MASTER

The Limits of Studying High-Spin States by
Discrete-Line Gamma-Ray Spectroscopy

L. L. Riedinger
Department of Physics, University of Tennessee
Knoxville, TN 37916, U.S.A.

and

AS05-76ER04936

Oak Ridge National Laboratory
Oak Ridge, TN 37830, U.S.A.

Abstract

The limits of studying high-spin states by discrete-line gamma-ray spectroscopy. L. L. Riedinger (Department of Physics, University of Tennessee, Knoxville, TN 37916, U.S.A.)
Physica Scripta (Sweden).

Recent (HI, xn) data on rotational Yb and Hf nuclei are used to describe the motivations and techniques for pushing discrete-line spectroscopy to the realm of the weakly populated yrast and non-yrast states. Three aspects of these studies are discussed: extraction of moments of inertia in different aligned bands, observation and understanding of high-frequency band crossings, and dependence of feeding patterns on nuclear structure.

Paper presented at Nobel Symposium on Nuclei at Very High Spin, Sven Gösta Nilsson in Memoriam; June, 1980; Sweden.

Lund

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EBB

1. Introduction

There have been many significant advances, both experimental and theoretical, in the past few years in understanding high-spin phenomenon. Many of these advances have been presented at this conference. On the experimental front, the availability of heavy-ion beams and the development of new γ -ray techniques have given rise to beautiful measurements in the area of Coulomb excitation, lifetime studies, g factors, continuum spectroscopy, and discrete-line spectroscopy. The physics to be learned from the first three items in this list is obvious and quite important: static and transition moments of levels, both high and low spins. Such nuclear properties are quite sensitive to deformation, quasi-particle composition, and pairing, and thus these measurements provide very detailed tests of the current theories. In spite of the importance of these types of measurements, I will confine my considerations to advances in spectroscopy work. Continuum measurements have given us new details about nuclei in the realm of $I=30-60$ in the form of sum-spectrometer work discussed at this symposium by Hagemann and Stephens and energy-energy correlation experiments described by Lindbald, Deleplanque, Pedersen, and Herskind. But the questions at hand are: why discrete-line spectroscopy, where do we stand, and what more can we learn? Is it worth the large effort to sort through an almost continuous maze of peaks in order to construct the jigsaw puzzle of discrete bands? My answer to the last question is yes, and in this paper I will attempt to justify this answer by providing answers to the previous questions of why, where, and what more.

There have been many fine examples of very significant discrete-line

γ -ray work in recent years, experiments made possible by improvements in techniques for looking at delayed γ emission, measuring multiplicities, and selectively gating on high total γ -ray energy. A very fertile region has been that of $N=82-86$. Kleinheinz discussed at this symposium the shell structure of nuclei in the vicinity of ^{146}Gd , while Khoo and Sunyar have described the measurements on the $N=86$ nuclei, where discrete lines up to $I \sim 37$ are observed. As discussed by Khoo, these measurements are at the very limit of discrete-line spectroscopy. The attempts to observe discrete lines within the anticipated rotational bands at higher spins have largely been unsuccessful, and thus one must use continuum techniques.

Since the spectroscopy measurements in the $N=82-86$ region have been covered well at this symposium by others, I will confine my remarks to experiments on rotational nuclei, $N \geq 88$. Yrast bands have been observed in most of the even-even nuclei in the $88 < N < 120$ nuclei, but theorists have gently needled experimentalists for some years to expand our knowledge of rotational states to non-yrast bands and to higher spins in the yrast bands. Vibrational (β and/or γ) bands had been observed to high ($I \sim 20$) spins in the $N=90$ nuclei, but there were few cases in which such spins were known in quasi-particle (q.p.) bands. Experimentalists have attacked these new frontiers with great vigor in the last year or so, and now we have data on high-spin states in a rather large number of bands. The Oak Ridge [1] and Brookhaven [2] measurements on ^{164}Er resulted in assignment of vibrational and q.p. bands up to $I \sim 20$. The theoretical explanation of these bands and their crossings provided one of the initial successes of the cranked shell model (CSM) calculations from the Copenhagen school [3-5]. More recently, a series of measurements in Copenhagen on multiple bands and crossings in

$^{160,161,162}\text{Yb}$ [6,7] yielded a rich array of data that can largely be explained in the CSM calculations, as discussed by Frauendorf at this conference. Dracoulis [8] has described a vast amount of data from Canberra on bands in Os and W nuclei, and Lieder [9] has discussed detailed measurements on ^{182}Os . At this symposium, Walus described experiments on multiple bands in ^{166}Yb from work in Lund and Copenhagen.

The above is by no means a complete list of cases where side bands are known in the vicinity of $I \approx 20$, nor will I discuss in detail all of the listed results. Rather I will use some of the above data, in addition to some new unpublished data, to demonstrate the crucial physics to be learned at this time from discrete line spectroscopy and indeed to demonstrate why we need to continue in this area in spite of the development of fine new continuum techniques. I would like to discuss three specific motivations for discrete-line studies of rotational nuclei:

1. Moments of inertia of different aligned rotational bands as a function of aligned q.p. number and type. Four different types of moments of inertia have been discussed at this symposium. Here I will discuss values of $I_{\text{band}}^{(2)}$ for different measured bands.
2. Higher band crossings. A second yrast crossing has been observed in ^{158}Er [10], ^{160}Yb [6, 11], and ^{156}Er [12], while transitions of high enough rotational frequency have been seen in ^{156}Dy [13] to demonstrate the absence of a similar crossing. Here we present new results on higher spins in ^{160}Yb and on the previously unknown yrast line in ^{164}Hf from work at Oak Ridge, results which pertain to the second backbend.

3. Feeding patterns. Rather large differences in the population of high-spin yrast and non-yrast states in (HI,xn) reactions seem to depend on the occurrence of high-frequency band crossings.

Much of the data discussed in this paper comes from measurements performed while I was on leave for a year at the Niels Bohr Institute and then later at Oak Ridge upon my return. My colleagues in these projects are listed in Table I.

2. Experimental Methods

The basic techniques for discrete-line γ -ray spectroscopy are well known and need no review here. However, one should perhaps consider the special techniques to be used in pushing spectroscopy to the level of the very weak high energy (~ 1 MeV) rotational transitions that are emitted from states in the vicinity of $I = 30$.

2.1. Multi-Ge arrays.

The multiplicity of (HI, xn) events is rather high (15-30), which argues against the classical arrangement of 2 Ge counters very near the target. Removing the counters to 7-10 cm obviously improves the peak to background ratio by reducing summing effects, but also enables one to position many Ge counters at similar distances. The arrangement used in our recent ^{164}Hf experiment at the Oak Ridge Isochronous Cyclotron (ORIC) is shown in Fig. 1. With high-multiplicity events, 3 Ge counters will often fire, which triples the number of entries into the desired 2-dimensional coincidence matrix. This helps one to gather the high statistics (50-300 million γ - γ pairs)

necessary to construct a complex scheme of multiple bands. Having counters at a variety of angles is very useful, in that comparing the total coincidence spectra in a certain multiplicity fold for the different detectors gives a reasonable measure of the dipole or quadrupole character of the γ rays. This less than perfect angular distribution measure may be the only one possible for weak transitions which are nearly invisible in a singles spectrum.

2.2. Filters.

Not only quantity, but also quality is important in this type of discrete-line measurement. A selection on high-multiplicity or large total γ -ray energy events discriminates against unwanted background from Coulomb excitation or from the reaction channel with an extra evaporated neutron. The former requires discrete NaI counters while the latter requires a very large volume NaI detector. Our ^{160}Yb experiment [6] at the Niels Bohr Institute used 4 Ge and 3 NaI counters and required 3 detectors to fire, at least 2 of which must have been Ge counters. The fold of each event was written on tape, which allowed flexibility in choosing the fold upon playback. In contrast, our ORIC measurement (Fig. 1) on ^{164}Hf involved 7 Ge counters in the median plane with a 25 cm x 25 cm NaI detector immediately below the plane and a 22 cm x 30 cm NaI above. The total energy deposited in these 2 counters was recorded and used to select high γ -energy events upon analysis. Different slices of the total energy spectrum emphasizes different reaction products, which can be used to associate unknown lines with certain

products.

2.3. Choice of Projectile.

To study the occurrence of crossings in aligned side bands, one would like to observe band members up to $I \sim 20$. Thus one must judiciously choose the projectile to insure side band population to high enough spin.

My feeling is that ^{16}O represents a good compromise, a very good projectile to use for the detailed spectroscopy of the near-yrast side bands. In our NBI ($^{16}\text{O}, 3n$) measurements to $^{160,161,162}\text{Yb}$ [6,7], l_{max} was approximately $30 \hbar$, and we observed side bands up to $I \sim 22$. The systematic work described by Dracoulis [8] was performed with ($^{16}\text{O}, 4n$) reactions. Of course, one then wishes to follow these bands (and the yrast band) to higher spins, so one can use a heavier projectile to supplement the level scheme so laboriously constructed with the lighter reaction. Our ($^{20}\text{Ne}, 4n$) ^{160}Yb experiment at ORIC resulted in a 5-fold increase in the intensity for the $I = 24$ yrast state compared to the ($^{16}\text{O}, 3n$) ^{160}Yb NBI measurement, and enabled us to assign states up to $I = 34$ in the yrast sequence and up to 27 or 28 in two side bands. Use of an even heavier projectile might slightly increase the yrast transitions but would probably decrease the population of side bands.

2.4. Analysis techniques.

An array of 7 Ge counters leads to rather efficient collection of high-multiplicity events but also complicates the analysis of the γ - γ coincidence data. Of course, these complications are reduced if angular distribution and efficiency differences in the counters are neglected and all γ - γ pairs

are treated equally. Then background-corrected coincidence gates can be extracted in the customary fashion. Or, a large 2K x 2K channel matrix, for example, can be sorted and then corrected to yield the positive correlations by subtraction of an uncorrelated background using techniques evolved from recent continuum experiments [14,15]. We have also experimented at Oak Ridge with correcting the events with the appropriate detector efficiency and then performing an iterative correction for the uncorrelated background. These large matrix-manipulation methods look promising for the future not only for the analysis of the continuum features of the coincidence data, but also for extraction of detailed discrete-line information.

3. Results and Discussion

3.1. Moments of Inertia.

Four distinct quantities related to the moment of inertia of the rotating nucleus have been discussed at this symposium. The quantities $I_{\text{band}}^{(1)}$ and $I_{\text{yrast}}^{(1)}$ result from first differences of the level energies within a band or along the yrast line, respectively, as a function of I^2 , whereas $I_{\text{band}}^{(2)}$ and $I_{\text{yrast}}^{(2)}$ are calculated from second differences. Here I wish to discuss the "band" moments (call them $I_b^{(1)}$ and $I_b^{(2)}$) as deduced from knowledge of discrete-line transitions in aligned bands [16].

The total angular momentum along the x (rotation) axis, I_x , can be written as the sum of a part from alignment of q.p. along the rotation axis, i , and a part from rotation of the non-aligned core, R :

$$I_x = i + R.$$

The rotational angular momentum can be written in terms of a collective moment of inertia, which seems to vary with frequency and can thus be parameterized by a Harris [17] expansion:

$$I_x = i + \omega (I_0 + I_1 \omega^2)$$

where I_0 and I_1 are VMI-type parameters. For $K=0$ bands the total angular momentum is along the x axis, and so $I_x = I + \frac{1}{2}$ [5]. The simplest definition of a moment of inertia is then

$$I_b^{(1)} = \frac{I_x}{\omega} = \frac{i}{\omega} + (I_0 + I_1 \omega^2).$$

This is half the usual effective moment of inertia plotted in the backbending graph, $2I/\hbar^2 = (4I-2)/E_\gamma$ for an $I \rightarrow I-2$ transition. Such a plot is made for the new data reported at this symposium by Walus on ^{166}Yb in Fig. 2a. A large increase in $I_b^{(1)}$ occurs at the backbend since the aligned angular momentum increases from a very small value in the ground band to a rather large quantity in the S band. After the backbend, i is approximately constant and so the first term in the above equation decreases with increasing ω , causing the characteristic droop in $I_b^{(1)}$ after the completion of the backbend.

The confusing effect of the alignment term in $I_b^{(1)}$ can be eliminated by defining a moment of inertia based upon second differences

$$I_b^{(2)} = \frac{dI_x}{d\omega} = I_0 + 3I_1 \omega^2.$$

For $K=0$ bands, $\hbar\omega$ is half of the transition energy, and so experimental estimates of $I_b^{(2)}$ can be deduced from $\Delta I_x / \Delta \omega$ for two consecutive rotational transitions in a band. The experimental values for ^{166}Yb are displayed in Fig. 2b. Such a second difference plot is, of course, very sensitive to band crossings, and thus the experimental points in the vicinity of the backbend are far off scale in Fig. 2b.

In Fig. 2a, one can easily observe the different behavior of the moment of inertia with rotational frequency in the ground versus the S

bands. While $I_b^{(1)}$ increases constantly with ω^2 in the ground band, this quantity is more constant in the S band. This is more easily seen in Fig. 2b, where the parameter I_1 expresses this difference: I_1 is 4.5 times larger in the ground band than in the S band. In addition, one notices a larger value of I_0 for the S band by extrapolating to $\omega=0$.

In Fig. 3 is presented a summary of I_0 and I_1 values extracted from experimental data in this way for ground and S bands in a number of light rare-earth nuclei. In order to extract reasonable values for an S band, one must know experimental 3 or 4 rotational transitions after the completion of the band crossing. This excludes from this systematic many backbending cases, especially if the crossing has the nature of a weak upbend.

The trend in Fig. 3 is clear: in all cases I_0 is larger and I_1 smaller for the S band compared to the ground band. The behavior for I_0 was noted recently by Bengtsson [18], who pointed out also an increase in I_0 for $i_{13/2}$ aligned bands in odd-A nuclei compared to the even-even cores. He presented calculations to show that slightly larger ground-state deformations exist for these odd-A nuclei, possibly explaining the larger I_0 values. Even more striking is the systematically smaller values of I_1 for S bands. In a loose way, I_1 can be viewed as the coefficient of the "stretching" term in the moment of inertia. This is not necessarily a physical stretching, but more an increase in I due to a gradual decrease in the pairing correlations, prompted by the nuclear rotation. The trend shows consistently less "stretching" in I for S bands compared to ground bands.

It is possible to extract believable values of I_0 and I_1 for S bands only if the alignment in these bands is constant with frequency. But,

this appears to be a good assumption, at least for bands at the beginning of the $i_{13/2}$ shell, as discussed by Bengtsson [18]. In the light Yb nuclei, our work [6,7] at the Niels Bohr Institute has established a number of q.p. bands of high (and evidently constant) alignment. The bands observed in ^{160}Yb are shown in the alignment plot of Fig. 4. All of these bands experience crossings, but it is possible to extract an estimate of $I_b^{(2)}$ in most cases before or between crossings. The values of $I_b^{(2)}$ for the ground, S, and side bands 1 and 2 ($\alpha\pi = 0^-$ and 1^- , respectively)¹ are given in Fig. 5. It at first appears that $I_b^{(2)}$ values are smaller for the side bands (which involve one aligned $i_{13/2}$ neutron) than for the S band (2 such neutrons). However, the values of $I_b^{(2)}$ for the S band may be unreliable due to the influence of the first and second backbends. In any case, the aligned side bands have larger I_0 and smaller I_1 values than the ground bands, similar to the consistent story presented for the S bands in Fig. 3.

The bands observed in our NBI measurements [6,7] on ^{161}Yb are shown in the alignment plot of Fig. 6. The yrast $i_{13/2}$ band has 4 rotational transitions before the upbend at $\hbar\omega = .35$ MeV, resulting in 3 points on the $I_b^{(2)}$ vs. ω^2 plot of Fig. 7. Band 2, a gradually aligning $h_{9/2}$ band based on the $3/2[521]$ orbit, backbends at $\hbar\omega \approx .23$ MeV, after which one has a 3-q.p. band involving one $h_{9/2}$ and two aligned $i_{13/2}$ neutrons. Band 1 is the 3-q.p. $\alpha = -\frac{1}{2}$ companion of band 2. The last point on the band 1 and on the band 2 curve in Fig. 7 comes from another recent measurement [19] and indicates an imminent second backbend in each case. One

¹ α is the signature of the band [4,5]; the angular momenta of the levels in the band are a series of even numbers plus α .

notes smaller I_1 values for the 3-q.p. bands than for the 1-q.p. bands, which in turn have smaller values compared to the ground band. This suggests a rather smooth trend of less "stretching", i.e. less increase in I with rotational frequency, as the number of aligned quasi-particles increases.

It is difficult to assess the best mode of comparison between these varying $I_b^{(2)}$ values for different bands in different nuclei. Rather than comparing I_1 values, it is perhaps better to compare values of $I_b^{(2)}$ at a certain rotational frequency, to try to find out how efficiently the nucleus rotates at a given frequency in different aligned q.p. configurations. There is no single frequency where all bands presented in Figs. 5 and 7 are known, so slight extrapolation of the lines (assuming constant I_0 and I_1 values for a given band) must be performed. In Fig. 8, $I_b^{(2)}$ values at $(\hbar\omega)^2 = 0.1 \text{ MeV}^2$, i.e. $E_\gamma = 666 \text{ keV}$, are compared for $^{160,161,162}\text{Yb}$. The values for the 1 q.p. $h_{9/2}$ and $i_{13/2}$ bands are smaller than those for the ground band, the values for the 2-q.p. side bands in $^{160,162}\text{Yb}$ are even smaller, and that for a 3-q.p. structure in ^{161}Yb is possibly smaller still by a slight amount. The $I_b^{(2)}$ for the S band in ^{160}Yb is included in Fig. 8, but perhaps it is affected by the first and second backbands.

If this correlation is real (i.e. if alignments are really constant), then it indicates some dependence of the moment of inertia on the number and nature of the aligned particles in the rotating nucleus. I present this tentative analysis for two reasons. The first involves a call to theorists to contemplate such effects. A naive experimentalist can imagine several distinct results from alignment of particles in a rotating nucleus. One might expect an increase in I due to a decrease in pairing

correlations when a q.p. is aligned. On the other hand, could the moment of inertia of the rotating core decrease when the rather strategic high- j particles decouple from the core? Of course, as more particles align, the nucleus becomes spherical and one reaches the rigid-body value of I . Detailed calculations are needed to assess these possibilities.

A second reason for presenting this analysis is to point out that it is important for discrete-line spectroscopists to probe these possible differences in moments of inertia in different q.p. structures. The elegant new energy-energy correlation technique allows one to deduce a collective moment of inertia averaged over many different bands in one nucleus (or more). This is very valuable information, especially at high spins unreachably in discrete-line work. But, the physics of the differences between at least a few of the bands must come from discrete-line measurements.

3.2 Higher Crossings.

Most neutron-deficient rare-earth nuclei exhibit a backbend in the yrast sequence around $I \sim 14$, and now three even-even nuclei have been found to exhibit a second crossing around $I \sim 26$, $\hbar\omega \sim 0.43$ MeV: ^{158}Er [10], ^{160}Yb [6,11], and ^{156}Er [12]. Comparison of these results to calculations of Faessler, Ploszajczak, and Schmid [20] and of Bengtsson and Frauendorf [5] indicates that the alignment of $h_{11/2}$ protons is responsible for this crossing. As experimentalists, we must try to verify this suggestion as well as possible by understanding the present cases (for example, by measuring the alignment gain in the crossing) or by searching for second backbends in adjacent nuclei or in other regions. In the following, I will describe two of our recent experiments at Oak Ridge

pertaining to these questions.

3.2.1 ^{160}Yb .

The measurements on ^{160}Yb performed in Copenhagen [6] utilized the ($^{160}, 3n$) reaction at 81 MeV and led to assignment of the yrast sequence up to 28^+ (see Fig. 4), in agreement with the results of Beck et al. [11]. More recently, we [see Table I] have performed measurements at the Oak Ridge Isochronous Cyclotron using the $^{144}\text{Nd}(^{20}\text{Ne}, 4n)^{160}\text{Y}$ reaction at 107 MeV, in the hope that the higher I_{max} of this reaction ($\sim 45 \hbar$) compared to that for the ^{160}Yb -induced reaction ($\sim 30 \hbar$) would lead to greater population of high-spin states. An array of 5 Ge counters and one 25 cm x 25 cm NaI detector was used in this work. This reaction led to a tremendous increase ($\sim$ five-fold) in the intensity of the states above $I = 20^+$, resulting in the tentative assignment of lines up to $I = 34$. These assignments are partially demonstrated by the background subtracted coincidence gates shown in Figs. 9 and 10. The spectrum in Fig. 9 results from a gate at 836 keV, previously assigned as the $26^+ \rightarrow 24^+$ transition. The strong self-coincidence in this spectrum leads to the placement of the $30^+ \rightarrow 28^+$ transition, and the $32^+ \rightarrow 30^+$ line at 878 keV is also obvious. The spectrum in Fig. 10 results from a gate on the $28^+ \rightarrow 26^+$ transition and suggests in addition the 953-keV transition as next in the yrast cascade. There are hints of other peaks in this spectrum, but they may not be statistically significant. Higher transitions also were assigned in 2 of the 4 known side bands, i.e. 1 and 2 of Fig. 4.

The yrast line and side bands 1 and 2 are entered into the I_x vs. $\hbar\omega$ plot of Fig. 11. It is assumed that $K=0$ for all 3 bands, and that $I_x = I - \frac{1}{2}$ for a $I \rightarrow I-2$ transition. The importance of establishing these bands

to higher spins is that the crossings are now completed and one can establish the alignment gain in the crossing and the moment of inertia of the 4-q.p. bands after the crossing. Concerning the latter, this estimate of $I_b^{(2)}$ is probably unreliable for the side bands 1 and 2, since each band is expected to upbend close in frequency to the second yrast crossing. However, one can (with some trepidation) estimate $I_b^{(2)}$ using the $I = 32$ and 34 points. This leads to the point far to the right in Fig. 5. By extrapolating the $I_0 = 25$, $I_1 = 80$ line, one might conclude that $I_b^{(2)}$ of the 4-q.p. band is less than that of the S band at a comparable frequency. However, this is a difficult situation, since the value of $I_b^{(2)}$ for the S band may be unreliable due to the strong crossings at higher and lower frequencies.

As mentioned above, the completed crossings can also give an estimate of the alignment gain in the crossing. This and the frequency of the crossing are the two fingerprints of a band crossing and can be calculated in the cranked shell model (CSM) [4,5]. As discussed earlier [6], band crossings around $\hbar\omega = 0.36$ MeV were observed in five bands in ^{160}Yb (see Fig. 4) and in the $i_{13/2}$ band in ^{161}Yb . The CSM calculations [7] predict a crossing at $\hbar\omega = 0.36$ MeV, $\Delta i = 6.6 \hbar$, due to the alignment of the second best $\alpha=0$ pair of $i_{13/2}$ neutrons. The most favorable $i_{13/2}$ level in the Routhian is blocked in all of these cases. The measured frequency agrees with the calculation, and now some estimate of Δi can be obtained from Fig. 11. By extrapolating I_x beyond the backbend for band 1, one gets $\Delta i = 6.6 \hbar$, in exact agreement with the predicted value. This lends strength to our explanation of the nature of this rather common crossing [6].

In extrapolating the S band in a similar manner, one obtains $\Delta i = 5.5 \hbar$ for the second yrast backbend. This and the observed frequency agree well

with the predicted values [5] of $6.0 \hbar$ and 0.44 MeV for $h_{11/2}$ proton alignment. A nagging question in this analysis, however, is how much the levels immediately below the second backbend are affected by this crossing of interaction strength larger than that of the first backbend. This question can be addressed after considering our ^{164}Hf measurement.

3.2.2 ^{164}Hf .

Recent calculations of Dudek [21] indicate that the second backbend observed in ^{156}Er [12] can best be explained as a neutron effect, partially $h_{9/2}$. To help decide on the origin of this crossing at $\hbar\omega = .43 \text{ MeV}$ in this region, it is important to learn more about the Z and N dependence of this phenomenon. We therefore performed very recently measurements on the "virgin" nucleus ^{164}Hf (not even the first $2+$ was previously reported). The $^{148}\text{Sm}(^{20}\text{Ne}, 4n)$ reaction at 114 MeV was used in conjunction with the 7-Ge , 2-NaI detector array described in section 2.1 and in Fig. 1. The beam energy was varied and the total energy spectrum was sliced in order to get a detailed excitation function on the observed γ rays. Known lines in ^{166}Hf and the regular behavior of the first $2+$ level with Z and N were crucial in concluding the transitions in ^{164}Hf from this detailed excitation function measurement.

A background subtracted gate on the 582-keV line is shown in Fig. 12. From this and other gates, we conclude that this case has a very sharp backbend, the $14 \rightarrow 12$ transition being even lower in energy than the $4 \rightarrow 2$. As happens in so many of these cases, the 582-keV peak has a self-coincidence, and we conclude that it contains the $8 \rightarrow 6$ and $18 \rightarrow 16$ transitions (an obvious illustration that the S band here has $i = 10 \hbar$). The coincidence spectrum resulting from the sum of the upper yrast gates is also shown in Fig. 12.

From these two spectra and others, lines up through the $26 \rightarrow 24$ 913-keV transition can be assigned. It is apparent that there is no second yrast backbend in this range.

The conventional backbending plot is shown for $^{164}, ^{166}, ^{168}\text{Hf}$ in Fig. 13. Although the higher-spin states are unknown in ^{166}Hf one can discern a pattern of oscillating interaction strength very similar to that known for Yb isotopes: ^{168}Hf is a sharp backbender (small interaction strength), ^{166}Hf upbends (large strength), ^{164}Hf is very sharp (small strength). This is almost identical to the pattern exhibited by $^{164}, ^{162}, ^{160}\text{Yb}$, respectively. Note that not the isotones but the isotones plus 2 neutrons are very similar. This oscillating interaction strength in Yb is well understood in the CSM calculations [22,5], and in the work of Faessler [23].

The comparison of the yrast bands in ^{160}Yb and ^{164}Hf is given in Fig. 14. Up to $I = 20$, the two yrast bands are amazingly similar. The ground bands are quite similar, as are the S bands initially and the backbend is very sharp in each case. I know of no other case of close lying nuclei so similar up to $I = 20$. Above that point, however, the two cases diverge, especially in the fact that ^{160}Yb has a second backbend and ^{164}Hf does not. This second crossing in ^{160}Yb evidently also affects the last few members of the S band ($I = 22, 24$) before the backbend, logical in view of the fact that the second crossing is one of larger interaction strength than the first crossing. Of course, this makes it difficult to estimate the alignment gain in the second crossing by extrapolating the S band to higher frequencies. The Δi of $5.5 \hbar$ extracted this way (discussed in section 3.2.1) is probably too low. A better estimate of this Δi might be obtained by assuming that the S band of ^{164}Hf is a better reference,

since this nucleus exhibits no second backbend and since the two yrast lines are so similar below $I = 22$. One obtains $\Delta i = 6.7 \hbar$ in this way, only slightly larger than the value of 6.0 predicted in the CSM calculations [5] for $h_{11/2}$ proton alignment.

The region of the second backbenders is shown in Fig. 15. For $M = 90$, the CSM calculations predict that the interaction strength in the $(h_{11/2})^2$ proton crossing should decrease from $Z = 66$ to 70, possibly explaining the observed trend of the second backbend for ^{156}Dy , ^{158}Er , ^{160}Yb . Likewise, the calculations predict large interaction between the crossing bands in ^{164}Hf [24], possibly explaining the absence of a second backbend. On the other hand, in the case of larger interaction the rotating nucleus must still gain $\sim 6 \hbar$ from the alignment of $h_{11/2}$ protons, but the gain will come gradually as opposed to the sudden gain in ^{160}Yb . The problem is that in Fig. 14 the S band of ^{164}Hf shows no sign of gradually gaining $6 \hbar$ of angular momentum [25]. Is this really a case of large interaction, or is this a very small interaction with a sharp second backbend about to begin at slightly higher frequency? The experimental answer to this question will be crucial for determining whether $h_{11/2}$ proton alignment is the cause of ^{160}Yb second backbend.

3.2.3 Future Tests.

Blocking experiments can be used to help ascertain the origin of the second backbend. If this crossing is blocked in a certain q.p. band in an adjacent odd-N or Z nucleus, then that quasi-particle is likely responsible for the crossing. Such a blocking experiment on ^{161}Yb [19] gives some indication that this $h_{9/2}$ neutron band is about to experience a crossing at $\hbar \omega \sim .4 \text{ MeV}$ (see Fig. 7), but the evidence is not conclusive. That

experiment tests the contribution of the $h_{9/2}$ neutron orbital to the second backbend, and a measurement on an adjacent odd-Z nucleus, e.g. ^{159}Tm , would test the contribution of the $h_{11/2}$ proton orbital by searching for a second backbend in the $h_{11/2}$ band.

Another test of importance would be to search for the second backbend in heavier nuclei, e.g. Os. A proton cranking calculation for ^{182}Os [24] is displayed in Fig. 16. In this region, the $h_{9/2}$ proton level, $\frac{1}{2}[541]$, is expected to be the easiest proton to align, giving rise to a crossing at $\hbar\omega = .43$ MeV. Lieder et. al. [26] have performed very extensive discrete-line measurements on ^{182}Os with an ^{16}O -induced reaction at the NBI accelerator. They observe the yrast line up to $I = 24$, $\hbar\omega \sim 0.4$ MeV, in addition to a number of side bands up to $\hbar\omega \sim 0.3-0.36$ MeV. A collaborative experiment will soon occur using the ^{22}Ne from ORIC to try to bring more angular momentum into the final nucleus and possibly observe the second yrast crossing in ^{182}Os . There is some slight possibility that $h_{9/2}$ proton alignment plays a role in the second backbend in Er and Yb nuclei [5], and thus it is important to observe this effect in a more favorable region.

3.3 Feeding Patterns.

An important aspect of discrete line spectroscopy is to investigate not only the structure of bands but also the pattern of side-feeding intensities to different bands and band members. The population intensity of a given state at a certain angular momentum is certainly dependent on the particular reaction used. But, there is evidently also a nuclear structure dependence in the feeding patterns. This is partially demonstrated by a comparison of data obtained for ^{160}Yb and ^{164}Hf . Both

were produced in (^{20}Ne , $4n$) reactions with similar l_{max} , but the intensities at the highest spins are very different. This is illustrated in Fig. 17, where the observed γ -ray intensities (normalized to the $4 \rightarrow 2$ transition) are plotted versus I of the parent level. In all 3 curves, the severe drop in I_γ ceases at the first backbend, after which the curves are more flat. It is possible also that the curves for ^{160}Yb level off again in the vicinity of the second backbend. But, even below the second backbend region, there are big differences in the (^{20}Ne , $4n$) curves for ^{160}Yb and ^{164}Hf . Even though the yrast bands for these two nuclei are very similar up to $I = 20$ (see Fig. 14), the ^{164}Hf S band is not populated as strongly. It is likely that the presence of a second backbend results in a gathering of intensity into the yrast line.

The strong dependence of population intensities on reaction channel is demonstrated in Fig. 17 by comparing the curves for ^{160}Yb produced in ^{16}O and ^{20}Ne induced reactions. The extra angular momentum of the latter reaction results in a very large increase in intensities for the high-spin states, which of course makes detailed spectroscopy at high spins possible.

As noted in Fig. 15, ^{162}Yb has only an upbend, a much more gentle crossing than the strong backbends in ^{160}Yb and ^{164}Hf . This greatly affects the intensities along the yrast line, as the curve for ^{162}Yb produced by the (^{16}O , $3n$) reaction would continue its sharp decline through $I = 16$, unlike the leveling that occurs for ^{160}Yb at $I = 12$. In the case of ^{162}Yb , this missing intensity in the range of $I = 12-18$ goes into side bands, some of which are populated even more strongly than the yrast band [7].

In the future it is important to perform experiments to delve more into these feeding patterns at high spin.

4. Future Techniques.

The recent increase in our knowledge of side bands and of second back-bends has been made possible by the development not only of heavy-ion beams but also of new detection and filtering techniques, as discussed very briefly in sec. 2. It now seems possible to somewhat systematically study discrete lines from rotational states of spins as high as 22-26 in non-yrast bands and 28-34 in yrast bands, given the appropriate beam and detection equipment in addition to a significant amount of accelerator time. But, it is important to consider future techniques and how they would benefit discrete-line spectroscopy.

4.1. Spin spectrometer (crystal ball).

A ball of 72 NaI counters is nearing completion at Oak Ridge, and one of an even larger number of detectors is under construction at Heidelberg. While it may not be easy or wise to use these devices for discrete line coincidence spectroscopy, they will permit tremendously interesting studies of feeding patterns for different bands through the simultaneous measure of multiplicity and total energy.

4.2. Compton - suppressed Ge ball.

The large uncorrelated compton background in γ -ray spectra obtained with Ge counters is a tremendous hindrance to the study of weakly populated bands in both discrete-line and continuum spectroscopy. One can obviously adapt the technique developed for radioactive-decay spectroscopy and use Compton suppression with the Ge counters, but the necessarily large size of a NaI annulus coupled with the need for many Ge detectors clustered around the target lead to very difficult engineering problems. The use of Bismuth-

Germanate (BGO) scintillators as anti-Compton annuli offers great promise for the future. The high stopping power of this type of crystal enables the construction of an annulus much smaller than the corresponding NaI device, and thus opens up the possibility of a multi-unit array of Ge counters with BGO annuli. The cost of such a BGO suppressor is currently high, but one can hope for more favorable costs in the future. Coincidence data acquired with such an array of counters should enable one to study even more weakly populated yrast and non-yrast structures.

4.3. Marriage of discrete-line and continuum spectroscopy.

As discussed by several people at this symposium and summarized by Herskind, very significant advances have been made in the use of the energy-energy correlation technique to study moments of inertia and crossings at high spins. One advantage in using Ge counters for these measurements is that one might learn something about the continuum features associated with discrete lines. Crossings are easily identified in these 2-dimensional correlation plots in the form of bridges across the rotational valley, but it is very difficult to associate these high-frequency crossings with specific bands known at lower frequencies. Triple correlation experiments, involving a mixture of Ge and NaI counters or possibly even Ge counters alone, would provide a way to associate observed continuum features with discrete bands.

5. Conclusions

An important aspect of nuclear structure to understand in detail eventually is the interplay between collective and single-particle modes in nuclei. The different features exhibited by various rotational bands

as a function of quasi-particle content and rotational frequency provide one way to test this interplay. These pertinent features of rotational bands which can be measured and calculated include moments of inertia, amount of particle alignment, and occurrence of band crossings. As discussed by Frauendorf at this symposium, the Cranked Shell Model calculations are rather successful at understanding the alignments, relative excitation energies, and crossings exhibited by bands in the light Yb nuclei [6,7]. Most of these features are dominated by the $i_{13/2}$ neutron, the highest - j particle near the Fermi surface in this region. Even in heavier nuclei, e.g. Os, the $i_{13/2}$ neutron seems to dominate the first yrast crossings [9,24,26]. But, the responses of other particles with smaller j values to rotation are less well understood. The second yrast backbend in N = 90 nuclei seems to be explainable as an $h_{11/2}$ proton crossing [5,20], but there are suggestions [21] that neutron alignment may be at least partially responsible for the second backbend in ^{156}Er [12]. Discrete-line spectroscopists need to provide more data in the light-rare earth region and in others (e.g. Os and Ce areas) to learn more about high-frequency effects in $h_{9/2}$ and $h_{11/2}$ proton and neutron bands. It is obviously important to experimentally map out the loss of pairing in rotating nuclei, whether it be in sudden steps (particle alignments-band crossings) or in gradual ones (moment of inertia changes between crossings). The rather recent development of techniques (e.g., multiplicity and total-energy filters) and the future advances (crystal balls, Compton-suppressors, energy correlation detector arrays) will provide us the opportunity to study these effects in detail.

6. Acknowledgements

The author gratefully acknowledges the large amount of help from his collaborators (see Table I) in Oak Ridge and in Copenhagen. The author's work at the University of Tennessee is supported by the U.S. Department of Energy (DOE) under Contract #DE-AS05-76ER0-4936; Oak Ridge National Laboratory is partially supported by the U.S. DOE under contract #W-7405-eng-26 with the Union Carbide Corporation. A year's visit to Copenhagen was made possible by partial support from the Niels Bohr Institute; the many conversations with Aage Bohr and Ben Motelson were very valuable.

References

1. Johnson, N. R., Cline, D., Yates, S. W., Stephens, F. S., Riedinger, L. L., and Ronningen, R. M., Phys. Rev. Lett. 40, 151 (1978).
2. Kistner, O. C., Sunyar, A. W., and der Mateosian, E., Phys. Rev. 17, 1417 (1978).
3. Bohr, A., and Mottelson, B., Proc. Int. Conf. on Nuclear Structure, Tokyo; J. Phys. Soc. Japan 44 (1978), Suppl. p. 157.
4. Bengtsson, R., and Frauendorf, S., Nucl. Phys. A314, 27 (1979).
5. Bengtsson, R., and Frauendorf, S., Nucl. Phys. A327, 139 (1979).
6. Riedinger, L. L., Andersen, O., Frauendorf, S., Garrett, J. D., Gaardhøje, J. J., Hagemann, G. B., Herskind, B., Makovetzky, Y. V., Waddington, J. C., Guttormsen, M., and Tjøm, P. O., Phys. Rev. Lett. 44, 568 (1980).
7. Riedinger, L. L., Proc. Int. Conf. on Band Structure and Nuclear Dynamics, New Orleans, 1980.
8. Dracoulis, G. D., Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum, Strasbourg, 1980.
9. Lieder, R. M., Proc. Int. Conf. on Band Structure and Nuclear Dynamics, New Orleans, 1980.
10. Lee, I. Y., Aleonard, M. M., Deleplanque, M. A., El Masri, Y., Newton, J. O., Simon, R. S., Diamond, R. M., and Stephens, F. S., Phys. Rev. Lett. 38, 1454 (1977).
11. Beck, F. A., Bozek, E., Byrski, T., Gehringer, C., Merdinger, J. C., Schutz, Y., Styczen, J., and Vivien, J. P., Phys. Rev. Lett. 42, 492 (1979).

12. Byrski, T., Beck, F. A., Gehringer, C., Merdinger, J. C., Schutz, Y., Vivien, J. P., Proc. Int. Conf. on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980.
13. Ward, D., et al., Canberra Conference.
14. Andersen, O., Garrett, J. D., Hagemman, G. B., Herskind, B., Hillis, D. L., and Riedinger, L. L., Phys. Rev. Lett. 43, 687 (1979).
15. Deleplanque, M. A., Stephens, F. S., Andersen, O., Garrett, J. D., Herskind, B., Diamond, R.M., Ellegaard, C., Fossan, D. B., Hillis, D. L., Kluge, H., Neiman, M., Roulet, C. P., Shih, S., Simon, R. S., Phys. Rev. Lett. 45, 172 (1980).
16. Frauendorf, S., private communication.
17. Harris, S. M., Phys. Rev. 138B, 509 (1965).
18. Bengtsson, R., Proc. Int. Conf. on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980.
19. Gaardhøje, J. J., Andersen, O., Garrett, J. D., Hagemann, G. B., Herskind, B., Riedinger, L. L., Tjøm, P.O., *ibid*.
20. Faessler, A., and Ploszajczak, M., Phys. Lett. 76B, 1 (1978).
Faessler, A., Ploszajczak, M., and Schmid, K. W., to be published.
21. Dudek, J., Proc. Int. Conf. on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980.
22. Bengtsson, R., Hamamoto, I., and Mottelson, B., Phys. Lett 73B 259 (1978).
23. Faessler, A., Proc. Int. Conf. on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980.

24. May, F. R., private communication.
25. Mottelson, B.R., private communication.
26. Lieder, R. M., Sletten, G., Pedersen, J., Børggreen, J., to be published; Lieder, R. M., Proc. Int. Conf. on Band Structure and Nuclear Dynamics, New Orleans, 1980.
27. Sayer, R. O., Smith III, J. S., and Milner, W. T., Nucl. Data Tables 15, 85 (1975).

FIGURE CAPTIONS

- Fig. 1. Array of 7 Ge counters used in $(^{20}\text{Ne}, 4n)^{164}\text{Hf}$ experiment at ORIC. Large NaI counters were also positioned above and below the median plane to provide total energy selection.
- Fig. 2. (a) Plot of $I_b^{(1)} = I_x/\omega$ vs. $(\hbar\omega)^2$ for the yrast band in ^{166}Yb .
 (b) Plot of $I_b^{(2)} = dI/d\omega$ for the yrast band in ^{166}Yb . The G and S refer to the ground and S bands, respectively. The data of Walus, reported at this symposium, are used for the states of highest spins.
- Fig. 3. Values of the moment of inertia parameters, I_0 and I_1 , for ground (dark symbols and lines) and S bands (open symbols) of some backbending nuclei. These values are extracted from experimental transition energies, as demonstrated in Fig. 2b.
- Fig. 4. Aligned angular momentum versus frequency for the yrast and side bands in ^{160}Yb [6].
- Fig. 5. Values of $I_b^{(2)}$ from rotational transitions in ^{160}Yb . The filled circles refer to the ground band, open to the S band, filled triangles to side band 2, open to side band 1 (see Fig. 4). The transition energies from which these values are extracted come from Ref. 6, except for that of highest frequency, which is discussed in sec. 3.2.1.
- Fig. 6. Aligned angular momentum versus frequency for the yrast and side bands in ^{161}Yb [6,7,19].
- Fig. 7. Values of $I_b^{(2)}$ from rotational transitions in ^{161}Yb . The circles refer to the yrast $i_{13/2}$ band, the closed triangles to the back-

bending $h_{9/2}$ band (#2 in Fig. 6), and the open triangles to the 3-q.p. band #1 of Fig. 6.

Fig. 8. Values of $I_b^{(2)}$ for bands in $^{160,161,162}\text{Yb}$ at $(\hbar\omega)^2 = 0.10 \text{ MeV}$.

Those points for $^{160,161}\text{Yb}$ come from Figs. 5 and 7, respectively.

Fig. 9. Background-subtracted coincidence spectrum resulting from a gate on the 836-keV peak in the ^{160}Yb experiment at Oak Ridge.

Fig. 10. Background-subtracted coincidence spectrum resulting from a gate on the 831-keV peak in the ^{160}Yb experiment at Oak Ridge.

Fig. 11. Plot of I_x vs. $\hbar\omega$ for the yrast (dot-dashed line) band in ^{160}Yb , in addition to side bands 1 (dashed line) and 2 (solid). The circled points resulted from the ORIC work, the others from the NBI measurements.

Fig. 12. Background-subtracted coincidence spectra resulting from the ^{164}Hf experiment at Oak Ridge. The bottom spectrum corresponds to a gate on 582-keV doublet peak, the top to a sum of yrast gates for $I \geq 14$.

Fig. 13. Backbending plot for yrast bands in $^{164,166,168}\text{Hf}$. The values for ^{164}Hf come from the present work, the others from the compiled literature [27].

Fig. 14. Plot of I_x vs. $\hbar\omega$ for yrast transitions (present measurements) in ^{160}Yb (filled circles) and ^{164}Hf (open).

Fig. 15. Survey of systematic of backbending yrast bands.

Fig. 16. Cranked-shell-model calculation of the proton q.p. energy in the rotating frame versus frequency for ^{182}Os [24]. The values for ϵ_2 , ϵ_4 , Δ , and λ in the calculation are shown at the top.

Fig. 17. Plot of relative γ -ray intensities measured for the yrast levels in ^{160}Yb and ^{164}Hf .

Fig. 1.

(a)

(b)

Fig. 2

Fig. 3

$$Q_b^{(2)} \left(\frac{\hbar^2}{\text{MeV}} \right)$$

Fig. 5

Fig. 6.

Fig. 7

Fig. 8

$^{144}\text{Nd} (^{20}\text{Ne}, 4n) ^{160}\text{Yb}$
 ORIC
 GATE ON 836 keV

Fig. 9.

Fig. 12

Fig. 13.

Fig. 14.

EPS2=.218 EPS4=.045 DEL=.09 LAM=6.065 Z=76 OS-182

Fig. 16.

Fig. 17.