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MASTER

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ABSTRACT

The present talk has three parts: first, a discussion of our current ideas about the physics of very high spin states; second some comments about noncollective behavior up to the highest spins where it is known, $\sim 40 \hbar$; and finally, a presentation of the newest method for studying collective behavior up to spins of 60–70 $\hbar$. The intention is that the overview presented in the first part will be sufficiently broad to indicate the relationship of the noncollective and collective behavior discussed in the other parts, and to provide some understanding of the compromise in behavior that seems to occur at the very highest spins.

Yesterday we heard about some "intermediate" spins between 20 and 30 $\hbar$, and this morning about "low" spins in the range 10 to 20 $\hbar$. Now I want to consider the highest spins it is possible to study. A practical limit for studying angular momentum is provided by the point where the fission barrier vanishes. Beyond this spin the "nucleus" lives for less than 10⁻²⁰ seconds and only very indirect methods can give information about the nuclear structure. The angular momentum for zero fission barrier, given by the liquid-drop model¹, is shown as the upper solid curve in Fig. 1. A maximum of $\approx 100 \hbar$ occurs around $A = 120$, with smaller values at both higher and lower masses. This limit would be applicable if we could produce nuclei in their ground states. In fact, the only way

Figure 1

Fission barrier of zero (solid line) and 8 MeV (dashed line). The stable shape is oblate below ℓ_1 and triaxial between ℓ_1 and ℓ_{II} .

known at present to produce nuclei with these angular momenta is the heavy-ion compound-nucleus reaction, and it, in general, leaves the nucleus highly excited. In order to survive fission these nuclei must decay faster by some alternate mode to a point below the fission barrier. This channel usually is particle evaporation, and empirically it is found that the particle evaporation is faster whenever the fission barrier is greater than about 8 MeV. The dashed line on Fig. 1 gives the location of an 8 MeV fission barrier, and this is seen to occur at $\approx 70 \hbar$ for $A = 120$ and again, lower for both higher and lower masses. This constitutes an estimate for the highest spins we can conveniently study in nuclei, though for $A < 100$, alpha-particle evaporation can sometimes set an even lower limit.

There is now developing a reasonably comprehensive overview of the physics of high-spin states. I will begin the discussion of it by

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describing the collective behavior of a classical system, and then consider the effects introduced by the microscopic and quantal aspects of nuclei. It is assumed that the nuclear flow pattern is rigid, corresponding to the expectation that the pairing correlations in the nucleus will be quenched for $I > 30 \hbar$. Two shapes, oblate, O, and prolate, P, are shown in Fig. 2, and each is considered to rotate around either of two axes — the symmetry axis, S, or an axis perpendicular to the symmetry axis, $\perp$. (Triaxial shapes would represent intermediate cases.) The moments of inertia of these systems are compared with those of a rigid sphere, $\mathcal{J}_0$; and with the above assumptions, their calculation is simply a geometrical problem. The results, to lowest order in the deformation, $\beta \approx \Delta R/R$, are given in Fig. 2, and one sees that the oblate shape rotating around its symmetry axis has the largest moment of inertia for a given deformation, a result well known to account for the shape of the earth and rotating galaxies. These expressions for the moments of inertia are only lowest-order estimates for moderate deformations. In fact, for deformations around $\beta = 0.3$ significant corrections are needed, and for $\beta \sim 0.8$ the P- $\perp$ moment of inertia exceeds that for O-S, in contrast to those in Fig. 2. If we now consider a nucleus with $A \sim 160$ and $\beta \approx 0.3$, then the rotational energies for these shapes are shown on the right side of Fig. 2. The energy of the oblate shape rotating about its symmetry axis is, of course, lowest, corresponding to its having the largest moment of inertia.

To these classical energies we have to add the shell energies which are, on the average, 3–4 MeV, and favor one or another of the shapes and axes depending on the particular nucleon orbits near the Fermi surface. For $I < 30 \hbar$, it is seen that the 3–4 MeV shell effects are large compared to the differences in energy due to the various shapes. This means that the shell effects dominate the geometrical aspects for these angular momenta. On the other hand, for $I > 40 \hbar$, the differences in the energies in Fig. 2 become larger than the shell effects and one expects to find predominately oblate shapes rotating about the symmetry axis, O-S, or prolate shapes rotating about an axis perpendicular to the symmetry axis, P- $\perp$.

Figure 2.

The left side shows the lowest order estimate for the rigid-body moments of inertia of prolate and oblate shapes rotating about various axes. The right side shows the corresponding energy trajectories for $\beta = 0.3$ and mass number 160.

Now comes the question of collectivity. Rotation about an axis perpendicular to the symmetry axis is allowed quantum mechanically, so that this corresponds to a real collective rotation, implying bands having smooth energies and strongly enhanced $B(E2)$ values. The known rotational nuclei are mostly of the P- $\perp$ type, but a few cases thought to be O- $\perp$ are known. A quantal system cannot rotate collectively about its symmetry axis. What is meant by such a rotation has recently been elucidated by Bohr and Mottelson², who point out that for such a case the angular momentum is carried by a few individual nucleons whose angular momenta are aligned along the symmetry axis, and hence it is not at all collective. However, they showed that for a Fermi

gas, the average trajectory of these levels was the same as that of the corresponding shape rotating classically about its symmetry axis. Thus there are no bands and no enhanced $B(E2)$ values, but the energy estimate of Fig. 2 still pertains, on the average. Since this is strictly a single-particle picture, one could wonder why the concept of rotation about a symmetry axis is introduced for nuclei. There are two reasons, I think. One is for the simple estimate of the average energy of such states as given above, and the other is to incorporate both the collective and non-collective types of behavior in a single simple conceptual frame.

This difference in behavior is illustrated in Fig. 3 which shows the non-collective yrast line for ^{154}Er and the collective one for ^{158}Dy . These two lines have about the same general shape, since for $\beta \approx 0.3$. The differences expected in β are not large (and, in any case, are dominated in this spin range by shell effects). However, the rotational ^{158}Dy nucleus has a very regular band structure, with smooth energies and lifetimes decreasing regularly from 2 ps to 0.2 ps between spins 10 and 26 h. Nuclei in this region are known to have prolate deformation. By contrast, the non-collective or shell-model nucleus ^{154}Er has a rather irregular yrast line, and lifetimes that vary randomly up to $\sim 10^4$ times longer than those for ^{158}Dy at the same spins. Nuclei in this region are either spherical or oblate, as will be discussed below.

The most detailed studies of spin states in the region above 30 h, involve γ -decay following heavy-ion fusion reactions. In such reactions (under the proper circumstances) neutrons or charged particles are first evaporated and remove most of the excitation energy. The γ decay then occurs in the region between the yrast line and a line roughly one neutron binding energy above it. This region is illustrated in Fig. 4, and the decay path is sketched for four different spin inputs. It is apparent that two types of γ rays occur: those that cool the nucleus to or toward the yrast line, called "statistical;" and those that are more or less parallel to the yrast line and remove the angular momentum, called "yrast-like." At each point there is a competition between these two types. The statistical γ -rays depend only on average matrix elements and level densities, and do not contain much nuclear structure information. The

yrast-like γ rays can be collective or not, and do contain information about the nuclear structure. The competition between these types depends on the excitation energy, which affects the level densities, and also on the degree of collectivity, which produces faster (enhanced) yrast-like transitions.

There is another division of the γ rays, into those that are resolved in the spectrum and those that are not. In order to be resolved, a transition must have a sufficiently large population (as a rough estimate, one percent), and this is not generally the case for the higher excitation energies, since there are thousands of possible pathways. Only up to spins 20 or

Figure 3.

Non-collective yrast line for the nucleus, ^{154}Er (left), and the collective yrast line for the prolate deformed nucleus, ^{158}Dy (right).

Figure 4.

Typical γ -ray deexcitation pathways to the ground state. The statistical transitions are the vertical arrows which lower the temperature of the system, whereas the yrast-like transitions are roughly parallel to the yrast line and remove the angular momentum of the system.

30 h (heavy arrows in Fig. 4) does enough population collect in the yrast or near-yrast states, to produce resolved lines. In just two or three cases this has gone as high as 36 or 37 h, and these cases will be discussed here. For the higher spin transitions one must work with unresolved, or "continuum" spectra, and the most exciting new technique being developed for this purpose is discussed in the last part of this talk.

Non-collective nuclei have so far been studied only by techniques involving resolved γ -ray; probably for two reasons. The first is that they lack the regularity of collective behavior and thus would be nearly hopeless to study without a resolved spectrum. And the second is that the lack of collective transitions makes the yrast-like γ -rays slower, so that the statistical transitions compete better and cool more of the population intensity to the yrast line at relatively high spin. A result is the occurrence of resolved lines up to considerably higher spins than in collective nuclei. This population pattern is discussed in a contribution to this meeting by Wakai. The most exciting region of nuclei for studying such behavior right now is just above 82 neutrons, around $Z = 64$, and I want to discuss that region briefly.

Figure 5.
Level scheme of
 ^{152}Dy .

The first level scheme to be worked out up to spins as high as 36 $\hbar$ was that of ^{152}Dy studied by Khoo et al.⁴ It is shown in Fig. 5. By contrast, one of the most recent level schemes studied in this region is that of ^{150}Gd , which is a contribution to this meeting by Baktash et al, and is shown in Fig. 6. These nuclei show the irregular level spacing and the existence of isomeric states that are characteristic of this non-collective mode of excitation in which individual particles provide the angular momentum. But the transition energies are not completely random; with very few exceptions they fall within the limits (700 ± 200) keV. Also, there are no E3 transitions, as might be expected from a pure spherical potential (and indeed are seen in the nuclei above ^{208}Pb). Another aspect, pointed out for ^{154}Er shown in Fig. 3, is that there are sequences of γ -rays of almost constant intensity which are of the same (E2) multipolarity and connect levels of

Figure 6.
Level scheme of
 ^{150}Gd .

Figure 7.
Plot of energy vs $I(I+1)$ for yrast
levels of ^{152}Dy assuming $I = 17$ for
the 60 ns isomer.

yrast line. Thus, at the present time, in Fig. 7 cannot be used to indicate deformation. Values for these nuclei must be determined by another method.

The measurement of the static quadrupole moment of a state gives clear information about deformation, and such measurements can in principle be made on nanosecond isomers using perturbed angular distribution techniques. The first such determination at high spin for nuclei in this region has been performed on the $(1 \sim 49/2^+)$ 500 ns isomer in ^{147}Gd at 7.50 MeV excitation energy.

the same parity. These two- or three-step sequences have transitions of (600 ± 100) keV and are connected to each other by lower energy lines. So there are certainly elements of weak collectivity present, waiting for a more detailed understanding.

A striking feature of these level schemes is illustrated in the plot of excitation energy vs $I(I+1)$ for ^{152}Dy in Fig. 7. Initially the experimental data rise rapidly, due to a decrease in the pairing, and then at about spin 16 $\hbar$ turn over into an approximately straight line up to the highest spin, 36 $\hbar$. The slope of this long straight portion of the curve leads to the determination of an effective moment of inertia. For ^{154}Er (Fig. 3) this yields $2\mathcal{J}/\hbar^2 = \sim 140 \text{ MeV}^{-1}$ and for ^{152}Dy , $\sim 142 \text{ MeV}^{-1}$. These values are 10-15 percent greater than those of a rigid diffuse sphere of the appropriate mass. This increase could be considered an indication of deformation, and if so taken, would correspond to $\beta \approx 0.2$ for a deformed oblate shape, a rather large deformation. Certainly for collective rotation, the slope of the curve, and hence the effective moment of inertia, is thought to bear a connection to the deformation of the nucleus. But here, near a magic number, where the angular momentum is being carried largely by a few particles aligned along the rotation axis, it seems more likely that shell effects will be large and might affect this slope. Results of several recent calculations support this view. For example, Fig. 8 shows curves calculated for several nuclei with neutron numbers around $N = 82$ using a cranked spherical Nilsson potential and BCS pairing⁵ and it can be seen that due to shell effects even larger differences in slopes appear than are seen in experiment. Similar results are found by Leander et al⁶, and these authors point out the importance of pairing in calculating these moments of inertia and the configurations of states along the

Ref. 603-765

Figure 8.

Plot of energy vs I^2 for the yrast levels of nuclei with the indicated neutron number as calculated with a rotating spherical Nilsson potential.

Ref. 603-771

Figure 9.

Unresolved γ -ray spectrum from targets of ^{119}Sn (left) and ^{124}Sn (right) bombarded with ^{40}Ar projectiles.

1.3 MeV seems to resemble the upper part of the rotational bump in the $^{159,160}\text{Er}$ product nuclei. This second bump develops very strongly with increasing multiplicity, showing that it comes from the highest spin states populated. The multipole composition of the γ -ray spectra, deduced from the 0° and 90° intensities with the assumption of only stretched dipole and quadrupole transitions, shows that the upper bump in $^{154,155}\text{Er}$ consists mainly of stretched quadrupole transitions. This is not true for the lower peak, which

The quadrupole moment obtained was $(3.14 \pm 0.17) b$, from which a deformation β of -0.18 was derived (the negative sign was assumed). This is a reasonably large deformation, two or three times that implied by the aligned particles alone. Thus it is the first real indication that sizeable oblate deformations might exist in this region. Nevertheless, these are very difficult experiments, and more such data are badly needed.

Resolved lines in nuclei around $N = 82$ can be found only up to $\sim 36 h$. To go higher in spin one must study the unresolved spectrum, and some work in that direction has been done. A group at Orsay⁸ has recently studied ^{154}Er in comparison with ^{160}Er by bombarding targets of ^{119}Sn and ^{124}Sn with ^{40}Ar beams of appropriate energy. They employed a multiplicity filter, NaI detectors at 0° and 90° , and a Ge(Li) detector to provide a gate on transitions from $4n$ and $5n$ products. The ^{164}Er compound nucleus has an unresolved γ -ray spectrum (Fig. 9) showing the characteristic yrast bump below 1.6 MeV with a flat region below 1 MeV. The ^{159}Er compound nucleus has a very different spectrum showing two bumps below 1.6 MeV separated by a valley at about 1 MeV. The low-energy bump has a high intensity and contains all the known discrete transitions around 0.7 MeV connecting states with spins up to $36 h$. The higher bump starts at ~ 1 MeV, and above its maximum at

has a large fraction of dipoles, in agreement with the known discrete lines in $^{154,155}\text{Er}$. The calculated spin at the top of the cascade is $\sim 60 \hbar$ and the moment of inertia is then $\sim 150 \text{ MeV}^{-1}$. The evidence seems quite good that, at about spin $40 \hbar$ the products $^{154,155}\text{Er}$ switch from oblate (or spherical) nuclei, carrying angular momentum by alignment of their high- j particles, to strongly deformed nuclei rotating collectively. The experimental results do not determine whether these shapes are oblate or prolate, but the similarities with the heavier Er nuclei suggest the latter.

I have already moved into the area of unresolved spectra, and from the previous discussion it can be seen that many techniques have been developed for such studies. The average transition multipolarity can be determined by angular correlation and conversion coefficient studies, the collectivity by lifetime measurements, and moments of inertia by relating gamma-ray energies to the spins of the states that emit them. But recently a technique has emerged that promises to give much greater detail about high-spin states than such methods. Thus, rather than attempting a review of this entire field, I want to spend the rest of my time describing these gamma-ray energy correlation methods.

The γ -ray spectrum from a rotational nucleus is highly correlated in time, spatial distribution, and energy. Part of a rotational energy-level diagram is shown on the left side of Fig. 10, and the corresponding γ -ray spectrum on the right side. This spectrum is seen to be composed of equally spaced lines, up to some maximum energy corresponding to the decay of the state with highest angular momentum, I_{max} . There are at least two kinds of correlation in this spectrum. One is of the maximum γ -ray energy with I_{max} , and that has led to the evaluation of effective moments of inertia in many rotational nuclei. The correlation that will be discussed here is that between γ -ray energies. One illustration of this correlation, which is immediately obvious from Fig. 10, is that no two γ -rays have the same energy.

A schematic two-dimensional spectrum of one γ -ray energy against another for a rotational nucleus is shown in Fig. 11. The dots represent the location of coincidences between γ -rays de-exciting states up to $I = 14$ in a perfect rotational band with moment of inertia $\mathcal{J}$. However, different bands might have somewhat different moments of inertia, and the lines through the dots represent bands having moments of inertia differing by ± 10 percent from $\mathcal{J}$. It is also well known that nuclei align angular momentum at relatively low spin values, and the crosses in Fig. 11 are coincidences between transitions from spins 16 to $26 \hbar$ in a band having $11 \hbar$ aligned, also with a moment of inertia $\mathcal{J}$. The light lines through the crosses again represent aligned bands differing in $\mathcal{J}$ by ± 10 percent. It is clear that even if bands are populated that differ considerably in moment of inertia and aligned angular momentum, a strong pattern remains in the two dimensional γ - γ coincidence spectrum. The valley along the diagonal, representing the absence of transitions of the same energy, is not at all filled, and the first ridge adjacent to it is rather clear. (Notice, however, that a single band with a changing moment of inertia or alignment has not been considered.) It is then of considerable interest to know whether these correlations are present in real spectra at very high spins.

To perform such correlation experiments requires good statistics and a method to reduce the number of uncorrelated events. A typical experiment might involve four detectors, resulting in six independent pairs. After equalizing the gains, every coincidence can be plotted on a single two-dimensional matrix. A background of uncorrelated events, N_{ij} , is then subtracted from this γ - γ matrix. This background is calculated for the point ij from the projections of the row, $\sum_k N_{ik}$, and the column, $\sum_l N_{lj}$, on the assumption that every observed

γ -ray is equally probably in coincidence with every other observed one. The correlated two-dimensional spectrum is then:

$$E_I = \frac{1}{2} \hbar^2 I(I+1)$$

XBL 903-9762

Figure 10.
Schematic energy level spectrum of
a rotor on the left, and its γ -ray
spectrum on the right.

XBL 903-482

Figure 11.
Schematic correlation plot for a
rotational nucleus. The dots locate
the coincidences for a band with
spins up to 14h and moment of inertia
 $\bar{I}$, and the heavy lines show the
effect of bands where $\bar{I}$ differs by
 ± 10 percent. The crosses show the
location of coincidences in a band
with spins 16 to 26 h, 11 h of
aligned angular momentum, and moment
of inertia $\bar{I}$. The light lines again
show the effect of bands differing
in $\bar{I}$ by 10 percent.

$$\Delta N_{ij} = \tilde{N}_{ij} - N_{ij} = N_{ij} - \sum_k N_{ik} \frac{\sum_l N_{lj}}{\sum_{l,k} N_{lk}}$$

1

There are some problems with this subtraction method, and others are being explored, but it seems clear that the results discussed here are not much affected by these problems. The first successful experiment was made by Andersen et al.⁹, however these experiments were limited by beam energies to

rather low angular momenta. I will discuss a later study¹⁰ applying this method to a system where the maximum angular momentum the nucleus can hold was brought in.

The correlated spectrum for the system $^{124}\text{Sn} + ^{40}\text{Ar} \rightarrow ^{164}\text{Er}^*$ at 185 MeV ^{40}Ar energy is shown in Fig. 12. Three features, believed to be general, have been pointed out. First, there is a distinct valley along the diagonal up to about 1 MeV (spin 40 $\hbar$) having a measurable width, and there is some possibility this valley also exists in the region above 1.1 MeV. Second, there are a few bridges across this valley beginning as low as 0.55–0.60 MeV, and continuing as far up as the valley persists. Also there are irregularities in the ridges alongside this valley. Finally, there is a general filling of the valley above ~1 MeV, which is rather complete around 1.1 MeV. There are many other features in Fig. 12 that one would hope to understand; however, thus far only these three have been carefully considered.

XEL 803-481

Figure 12.
Correlation spectrum from the reaction $^{124}\text{Sn}(^{40}\text{Ar}, \text{xn})^{164}\text{xEr}$ at 185 MeV. The data were taken on GeLi detectors and treated according to Eq. 1. The plot shows contours of equal numbers of correlated events, where the darker regions have more counts according to the scale at the right edge.

XEL 803-502

Figure 13.
Schematic illustration of the bands in a decay pathway (solid lines) and their envelope (dashed lines).

The interpretation of these data is somewhat speculative, but promises to be quite interesting. The type of decay pathway envisioned is illustrated in Fig. 13. The scalloped pattern represent successions of rotational bands through which the population flows to the ground state. The transition between bands might be a simple band crossing as shown, or might occur via a statistical transition from a higher band (change of temperature); the assumption is that the band character is not a strong function of temperature. (This is not known to be the case, but represents the simplest starting assumption, and there is no evidence to the contrary.) The mathematical description of such a band structure is reasonably straightforward. The energy in each band is given by:

$$E(I) = \frac{\hbar^2}{2\mathcal{J}_{\text{coll}}} \frac{R^2}{2} + E(j_a) = \frac{\hbar^2}{2\mathcal{J}_{\text{coll}}} (I-j_a)^2 + E(j_a) \quad , \quad 2$$

where $\mathcal{J}_{\text{coll}}$ is the moment of inertia for collective rotation, j_a is the aligned angular momentum, $E(j_a)$ is the bandhead energy for the aligned bands, and one is neglected compared to $I-j_a$. One possible assumption is that $\mathcal{J}_{\text{coll}}$ and j_a change smoothly with spin in a band; however, that is not what happens at low spins in the backbending region and it is not suggested by the irregularity of the observed correlation spectrum at high spins. The other limiting assumption is that taken in Fig. 13; that $\mathcal{J}_{\text{coll}}$ and j_a are approximately constant in a band and change sharply between bands. In fact, $\mathcal{J}_{\text{coll}}$ is also taken to be constant in Fig. 13, and only j_a and $E(j_a)$ change between bands. It is apparent that Eq. 2 describes a parabola, displaced from the origin horizontally by j_a and vertically by $E(j_a)$, and the bands in Figure 13 are sections of these parabolas. The γ -ray transition energy within one of these bands, holding $\mathcal{J}_{\text{coll}}$ and j_a constant, is:

$$E_\gamma = 2 \left(\frac{dE}{dI} \right) j_a + \mathcal{J}_{\text{coll}} = \frac{\hbar^2}{2\mathcal{J}_{\text{coll}}} 4(I-j_a) \quad . \quad 3$$

The usual form of this equation for a rotor, can be approximated:

$$E_\gamma = \frac{\hbar^2}{2\mathcal{J}_{\text{eff}}} 4I \quad , \quad 4$$

where $j_a = 0$, corresponding to no horizontal displacement. This just gives the envelope of the bands and is the dashed curve in Fig. 13. This moment of inertia must be "effective" since the spin I is composed of both collective rotations, R , and aligned angular momentum, j_a . The relationship between the moments of inertia is then:

$$\mathcal{J}_{\text{eff}} = \frac{I}{I-j_a} \mathcal{J}_{\text{coll}} \quad . \quad 5$$

Since j_a is expected to be large -- around one half of I in the backbend region, and probably not relatively smaller at higher spins -- $\mathcal{J}_{\text{coll}}$ must be much smaller than $\mathcal{J}_{\text{eff}}$, reflecting the fact that a single particle cannot contribute fully both to the aligned angular momentum and to the collective

moment of inertia. Only I and E_γ are usually measured, so it is $\mathcal{J}_{\text{eff}}$ that is normally determined and found to be roughly equal to the rigid-body value.

The width of the valley in a correlation spectrum is related to the difference between successive transition energies, or to the curvature of the energy expression (Eq. 2). Assuming again that these occur within a band of constant $\mathcal{J}_{\text{coll}}$ and j_a :

$$\Delta E_\gamma = 4 \left(\frac{d^2 E}{dI^2} \right)_{j_a, \mathcal{J}_{\text{coll}}} = 8 \frac{\hbar^2}{2\mathcal{J}_{\text{coll}}} \quad . \quad 6$$

Thus, the valley width measures $\mathcal{J}_{\text{coll}}$ and should give values considerably smaller than the $\mathcal{J}_{\text{eff}}$ determined from γ -ray energies. The first results on this point¹⁰ suggest that this is indeed the case, with values of $\mathcal{J}_{\text{coll}}$ as low as $\sim 0.6 \mathcal{J}_{\text{eff}}$. However, these results are tentative and more data are needed. If $\mathcal{J}_{\text{coll}}$, $\mathcal{J}_{\text{eff}}$, and I can be reliably measured, then one can obtain j_a , which would be a very interesting quantity to know for these high-spin states.

The lowest-energy bridges in Fig. 12 are due to known backbends in the nuclei produced. The large one at 0.55 MeV ($\omega \sim 0.27$ MeV) corresponds to the first backbends in ^{158}Er and ^{160}Er (the major even-even products). Backbending or upbending behavior implies several γ rays of similar energies in the band and thus tends to fill the valley. The work discussed by Lee Riedinger yesterday demonstrated that a given level crossing will show up in many bands at the same rotational frequency (the same γ -ray energy). This must be true for the second large bridge at ~ 0.8 MeV ($\omega \sim 0.42$ MeV), at the location of the second backbend in ^{158}Er , since the population of that backbend in the yrast sequence is quite weak but the bridge is a prominent feature. It is known that the first backbend in this region of nuclei involves the alignment of two $i_{13/2}$ neutrons, and the second probably the alignment of two $h_{11/2}$ protons. There are at least two more higher-energy bridges in Fig. 12, each of which must involve many bands since they have not been observed in any discrete-line studies. It is not yet clear which orbitals are involved in these higher bridges. However, the general behavior up to about 1 MeV γ -ray energy seems reasonably clear—a deep valley reflecting good rotational behavior, and a few large irregularities in both the valley and ridge structure resulting from alignment of specific high- j orbitals.

Above 1 MeV in Fig. 12 the valley is largely filled, and completely so in places. It is not really clear what causes this, but a reasonable extension of the features described above seems able to do it. The bridges are caused by level crossings, and around deformation $\beta \approx 0.3$ and frequencies 0.5 MeV ($E_\gamma = 1.1$ MeV), there are a number of special levels calculated to come steeply down to the Fermi surface, crossing many other levels. For protons, these special levels come from the shell above ($N = 5$ with $N = 6$ intruder), and in fact correspond to the highest aligned $i_{13/2}$ ($N = 6$) components together with the most aligned $h_{9/2}$ level. An $N = 6$ level coming down into the basically $N = 4$ shell ($\Delta N = 2$) is particularly interesting since it has the same parity and thus can mix into these levels. The neutrons in this region do the same thing ($N = 7$ ($J_{15/2}$) coming into the $N = 5$ shell) at about the same frequency. Thus one might expect many level crossings and very disturbed rotational bands. Perhaps this can account for the general filling of the valley in this region. If true, it could be a reasonably general phenomenon implying tendencies for the nucleus to become more triaxial and more deformed. It will be interesting to try to verify such behavior.

Studies of very high spin states are exciting right now. We are learning a lot about non-collective behavior — how it is related to nuclear shapes, and how collective features are introduced. Collective behavior at the highest spins seems to be the general case, though non-collective aspects — especially increasing numbers of aligned single particles — are indicated. It appears that nuclei reach some compromise at very high spins, and we are rapidly learning more about the nature of this compromise.

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