Effect of Alignments on the Shape of ^{158}Yb

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Levels in ^{158}Yb have been established up to 38ħ in the yrast band and about 30ħ in two sidebands. Below spin 20, the similarity to the isotone ^{156}Er is striking, but up to spin 34 ^{158}Yb remains rather collective while ^{156}Er becomes triaxial and evolves toward an oblate shape. This appears to result from small shifts in particle-alignment (backbend) frequencies; a proton alignment occurs before neutron ones in ^{158}Yb, whereas the reverse is true in ^{156}Er.

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High-spin states in the transitional nuclei with $64 \leq Z \leq 70$ and $82 \leq N \leq 92$ have several interesting properties. First, they can assume a variety of shapes, ranging all the way from oblate to superdeformed prolate. However, questions about the mechanism of the shape changes and the extent to which the different shapes coexist are virtually unexplored. Second, there are reasonably good closed shells at $Z = 64$ and $N = 82$ (for spin 0) and, for all the nuclei having up to about twelve additional (valence) nucleons, this produces large shell effects at particular (higher) spins. Finally, the pairing correlations must be quenched with increasing spin, though the details depend strongly on the number and type of nucleons (among other things). Clearly, all three of these properties are interrelated, making high-spin physics of this region rich but complicated.

Fortunately the cranked-shell-model (CSM) calculations are now sufficiently well developed to account rather well for the high-spin properties of such nuclei, and they can provide considerable help in sorting out these various effects. The variety of observed shapes in this region comes about due to rather flat (soft) potential-energy surfaces as a function of shape. Thus, small driving forces can produce large changes. One of the interesting shape-driving forces has to do with the nucleon orbits themselves. Even though these can be complicated mixtures of simple shell-model wave functions (which we label $A,B,C, \ldots$), they have particular (readily calculable) shapes and tend to pull the entire nucleus toward that shape. Sudden shifts in orbit population sometimes come about when the pressure to generate angular momentum causes a pair of high-j orbits to "align"—become fully occupied and align their angular momentum with that of the rest of the core. A secondary effect of this alignment is the shape-driving tendency of the newly occupied orbits. In soft-nuclei like ^{158}Yb these can produce dramatic shape changes that depend critically on which nucleons align.

The nucleus ^{158}Yb has twelve particles (six protons and six neutrons) outside the above-mentioned closed shells, and lies just at the edge of the region of strongly deformed nuclei. The soft-rotational behavior at spin 0 becomes reasonably good rotational behavior by spin 8 or 10, and this extends up to at least spin 20. A recent study[1] found anomalous ("quasivibrational") behavior above spin 24, together with some oblate states (band terminations[2]). We have restudied ^{158}Yb, and found two new bands as well as several discrepancies with the previous study. Based on our data, together with a knowledge of level structures[3,4] in ^{156}Er and ^{158}Er, where clear band terminations are observed, we reinterpret the high-spin states of ^{158}Yb. Our interpretation involves particle alignments rather than quasivibrational behavior and band terminations.

The nucleus ^{158}Yb was produced at the 88-in. cyclotron and its decay observed with the 21 Compton-suppressed germanium detectors of the HERA array. First a reaction ^{122}Te(^{40}Ar,4n) at 175 MeV was used on a 1-mg/cm^2 lead-backed target, producing about 10^8 double coincidences in 12 h. All the lines seen were sharp, being emitted from nuclei stopped by the lead backing in about 1 ps. In addition a reaction ^{122}Sn(^{40}Ca,4n) at 195 MeV was used on two unbacked 0.5-mg/cm^2-thick targets, generating about 2×10^8 coincidences. The lines were broader due to Doppler effects from the recoiling nuclei, but no additional lines (that would have been smeared out during the slowing down in the lead backing of the Te target) were observed. This shows that all the presently resolvable lines in ^{158}Yb are emitted after delays of $\gtrsim 1$ ps. Normally, this implies that the decay passes through regions of noncollective behavior.

The level scheme shown in Fig. 1 was established rather unambiguously from the coincidence relationships. A spectrum in coincidence with the 761-keV transition is shown in Fig. 2, where a discrepancy with the previous work[1] can be seen. We do *not* find the 761-keV transition in band 1 to be in coincidence with itself, thereby removing one transition (and 2ħ) from the previous level sequence. Though not such a large experimental difference, this lowers all the highest spins previously proposed by 2ħ, and removes the previous argument[1,2] for a band termination at spin 36. We have also changed the order of transitions in band 1 rather significantly, because of a previously unobserved ~20% branching at spin 14 to a second 12^+

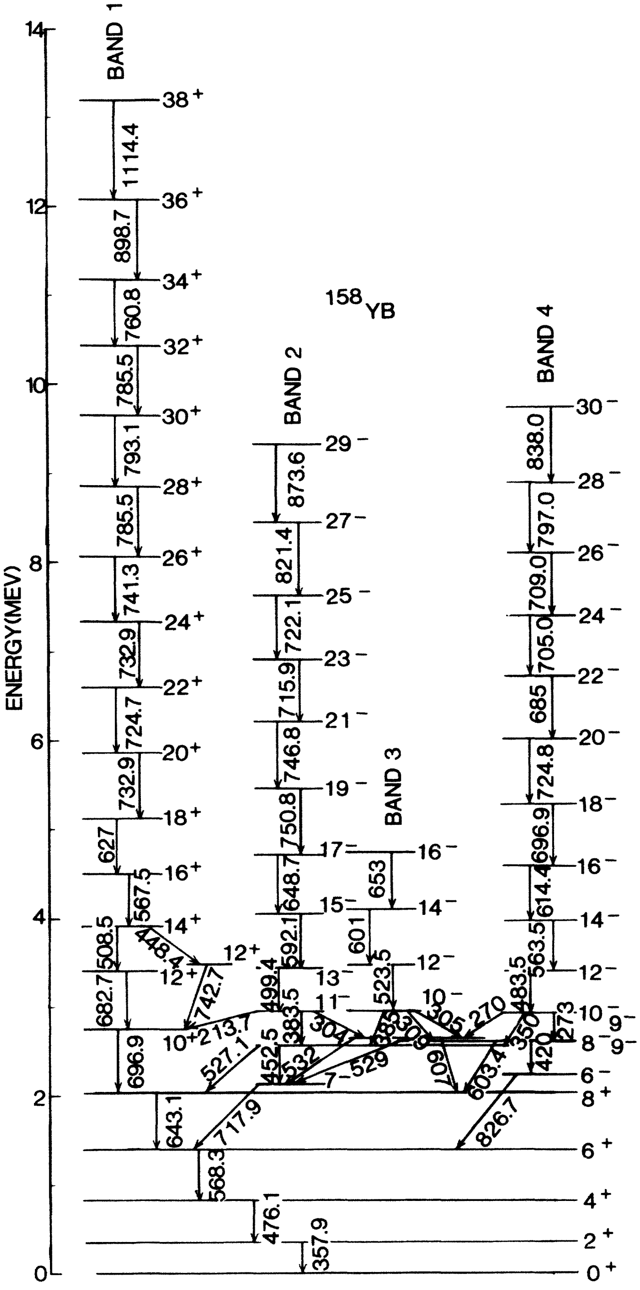

FIG. 1. Level scheme of ^{158}Yb.

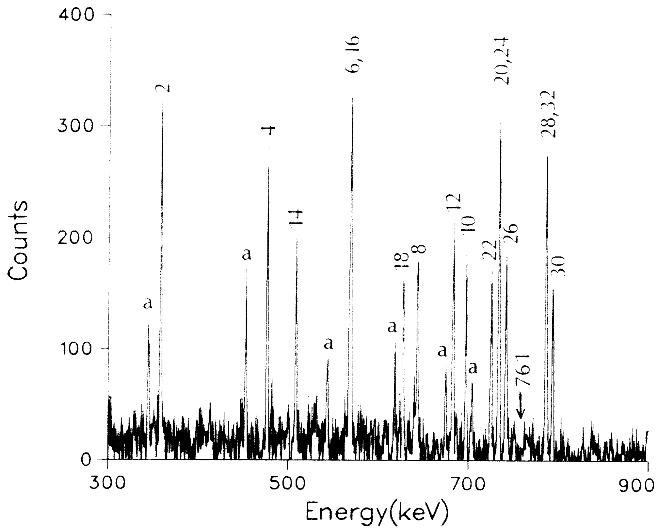

FIG. 2. Spectrum in coincidence with the 761-keV transition ($34^+ \rightarrow 32^+$). The spins refer to the initial state for the transition in ^{158}Yb, and the a's indicate lines of ^{156}Er, a contaminant of this gate. The location of the 761-keV gate is indicated.

state. (This branching affects the γ-ray intensity arguments upon which the order is based.) Our ordering is not completely unambiguous, but the main uncertainties are the location of the 793-keV transition relative to the two 786-keV ones, and the 725-keV transition relative to the two 733-keV ones. The small energy differences involved in any such interchanges will not affect the arguments we make later.

The spin assignments are based on a type of angular-correlation studies that was described in Ref. 3. The assignments for bands 1, 2, and 3 are reasonably unambiguous, as is the (second) 9^- assignment for the 2652-keV level. Band 4 is more difficult due to nonstretched dipoles connecting it with the ground band, and mixed dipole-quadrupole transitions to the other negative-parity states. Rather lengthy arguments can be made showing that the spins in band 4 are very likely, and its negative parity probable. Although spin and parity assignments based solely on angular-correlation measurements are never certain, we feel those in Fig. 1 are rather good.

We can give these bands shell-model assignments, using the usual nomenclature,[5] where A, B, and C are the lowest-lying (mixed) configurations based on the unique-parity orbitals-$i_{13/2}$ for neutrons (ν), and $h_{11/2}$ for protons (π)—and E and F are the lowest-lying normal-parity neutron configurations—based on mixed $f_{7/2}$ and $h_{9/2}$ orbitals. Thus band 1 is initially the vacuum configuration, which undergoes a νAB alignment at around spin 12. Bands 2 and 4 are very likely νAE and νAF, respectively. Only band 3 presents any problem, and it can well be νBE, although this configuration is not often observed. The extra 9^- level (at 2652 keV) is probably a member of the octupole band, which typically lies at such energies in this region of nuclei.[6]

Nuclear properties are mainly a function of neutron (rather than proton) number in the vicinity of ^{158}Yb. Thus the most similar well-studied[3] nucleus should be ^{156}Er, and below spin 20 the similarity is quite striking as can be seen in Fig. 3. Here we show spin I versus rotational freqeuncy $\hbar\omega$ for bands 1 (bottom) and 2 and 4 (top); and, insofar as these three main bands are concerned, there is no doubt that ^{158}Yb is very much like ^{156}Er over this spin range. The analog of band 3

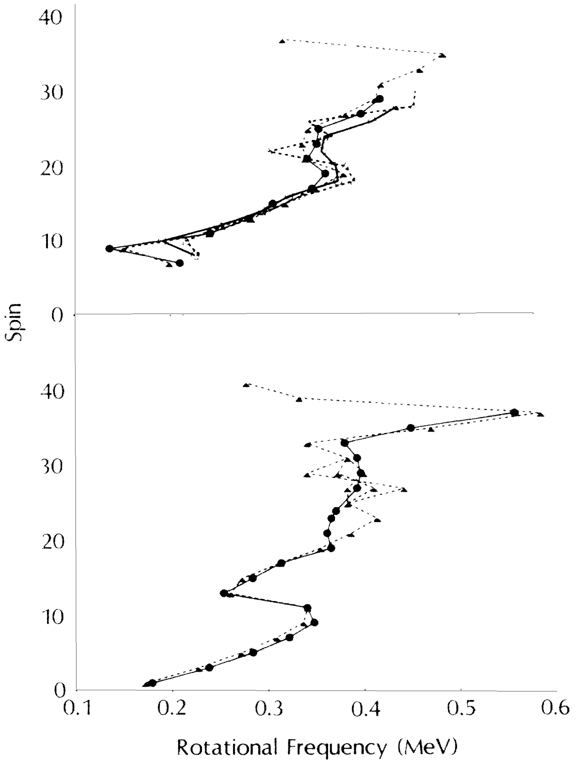

FIG. 3. Plots of spin I vs rotational frequency $\hbar\omega$ for (bottom) the yrast sequences (band 1) in ^{158}Yb (circles) and ^{156}Er (triangles) and (top) the AE (open symbols) and AF (closed symbols) sequences in the two nuclei.

was not seen in ^{156}Er, and conversely the analog of two or three weak bands seen in ^{156}Er (one being the collective octupole band) are not seen in ^{158}Yb, but this is probably due only to slightly different population patterns.

Because of the close similarity below spin 20, the differences between ^{158}Yb and ^{156}Er above spin 20 are especially interesting. There are at least three of these. The first concerns the 30^+ levels in band 1. In ^{156}Er this level branches at least five ways, none of which carries more than $\sim\frac{1}{3}$ of the total intensity. It is connected by three completely different routes to the lower part of band 1, though in total these account for only half the decay of the 30^+ level. The suggestion is strong that this 30^+ level in ^{156}Er is not closely related to the lower part of the band 1, and a shift to a more triaxial shape has been suggested.[3] By contrast, in ^{158}Yb there is no observed branching at all in this spin region. The population of this band falls gradually to $\sim 5\%$ at spin 34 and then drops suddenly by a factor of 5. Thus the top two transitions, 899 and 1114 keV, are very weak, and their relation to the rest of the band is not so clear. However, below spin 34, our tentative conclusion is that ^{158}Yb does *not* change shape like ^{156}Er.

A second related difference has to do with the second backbend (or upbend) in band 1. Figure 3 (bottom) shows that band 1 in ^{158}Yb bends strongly up at $\hbar\omega = 0.36$ MeV, whereas in ^{156}Er it does not do so until $\hbar\omega = 0.41$ MeV. Thus something about this backbend changes between the two nuclei. Above its backbend at 0.41 MeV, ^{156}Er is irregular and reaches the triaxial 30^+ state via several pathways. On the other hand ^{158}Yb behaves smoothly, apparently undergoing another (third) backbend (or upbend) at $\hbar\omega = 0.39$ MeV, ending in the above-discussed 34^+ state. Before discussing this behavior, we will consider the sidebands. In ^{158}Yb both sidebands have backbends at $\hbar\omega \approx 0.36$ or 0.37 MeV, extremely close to band 1 in that nucleus. They do not, however, seem to show the double-upbend behavior of band 1, though they may start to kink upward again at $\hbar\omega \approx 0.41$ MeV. In ^{156}Er, the sidebands are similar to those in ^{158}Yb, backbending a bit higher in frequency (~ 0.39 MeV), but pretty clearly below the band-1 frequency in ^{156}Er. There is, we believe, a simple and consistent interpretation of these characteristics, involving the three alignments reasonable for this frequency range in these nuclei: νBC, νEF, and πAB. In band 1, νBC is blocked (B is occupied) and, in the sidebands, νEF is blocked (E or F is occupied). Thus, if the simultaneous upbends in all bands of ^{158}Yb are due to the same alignment, it must be πAB. Conversely, band 1 of ^{156}Er does *not* seem to backbend where the sidebands do, suggesting that at least the lower of these (in the sidebands) is not πAB. It must then be νBC. If the upbend in band 1 of ^{156}Er were νEF, we could understand the dramatic behavior resulting, since (1) alignment of the third and fourth neutron (out of six) will surely affect the neutron pairing drastically, and (2) CSM calculations[7] show that the configuration νEF is strongly triaxial and oblate driving, whereas πAB and νBC are not. For similar reasons, if the second part of the double upbend in ^{158}Yb were νEF, we could understand why that band stops—the prolate shape has been destabilized. There is no good evidence as to the shape beyond spin 34, whereas at, and just below, this spin the regularity of the band and the lack of any branching argue that it is still reasonably collective (not oblate).

The third difference is the absence in ^{158}Yb of the strong interband transitions that occur among the negative-parity bands in ^{156}Er at the $\hbar\omega \sim 0.39$ MeV backbend. This follows naturally from the above assignments. In ^{156}Er it is a νBC alignment, which will very likely quench the neutron pairing correlations (again only one pair of neutrons is left above the $N = 82$ shell) as has been suggested.[3] What then happens to the shape is not clear since νBC is not strongly triaxial driving, but, because of the quenching, some dramatic behavior is not surprising. In ^{158}Yb we have argued that this alignment is πAB, with no dramatic implications. The upward kinks at $\hbar\omega \sim 0.42$ MeV in the ^{158}Yb sidebands might be νBC, but unfortunately the population was too weak for us to extend these bands.

Both CSM calculations and empirical systematics suggest that the above-proposed alignments are reasonable. The πAB alignment decreases in frequency from 0.5 to 0.4 MeV as the neutron number decreases from 95 to 89 in Er and Yb nuclei,[8] and the calculations indicate that this is caused by a decrease in deformation. This alignment is, therefore, expected around 0.4 MeV for $N=88$, though why it is somewhat lower in ^{158}Yb than ^{156}Er is not clear. The νBC alignment is generally found experimentally[6] between 0.3 and 0.4 MeV, and increases from 0.3 to 0.4 MeV between $N=92$ and $N=89$ and thus is also expected around 0.4 MeV for $N=88$. Again the reason ^{156}Er has this alignment at slightly lower frequency than ^{158}Yb is not obvious. There are no very clear data on the νEF alignment, but the CSM calculations[9] predict it at frequencies around 0.4 MeV for $N=88$. Thus, although there are details to be understood, the alignments proposed here do seem plausible.

There are a couple of points that require further comment. The observed states in ^{158}Yb above spin 34 look rather similar to those in ^{156}Er (see Fig. 3). In ^{156}Er these states are rather clearly related to the special 30^+ state (discussed above), and very likely comprise part of a triaxial band terminating in an oblate shape at the fully aligned 42^+ state. In ^{158}Yb, no such 30^+ state is observed and we have proposed a more collective behavior up to spin 34. Nevertheless the analog of the triaxial band observed in ^{156}Er could cross the collective sequence at $I=34$ in ^{158}Yb, making the similarity at high spins in Fig. 3 significant. Whether this is the case, or whether the extra two protons in ^{158}Yb play a role, and the similarity is just accidental, we cannot say based on the present data. A related point has to do with the energy of levels in ^{158}Yb relative to those of a rigid rotor. Above spin 28, the energy of band 1 in ^{158}Yb decreases by around 0.3 MeV relative to a rotor of the appropriate rigid-body moment of inertia (71 MeV^{-1}). This has been cited[1,2] as evidence for a change to an oblate shape. Indeed, ^{156}Er behaves rather similarly; however, the full drop there is about 1.3 MeV—some 4 times larger than the drop so far observed in ^{158}Yb. Shell effects can also cause the energies to drop locally relative to the rigid-body values, and we believe that a shell effect—the double (πAB and νEF) alignment—could account for the small drop in ^{158}Yb. This may well be accompanied by sizable triaxiality, but probably not a band termination, which requires an oblate shape.

In summary, the evidence suggests to us that ^{158}Yb remains rather collective in the yrast band up to at least spin 34. The apparent reason it differs from ^{156}Er in this respect is that in ^{158}Yb the proton alignment (πAB) occurs before the neutron alignment (νEF) and, whereas νEF tends to induce both shape and pairing changes, πAB does not. A related effect appears to be that πAB in the ^{158}Yb sidebands also produces normal backbends, whereas νBC in ^{156}Er causes strong interband transitions, probably directly or indirectly due to the severe reduction or collapse of the neutron pairing correlations. This behavior really illuminates the fact that specific nucleon alignments imply specific shape and/or pairing changes. Thus relatively small shifts in alignment frequencies can replace one alignment by another, producing large differences in the band behavior.

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