Rotational Behavior at High Spin in ^{168}Hf

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The yrast sequence in ^{168}Hf has been extended to $I^\pi = 34^+$ and two negative-parity sidebands have been observed to $I^\pi = 33^-$ and 30^-. At high rotational frequencies all three bands have little spin alignment and have moments of inertia which remain constant as a function of frequency. Possible evidence for the vanishing of pairing correlations is discussed.

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The γ-ray decay deexciting a deformed nucleus with large angular momentum proceeds along a sequence which is composed of various rotational bands. Following the discovery of backbending[1] in 1971 most experimental and theoretical work has focused on an understanding of the rotational frequencies at which such a decay crosses from one rotational band to another (i.e., band-crossing frequencies). Hafnium-168 was chosen for the present study as, by virtue of its deformation and the positions of its Fermi levels for neutrons and protons, it is expected to be a case where the frequency difference between the lowest and next-lowest band crossings along the yrast sequence is as large as possible. This feature allows the study of rotational bands over a large range of angular momentum (or angular frequency $\hbar\omega \approx E\gamma/2$). It is found that, in the frequency range $0.38 \leqslant \hbar\omega \leqslant 0.50$ MeV, the yrast sequence behaves as the best rotor yet observed in nuclei.

The yrast sequence[2] of ^{168}Hf has been extended to $I^\pi = 34^+$ and two other sequences have been established to $I^\pi = 33^-$ and 30^- (see Fig. 1) by measuring γ-γ coincidences following the reactions ^{124}Sn(^{48}Ti, $4n$) and ^{156}Gd(^{16}O, $4n$). The 216-MeV ^{48}Ti(11+) and 85-MeV ^{16}O(8+) beams were provided by the tandem accelerators at the Daresbury Laboratory and the Niels Bohr Institute, respectively. The γ-ray coincidences were observed with an array of five or six Compton-suppressed Ge detectors[3] (TESSA). In the Daresbury experiments, γ-ray multiplicity (M_γ) and total γ-ray cascade energies also were recorded

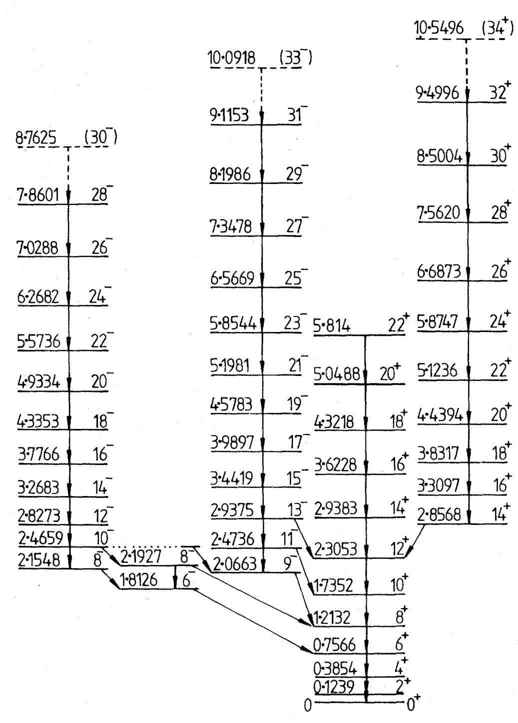

FIG. 1. The level scheme for ^{168}Hf.

with an array of fifty bismuth germanate scintillation crystals subtending a physical solid angle in excess of 90%. Typical spectra for $M_\gamma \geq 15$, obtained by summing the spectra derived from gates on individual transitions within a sequence, are shown in Fig. 2. The I^π assignments given in Fig. 1 were established up to 26^+, 25^-, and 24^- from angular distribution and conversion electron measurements at the Niels Bohr Institute. These assignments for the yrast sequence are in agreement with previous work.[2] For higher-spin states the assignments are based on relative coincidence intensities and angular correlations which are consistent with $E2$ transitions.

The interpretation of the lower-spin portion of the decay scheme is similar to that of many even-even rare-earth nuclei, e.g., Bengtsson and Frauendorf[4] and Lisle *et al.*[5] The dominant intrinsic configurations of the lowest portions of the odd- and even-spin negative-parity sequences [labeled $(\pi,\alpha)=(-,1)$ and $(-,0)$, where the signature is defined by $I=\alpha \bmod 2$] are the two signatures of the lowest $\pi = -$ quasineutron configuration coupled to the lowest $\pi = +$ quasineutron. Band crossings corresponding to the alignment of a pair of $i_{13/2}$ quasineutrons[6] are observed in both the yrast and negative-parity sequences. Above the band crossing the intrinsic configuration of the yrast sequence (the so called S band) is an aligned pair of $i_{13/2}$ quasineutrons and the negative-parity configurations are four-quasineutron states involving three $i_{13/2}$ quasineutrons. The present data represent the highest rotational frequencies at which these three intrinsic configurations have been observed.

An interesting feature of the data is that for the sequence of yrast transitions from $22^+ \to 20^+$ to $32^+ \to 30^+$ inclusive, the difference in γ-ray energies of successive transitions ΔE_γ is remarkably constant (average $\Delta E_\gamma = 63.0$ keV). This observation is equivalent to a constant dynamic moment of inertia, $\mathcal{J}^{(2)} \equiv dI/d\omega$, in the above spin range. The constancy of ΔE_γ is expected for a rigid rotor. Indeed, for the states under discussion the ratio of the coefficients in the expansion of the excitation energy in terms of the angular momentum,

$$E^* = AI(I+1) + BI^2(I+1)^2,$$

is $B/A \simeq 7\times10^{-6}$. This value is almost 10 times smaller than the ratio for the rotational band based on the fission isomer[7] in ^{240}Pu hitherto regarded as the best nuclear rotor.

As seen from Fig. 3, nonlinear terms in $\hbar\omega$ are necessary to describe the projection of the angular momentum along the rotation axis, I_x,

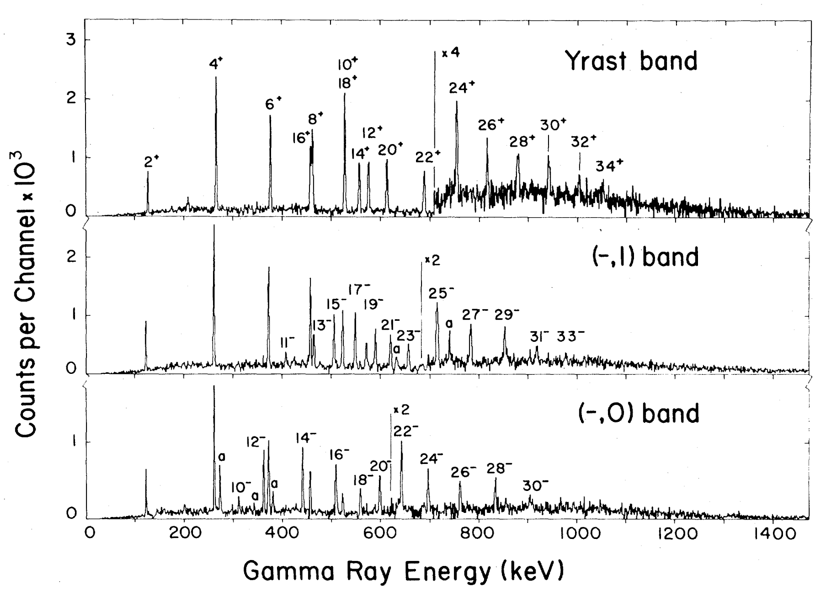

FIG. 2. Gated spectra for the yrast and two sidebands of ^{186}Hf excited by the reaction ^{124}Sn(^{48}Ti, $4n$). The composite spectra are obtained by summing individual spectra associated with a number of gates within the corresponding band. The following gates, denoted by their parent states were used. Yrast: 22^+, 24^+, 26^+, 28^+. $(-,1)$ band: 19^-, 21^-, 23^-, 27^-, 29^-, 31^-. $(-,0)$ band: 18^-, 24^-, 26^-, 28^-, 30^-. The letter a denotes known cross-band transitions.

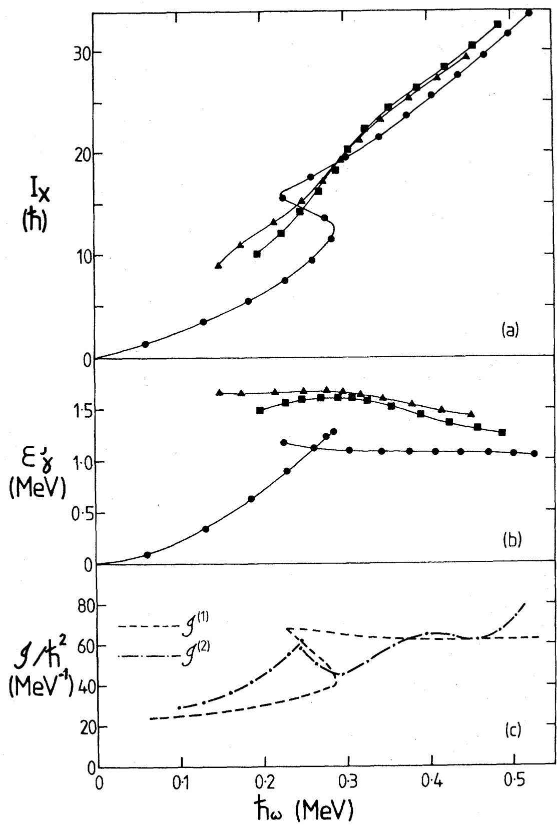

FIG. 3. Plots as functions of $\hbar\omega$ for (a) total aligned angular momenta, I_x, (b) relative Routhians, ϵ_r', and (c) moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ for the yrast band. In (a) and (b) the yrast, $(-,1)$, and $(-,0)$ bands are indicated by circles, squares, and triangles, respectively. The reference used in (b) is $\mathcal{J}_0=62.5\hbar^2$ MeV^{-1} and $\mathcal{J}_1=0$.

for the S band below $\hbar\omega=0.38$ MeV. A fit of the S band in the region $0.26 \leq \hbar\omega \leq 0.38$ MeV by the expression[8]

$$I_x = i + R = i + \mathcal{J}_0\omega + \mathcal{J}_1\omega^3 \quad (1)$$

yields $i = 9.7\hbar$, $\mathcal{J}_0=23.3\hbar^2$ MeV^{-1} and $\mathcal{J}_1 = 95.5\hbar^4$ MeV^{-3}. Such values are typical for the lower-spin portion of the S band in this mass region.[9]

At higher rotational frequencies, where the present data are unique, the I_x of the S band increases almost linearly with $\hbar\omega$. A fit to the yrast sequence for $0.38 \leq \hbar\omega \leq 0.50$ MeV yields a vanishingly small $\mathcal{J}_1$ with $\mathcal{J}_0=64\hbar^2$ MeV^{-1} and $i=-0.3$. This is equivalent to a constant kinematic moment of inertia $\mathcal{J}^{(1)} (= I_x/\omega)$ and implies $\mathcal{J}^{(1)} \simeq \mathcal{J}^{(2)} \simeq 63\hbar^2$ MeV^{-1} [see Fig. 3(c)]. The ω^3 term, included in Eq. (1) to account for an increase in $\mathcal{J}$ with increasing $\hbar\omega$ due mainly to a gradual loss of pairing correlations,[10] is not necessary at these large values of $\hbar\omega$. However, the observed moment of inertia is still somewhat less than that of a deformed rigid rotor with $A=168$. (For $\epsilon_2=0.24$ and a radius of $1.2A^{1/3}$ fm, $\mathcal{J}_{\rm rig}=76\hbar^2$ MeV^{-1}.)

Similarly no ω^3 term is needed to describe either negative-parity decay sequence above the band crossing, i.e., $\hbar\omega \geq 0.36$ MeV. Such data, which extend over a smaller number of transitions, show an alignment of about 1–2 units relative to that of the yrast sequence [see Fig. 3(a)].

At $\hbar\omega \geq 0.38$ MeV the yrast and negative-parity bands of ^{168}Hf are characteristic of a macroscopic rigid rotor. Therefore it is tempting to conclude that the neutron-pairing correlations have effectively disappeared at these large rotational frequencies.[11] Additional information, e.g., large moments of inertia and small relative alignments of the negative-parity configurations in these and neighboring nuclei,[12,13] supports such an interpretation. The nucleus, however, is a quantal system in which the angular momentum properties are strongly influenced by a few nucleons moving in highly alignable orbitals. In a microscopic description of such a rotating unpaired quantal system for midshell nuclei (e.g., $N=96$) the dynamical moment of inertia, $\mathcal{J}^{(2)}$, is expected to be somewhat less than the kinematical moment of inertia, $\mathcal{J}^{(1)}$. For the system being considered, the most alignable orbitals of the valence shell, associated with high j and low Ω, are occupied. At the frequencies under discussion they should contribute[14] to $\mathcal{J}^{(1)}$ but not to $\mathcal{J}^{(2)}$.

These data cannot be understood microscopically for a paired system, unless a sizable frequency dependence of deformation $(\epsilon_2, \epsilon_4, \gamma)$ or pairing strength (Δ_n, Δ_p) is assumed. Such a description requires that the effect of the frequency-dependent terms is to provide nearly exact cancellation of differences in $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ over a significant $\hbar\omega$ range in the yrast sequence of ^{168}Hf and in other rare-earth nuclei.[12,15] A further possible explanation is that current microscopic models do not correctly predict the alignability of the high-spin orbitals.

Most of the spectroscopic features studied at intermediate spins in well deformed nuclei have been dominated by pairing correlations and their associated uncertainties. Spectroscopy at very high spins, where such pairing-related uncertainties are minimized, should focus on other features. Such studies offer promise of exciting developments.

The constant moment of inertia observed in the high-frequency region provides a convenient and readily identifiable reference for determining relative energies in the rotating frame. Routhians ϵ_r' based on a reference moment of inertia $\mathcal{I}_0 = 62.5\hbar^2\ \mathrm{MeV}^{-1}$ and $\mathcal{I}_1 = 0$, are shown in Fig. 3(b) for the bands of ^{168}Hf. If the neutron pairing loss is complete a particularly simple interpretation can be made for the nearly constant value of e_r' (≈ 1.1 MeV) for the S band for $\hbar\omega \geq 0.38$ MeV. This corresponds to the difference in vacuum energies between the paired phase at $\hbar\omega = 0$ and unpaired phases at large $\hbar\omega$ and is sometimes referred to as the pair-correlation energy of the quasiparticle vacuum.[16]

At the highest rotational frequencies [$\hbar\omega \approx 0.50$ MeV for the yrast sequence and perhaps as low as 0.48 MeV for the $(-,1)$ sequence] an increase in alignment is observed. This presumably corresponds to the alignment of a pair either of $h_{11/2}$ or $i_{13/2}$ quasiprotons. A similar feature is observed[13] at a slightly lower frequency in the yrast band of ^{170}W, an isotone of ^{168}Hf. The moment of inertia of the yrast band and the indications of a second band crossing suggest that at least a portion of the proton pairing remains.

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