sim 1/2$ the system.

ball, the photomultiplier tubes go up from the top faces of the sectors, and for those in the lower half, the tubes go downwards from the bottom faces. A cut-away perspective drawing of the system is shown in Fig. 5.

With 21 of our detectors at 15 cm from the target, an event rate of $10^5/\text{second}$ (the order of our usual rate in a $(^{40}\text{Ar}, \text{xn})$ reaction), and an average γ -ray multiplicity of 20, we estimate the double-, triple-, and quadruple-coincidence rates to be 11 K/s, 2.2 K/s and 280/s, respectively. We have already performed experiments with 9, 12, and 15 Compton-suppressed Ge detectors (but without the

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FIGURE 6 Photograph of 12 Compton-suppressed Ge modules in place around a small target chamber.

central BGO ball), and do get the corresponding calculated rates.

Where we were 3-4 months ago (Summer, 1984) is shown in Fig. 6, a photograph of 12 Compton-suppressed Ge modules in place around the target inside a small chamber. The beam-line to the chamber passes between the two middle modules in the horizontal plane. The Ge detectors are out of sight inside the BGO shields, but their small liquid-nitrogen dewars are visible, as are the pre-amps for the shields. We now have all 21 Ge detectors and 16 of the BGO shields; the last of the latter are due by February, 1985. We shall go out to bid for the NaI caps for the BGO shields before the end of this year. By the beginning of 1985 we

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should have a new system of fast 8-channel multiplexers and of ADC's and a fast CAMAC crate in operation for acquiring data. All that will remain to build is the central 860 ball, and its design has been completed.

One of the goals of the High-Resolution Ball is to push the limits of discrete γ -ray spectroscopy to higher spin into the bottom of the present continuum region, in order to gain the much more detailed information possible with discrete-line studies. This will be accomplished by cutting down the number of de-excitation pathways being observed both by cuts on the total energy and multiplicity measured with the central ball, and by simultaneously gating on single, high-spin discrete lines (and "looking up" in coincidence above the last known discrete lines). Since we do not have a central ball yet, we can only do the latter at present, and for our first experiments we have chosen to look at the region around $Z = 64$ and $N \geq 82$. We have taken data on some eleven nuclei. This choice was made for three reasons. First of all, most nuclei in this region are expected to have long enough feeding times (picoseconds) into the range of high-spin states which we want to study that they will be stopped in lead-backed targets before they emit their de-excitation γ rays. Thus, there will be no problem with Doppler broadening. Secondly, the level schemes are apt to be quite complex, as these are not good collective rotors having bands with approximately rotational spacings, but involve mainly single-particle states with possibly weakly collective interactions. For this reason many of them have not yet been studied to high spin and they represent a challenge, though a difficult one. Thirdly, they are in a region where the physics appears to be varied and interesting, involving

FIGURE 7 Spectrum of ^{156}Er in coincidence with the 452 KeV, $4^+ \rightarrow 2^+$ ground-band transition.

shape changes, and possibly the theoretically predicted transformation to superdeformed shapes (2:1 axis ratio) at relatively low spins and also band terminations.

I shall show you some data on ^{156}Er which are being analyzed by Frank Stephens. They were taken with 9 Compton-suppressed Ge detectors in two days running at the 88" cyclotron with a ~ 1 pna beam of 175 MeV $^{40}\text{Ar}^{8+}$ on a lead-backed ~ 1 mg/cm 2 ^{120}Sn target. The data consist of $\sim 1.5 \times 10^8$ double- and $\sim 10^7$ triple-coincidence events. A spectrum in coincidence with the 452 KeV, $4^+ \rightarrow 2^+$ transition of the ground band shows the number of lines observed in ^{156}Er , essentially clean of $^{157,159}\text{Er}$ (Fig. 7). Actually, the total γ - γ projection spectrum is clean enough so that the small peak at 884 KeV, the $28^+ \rightarrow 26^+$ transition that has only $\sim 3\%$ the strength of the ground-band $4^+ \rightarrow 2^+$ transition, can be used as a gate to provide the very nice

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FIGURE 8 Spectrum of ^{156}Er in coincidence with the 884 KeV, $28^+ \rightarrow 26^+$ transition.

spectrum shown in Fig. 8. The $\nu i_{13/2}$ backbend at spin 12 $\hbar$ shows clearly, as does the discontinuity at spin 26 $\hbar$, but also one at 30 $\hbar$. This part of this cascade is no longer rotational, but appears to be made of single-particle states. It would be interesting to determine the transition lifetimes here. Note that in this positive-parity yrast band there are two lines that are double and one that is triple. In fact, of the more than 100 lines Frank has assigned to the decay scheme, more than half are double, triple, or higher fold, and there are six transitions at 766 ± 1 KeV. A spectrum brought back as the result of a double gate on 344 KeV is shown in Fig. 9. That is, the $2^+ \rightarrow 0^+$ transition of the ground band is weakly coincident with another γ ray of the same energy, and the result-

FIGURE 9 Triple coincidence spectrum of ^{156}Er with a double gate set on two 344 KeV transitions. The spectrum has been smoothed once using a simple three-channel algorithm.

ing triple-coincidence spectrum is shown. The ground band is observed through the first backbend, and then there are a number of transitions in the energy range of 550-600 KeV which must involve the other 344 KeV transition, but they have not all been placed in the scheme yet.

The preliminary level scheme for ^{156}Er is given in Fig. 10. Positive-parity levels above spin 26 $\hbar$ and negative-parity levels above $\sim 23 \hbar$ are mostly new; a few lower levels have been changed from previous work.^{4,5} The number of transitions and levels have been doubled over those in earlier schemes. Spin assignments for the new states are tentative and based solely on the angular correlations of the cascade transitions. The new spin and parity assign-

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FIGURE 10 Preliminary level scheme for ^{156}Er .

ments for the right-hand band in the figure are also tentative and will have to be checked by conversion-electron measurements. A plot of energy vs. $I(I + 1)$ for the levels is shown in Fig. 11. The lines are drawn only

FIGURE 11 Plot of excitation energy E vs. $I(I + 1)$ for the three main bands of ^{156}Er . Corresponding to Fig. 10, they are: the left-most (positive-parity) band, including the non-collective region at the highest spins, circles; the right-most (negative-parity, even-spin) sequence, triangles; and the center (negative-parity, odd-spin) band, squares.

to guide the eye, but the points do seem to group into three different regions with different slopes. First comes the ground band below spin $10 \hbar$ (0 quasiparticles) then all bands between spins $\sim 12 \hbar$ and $\sim 25 \hbar$ (2 quasiparticles), and finally all levels above spin $\sim 25 \hbar$ (4 or more quasiparti-

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cles). The increasing moment of inertia given by the three slopes is probably the result of decreasing pairing and increasing particle alignment as the number of quasiparticles increases. Although $J_{\text{eff}}^{(1)}/\hbar^2 = I/\hbar\omega$ is an integral quantity and so not very sensitive to local structural changes, it is somewhat surprising that all the points seem to lie so well on the three straight-line segments. The right-hand band in Fig. 10 has been re-assigned as a negative-parity band, probably the unfavored even-spin partner of the already assigned negative-parity odd-spin band. Both of these start out with an aligned spin of $7-8 \hbar$ relative to the ground band and show the "blocked" $\nu i_{13/2}$ backbend at $\hbar\omega \approx 0.35$ MeV with an additional alignment of $7-8 \hbar$, as expected for the lowest negative-parity bands in this region. Above the backbend the odd-spin band splits into two very similar branches (which was not expected) and the even-spin band continues, possibly as a still-collective one. This scheme can be compared with Cranked-Shell-Model calculations,⁶ and the agreement is reasonably good, especially for the predicted onset of non-collective or single-particle behavior (oblate shape) taking over from collective rotation (prolate shape) in the neighborhood of spin $30 \hbar$. A low-lying calculated state of spin $42 \hbar$ is interesting and probably corresponds to the highest spin state observed experimentally and tentatively given that spin. It is possible that the observation of the high-spin positive-parity states even depends upon this state, as it may be the source of the lifetime (>1 picosecond) necessary to hold up the following cascade long enough for the recoiling nucleus to stop first in the lead backing. Otherwise the lines would not be sharp, particularly in the detectors near 90° to the beam. It

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will be interesting to compare this decay scheme with those of the neighboring nuclei that we are also studying in order to observe the systematics of the changes in nuclear structure and shape in this region of the Periodic Table and see how well they agree with theoretical predictions.

It has become quite clear that the use of Compton-suppressed Ge detectors is an exciting step forward in nuclear γ -ray spectroscopy. The beautiful spectra taken by the Daresbury and Copenhagen groups during the past 1-2 years give eloquent testimony. Their work was done with six large NaI suppressors. The use of bismuth germanate permits much more compact shields, and so allows more Ge detectors to be grouped closer to the target or radioactive source than is possible with NaI. As a result, higher-order coincidences can be obtained which correspond in favorable cases to effectively higher resolution. In addition, adequate statistics can be obtained in a much shorter time. In this talk I have discussed our design of a high-resolution Ge array, where it is now in construction, and some first results from a partial array whose spectra do show the superior qualities we had hoped for. In closing I would like to point out that although I have only shown results of discrete γ -ray studies, we intend to use the array for continuum work also, as the shielded Ge detector response function is about as good as that of the large NaI detectors usually used in continuum studies. To learn about the properties of the highest spin states we shall have to study their average behavior as given by continuum γ -ray measurements; this will require significant improvements in our continuum techniques. But we can look forward to great increases in our knowledge of nuclear structure at high spin and at high temperature from a combination of the

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detailed measurements of discrete γ -ray studies and of the average behavior exemplified in continuum work.

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