High-Spin Multiquasiparticle Yrast Traps in ^{176}Hf†

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We have identified several high-K four- and six-quasiparticle states between 2.5 and 5 MeV excitation in ^{176}Hf, which are well described by the collective model with axial symmetry. Isomers with $K^\pi = 14^-$, 19^+, and 22^- form traps at or near the yrast line. The yrast structure changes from the ground band to a $K^\pi = 16^+$ band at $I = 16$ and again to a $K^\pi = 22^-$ state at $I = 22$, providing the first demonstration that intrinsic excitations of a heavy deformed nucleus can become yrast.

The high-spin states of deformed nuclei that have been observed to date arise largely from collective rotation, involving the coherent motion of many nucleons. This is true whether the yrast structure remains the ground-state band, or develops into decoupled or unpaired bands, as occurs after back bending. The question arises as to whether few-nucleon degrees of freedom can also play an important role in the structure of nuclei at high spin. This matter is of relevance to nuclear behavior at spins exceeding $30\hbar$. Indeed, Bohr and Mottelson[1,2] have predicted that in this domain the large angular momentum of yrast states may in some cases be generated by aligning the spins of a few nucleons. Present experimental techniques do not allow us to observe individual levels at such ultrahigh spins. Nevertheless, it may be possible to investigate the interplay of collective and few-nucleon motion through the study of discrete levels by judiciously selecting a system in which the intrinsic excitations lie close to the yrast line at relatively low spins [$(10-20)\hbar$].

Such an investigation entails the study of multiquasiparticle (qp) configurations in a region of nuclear excitation (2.5–5 MeV) that has hitherto not been explored in detail. It is hence also of interest to determine whether the collective model, which has been remarkably successful at lower spins and energies, is still applicable in this new regime. Specifically, are there still simple intrinsic excitations with well-behaved rotational bands built on them, and are the radiative transitions adequately described? It is also important to ascertain whether K remains a good quantum number. Numerous (heavy-ion,xn) studies have identified no high-spin isomers which can be associated with band heads of high K; this may imply a breakdown of a coupling scheme associated with axial symmetry.[2]

A promising system to investigate is ^{176}Hf in which we had previously identified a 401-μsec four-qp isomer at 2866 keV, in addition to many high-K two-qp states at lower excitation.[3,4] In the reaction ^{176}Yb(α, 4n)^{176}Hf with a 48-MeV α beam, the 401-μsec isomer receives ~30% of the (α, 4n) cross section. We have employed a delayed coincidence technique similar to that described in Ref. 3 to isolate the γ rays populating this isomer. Some of these γ rays were themselves found to be delayed in separate experiments in which γ-ray, conversion-electron,[5] and three-parameter γ-γ-t coincidence data were accumulated with the beam pulsed off. In addition, in-beam prompt γ-γ coincidence, γ-ray angular distribution, and excitation function data were obtained. Thus, we used a large variety of spectroscopic information to develop the level scheme of Fig. 1. The transition multipolarities

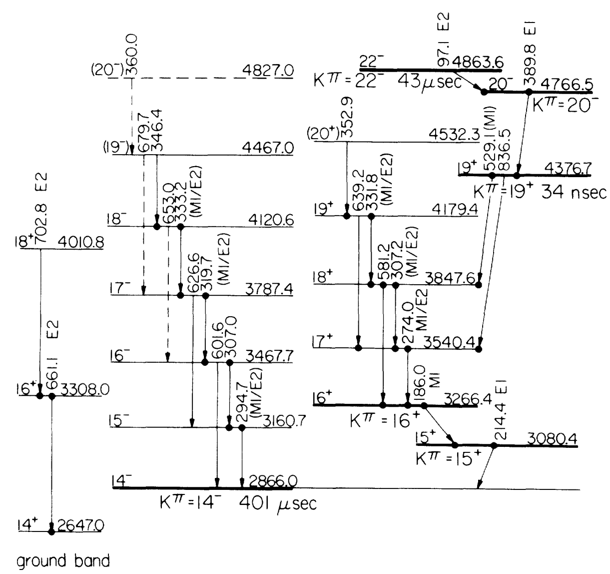

FIG. 1. Partial level scheme for ^{176}Hf showing four- and six-qp excitations and upper portion of ground band. Assignments in parentheses are tentative. Filled circles indicate γ rays entering and leaving a level in prompt coincidence.

and spins have been deduced using K and L internal conversion coefficients from direct electron-γ ratios, total conversion coefficients from intensity balance considerations in delayed spectra, and angular distribution and excitation function data.

Figure 1 shows the upper portion of the ground band and two other intrinsic rotational bands. One intrinsic band is based on the 401-μsec iosmer to which we had previously[4] assigned $I,K^\pi = 14, 14^-$; the other band is built on a $I^\pi = 16^+$ level, which is thus a $K^\pi = 16^+$ band head. The identification of these intrinsic bands was fairly straightforward because of the very regular rotational energies, spin sequence, and γ-decay pattern. The rotational parameters, A and B, where $E = AI(I+1) + BI^2(I+1)^2$, are 10.8 keV and -2.31 eV for the $K^\pi = 14^-$ band and 6.25 keV and 3.33 eV for the $K^\pi = 16^+$ band. Furthermore, the cascade-crossover ratios and angular distribution data of the intraband transitions yield[6] intrinsic g factors, $g_K = 0.57 \pm 0.04$ ($K^\pi = 14^-$) and 0.54 ± 0.05 ($K^\pi = 16^+$), in agreement with the values, 0.57 and 0.50, expected for the four-qp configurations suggested in Table I. In addition, the energies of the band heads are in reasonable agreement with expectations based on the energies of the constituent two-qp states, particularly when residual interactions between quasiparticles are considered[4,7] (see Table I).

From energy and decay systematics it is clear that the 3080-keV level is not a member of the $K^\pi = 16^+$ band, but is probably the band head of a $K^\pi = 15^+$ state of four-qp character (see Table I). The 34-nsec isomerism of the $I^\pi = 19^+$ level at 4377 keV suggests K forbiddenness and, hence, a $K^\pi = 19^+$ assignment. Since the $I^\pi = 20^-$ and 22^- levels at 4766 and 4864 keV decay through the $K^\pi = 19^+$ state (instead of through the energetically favored 19^+ member of the $K^\pi = 16^+$ band) they also have very large K and are most likely band heads with $K^\pi = 20^-$ and 22^-, respectively. The occurrence of such very high ($\geqslant 19$) K states at the observed energies suggests that the states are of six-qp character, with probable configurations given in Table I. The proposed configurations provide an explanation for the retarded 43-μsec decay between the $K^\pi = 22^-$ and 20^- levels in terms of the $\frac{5}{2}(512)_n \rightarrow \frac{1}{2}(521)_n$ transition, which is observed to be slow in neighboring off-Hf nuclei.[8]

The six-qp states and the four-qp rotational bands are observed for the first time. Indeed, there are more high-spin states here than have been identified in any other nucleus. The 22^- isomer is the highest spin isomer observed to date. The properties of these highly excited intrinsic states are well described by the collective model, indicating that there is no breakdown of this mod-

TABLE I. Suggested configurations for four- and six-qp states observed in ^{176}Hf.

Band-head energy (keV) Exp.	Calc.	K^π	Configuration[a]
2866	2838[b]	14^-	$7/2_p\ 9/2_p\ 7/2_n\ 5/2_n$
3080	3190[b]	15^+	$7/2_p\ 9/2_p\ 9/2_n\ 5/2_n$
3266	3061[b]	16^+	$7/2_p\ 9/2_p\ 7/2_n\ 9/2_n$
4377	4600[c]	19^+	$7/2_p\ 9/2_p\ 7/2_n\ 9/2_n\ 5/2_n\ 1/2_n$
4766	5000[c]	20^-	$7/2_p\ 9/2_p\ 7/2_n\ 9/2_n\ 7/2_n'\ 1/2_n$
4864	5000[c]	22^-	$7/2_p\ 9/2_p\ 7/2_n\ 9/2_n\ 7/2_n'\ 5/2_n$

[a]Single-particle orbitals are $7/2_p$, 7/2(404); $9/2_p$, 9/2(514); $7/2_n$, 7/2(514); $9/2_n$, 9/2(624); $5/2_n$, 5/2(512); $1/2_n$, 1/2(521); $7/2_n'$, 7/2(633).

[b]Calculated as described in Ref. 4, using the δ force given there as the residual interaction.

[c]Estimated from constituent four- and two-qp energies, using empirical values when known. Effects of residual interactions and of pairing gap variation due to two broken neutron pairs are not properly included in the estimate.

el at energies between 2.5 and 5 MeV. In particular, K appears to remain a good quantum number (at least for large K values), as is also illustrated by the K-forbidden isomerism of the $K^\pi = 14^-$ and 19^+ band heads. Thus, axial symmetry is preserved.

Inspection of Fig. 1 reveals that the $K^\pi = 16^+$ band head lies lower than the 16^+ state of the ground band. The yrast structure thus switches character for $I \geq 16$ from the ground band to the members of the $K^\pi = 16^+$ band. A further change occurs at spin 22 when the $I, K^\pi = 22, 22^-$ state becomes yrast. Structural changes in the yrast line also occur in ^{178}Hf.[9] This demonstrates vividly that the energetically favored states at high spin do not necessarily arise from collective rotations (ground band) but may instead be associated with few-nucleon structures.

The dominance of high-K multi-qp structures along or near the yrast line for $I \geq 16$ has important implications for the electromagnetic decay of the yrast states. For instance, the 22^- and 16^+ yrast levels de-excite not by collectively enhanced stretched $E2$ transitions but by slower single-particle transitions. Thus the 22^- isomer at almost 5 MeV is a yrast trap, while the $K^\pi = 19^+$ and 14^- isomers are traps which occur very close to the yrast line. There are many similarities between these traps and those which have been predicted[1,2] to occur at ultrahigh spin values, when some nuclei are expected to become oblate. Both cases involve the motion of a few nucleons around the symmetry axis; the large spin generated by alignment of nucleon orbits thus lies along the symmetry axis. (Most of the orbits of present interest have large Ω. Thus the particle trajectories are concentrated near the equatorial plane, and involve revolutions around the nuclear symmetry axis.) In contrast, the spin in collective rotation is *perpendicular* to the symmetry axis.

Bohr and Mottelson[1,2] have recently shown that the energy expended in generating angular momentum by alignment of particle orbits has a rotationlike relationship with spin. Furthermore the effective moment of inertia is that for rigid body rotation about the axis around which the nucleons move. A plot of the energies (from this work, Ref. 3, and Khoo *et al.*[10]) of the lowest band head of each spin in ^{176}Hf as a function of $I(I+1)$ is shown in Fig. 2. The data are distributed about a straight line which represents a moment of inertia $2\mathscr{I}/\hbar^2 = 130$ MeV^{-1}. For rigid body rotation about the *symmetry* axis of an ellipsoid

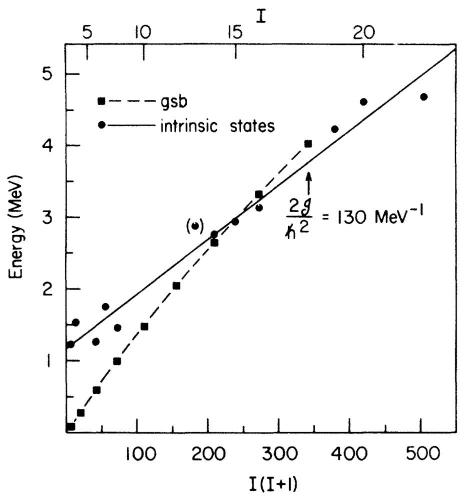

FIG. 2. Plot for ^{176}Hf of lowest band-head energies for given I (circles) and ground-band energies (squares) versus $I(I+1)$. For band heads, zero-point energies for rotation about an axis *perpendicular* to the symmetry axis have been subtracted as described in Ref. 4. Points for intrinsic states are closely distributed about a straight line with slope corresponding to $2\mathscr{I}/\hbar^2 = 130$ MeV^{-1}; for rigid body rotation about the symmetry axis, $2\mathscr{I}_3/\hbar^2 = 126$ MeV^{-1}.

with $\delta = 0.28$, the ground-state deformation, we have $2\mathscr{I}_3/\hbar^2 = 126$ MeV^{-1}, a value close to the above. Although it is tempting to treat the data of Fig. 2 as evidence for the concept[1,2] of a moment of inertia associated with the alignment of single-particle orbits around a symmetry axis, the large effect of pairing interactions in the configurations considered raises serious questions about such an interpretation. The near rigid value of the moment of inertia for the band heads may be fortuitous, perhaps occurring because of the opposing tendencies of pairing effects (which tend to decrease the effective moment of inertia by increasing the intrinsic energies) and shell effects (viz., the predominance of high-Ω orbitals near the Fermi levels, which lowers the energies of high-K states). Nevertheless the small scatter of the points about the solid straight line of Fig. 2 is quite remarkable and suggests that efforts should be made toward constructing similar plots for other nuclei by identifying high-K qp states over a wide range of spin.

Although the concept of rotation about a symmetry axis has not been unambiguously demonstrated, many of the other physical concepts introduced by Bohr and Mottelson[1,2] in connection with the behavior of nuclei in a higher spin domain have found their first demonstration in this study, but at lower spins. For instance, it has been shown that the yrast structure for a deformed nucleus can change from collective rotation to few-nucleon motion; that a few nucleons can then align to generate spin along the symmetry axis; and that yrast traps can occur under these circumstances. This is of significance to the study of nuclei at ultrahigh spins.

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Etch Induction Time in Cellulose Nitrate Track Detectors

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An etch parameter almost unnoticed previously, etch induction time, has been measured in Kodak Pathé cellulose nitrate track detector films using ^{4}He, ^{6}Li, ^{12}C, ^{14}N, and ^{16}O ions of known low energy per unit mass for calibration. The etch induction time appears to vary with the parameter $(dE/dx)_{W<1000}/Z^*$ where Z^* is the effective ion charge and $(dE/dx)_{W<1000}$ is the restricted energy loss, calculated for a δ-ray cutoff energy of 1000 eV.

The recent book by Fleischer, Price, and Walker describing techniques and applications of solid-state track detectors devotes an entire chapter to "methods of nuclear particle identification."[1] The procedures described entail a significant amount of careful scanning by microscope. In this Letter, we introduce an alternative method and a new etch parameter which may materially assist in particle identification.

It has been previously observed that latent damage trails in the surfaces of Kodak Pathé CA 80-15 (and other) track detectors do not start to etch for some small but discernable period of time following the beginning of etch. This delay has been implicitly noted by Baroni *et al.*,[2] and explicitly by Monnin[3] and also by Lück.[4] The latter developed certain techniques for eliminating this "incubation" time from his special highly sensitive cellulose nitrate. Monnin found that the presence of free oxygen decreased etch induction time in Lexan polycarbonate but had little or no effect on this parameter in cellulose nitrate.

In the course of an experimental program to determine the etch rates and the lengths of fully etched tracks of heavy ions in Kodak Pathé cellulose nitrate track detectors, it became apparent that the latent damage trails of ^{16}O ions of known specific kinetic energy, E/M, had their visible etch initiated only after a period of time, and that this period was (roughly) proportional to the E/M value of the incident particle. Moreover, a ^{4}He ion of comparable E/M value initiated its etch after a much longer etch induction time. It was thus postulated that there should be a regular re-