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Rotational bands in ^{167}Hf

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Abstract. High-spin states in ^{167}Hf, populated in the ^{141}Pr(^{30}Si, p3n)^{167}Hf reaction, have been studied using the NORDBALL Ge detector array. Three rotational cascades have been observed for the first time and the previously-known level scheme has been extended to significantly higher spin. Band-crossing effects are discussed within the framework of Woods-Saxon cranking calculations and are found to be in good agreement.

PACS. 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

1 Introduction

The backbending phenomenon in atomic nuclei is well understood to be a consequence of the alignment of a pair of protons (π) or neutrons (ν) along the axis of rotation under the influence of the Coriolis force acting in a deformed rotating field. Previous studies of hafnium nuclei in the mass range $A = 160$ to 172 [1–8] have shown that both neutron ($i_{13/2}$) and proton ($h_{11/2}$ and $h_{9/2}$) orbitals are active in the alignment process. A second band crossing, after the first pair of $i_{13/2}$ neutron alignments, has been reported in a number of Hf nuclei [3,5,6] and interpreted as the alignment of either a $\pi h_{9/2}$ or $\pi h_{11/2}$ pair or a second $\nu i_{13/2}$ pair.

We report here on the spectroscopic study of rotational bands in the isotope $^{167}_{72}$Hf$_{95}$. The yrast sequence (band 1) of ^{167}Hf was known previously [9–13] up to spin $\frac{49}{2}^+$, the first band crossing having been established. In the present work, the band has been extended to a spin of ($\frac{77}{2}^+$), and a second crossing is observed at higher rotational frequencies. Two additional bands (bands 2 and 3) have also been extended to significantly higher spin, and three new rotational sequences (bands 5 – 7) are reported here for the first time. The properties of the bands are interpreted in terms of Woods-Saxon cranking calculations, and are found to be in generally good agreement with theory.

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2 Experimental details

The structure of the ^{167}Hf nucleus was the subject of an experiment performed using the NORDBALL Ge detector array situated at the Niels Bohr Institute, Risø, Denmark. High-spin states were populated following the ^{141}Pr(^{30}Si, p3n)^{167}Hf reaction using two stacked self-supporting targets of thickness 670 and 770 μg/cm^2 and a bombarding energy of 155 MeV. The NORDBALL array consisted of 18 Ge detectors and two low-energy photon spectrometers (LEPS), together with a multi-element 4π BaF$_2$ multiplicity filter. The data were sorted into several $\gamma - \gamma$ coincidence matrices, with various conditions applied to the multiplicity M_γ (or fold k) in order to identify the reaction channels of interest. For the p3n exit channel to ^{167}Hf, only high-fold ($k > 12$) events were considered. A further matrix was also sorted, in order to determine angle-dependent intensity ratios. For this asymmetric matrix, energies measured by detectors at 37° relative to the beam axis were sorted onto one axis, with those measured at 79° sorted onto the second axis. Data analysis was performed using the software packages RADWARE [14] and Ana [15].

3 Results

In total seven rotational bands have been observed, four of which (bands 1 – 4) have been previously reported [9–13]. The new sequences (bands 5 – 7) have been assigned to ^{167}Hf through observed coincidences with known low-lying transitions in the nucleus. Examples of gated coincidence

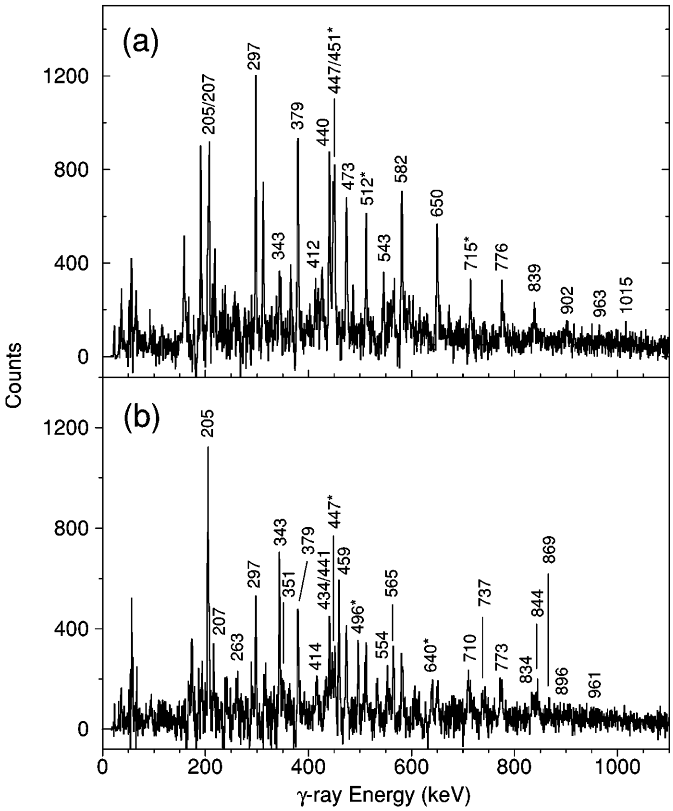

Fig. 1. Coincidence spectra for (a) band 5 and (b) band 6 of ^{167}Hf. In-band transitions, and γ-rays in coincidence with the bands, are labelled with their transition energy. Gates used to produce the spectra are indicated by a " * "

spectra for some of the new cascades are shown in Fig. 1. Information on the multipolarity of γ-ray transitions has been obtained, in order to make spin and parity assignments, by measuring angle-dependent intensity ($I_\gamma(\theta)$) ratios using a method based on the directional correlation of decays from oriented nuclear states (DCO) [16]. The ratio

$$R_{DCO} = \frac{I_\gamma(37°)}{I_\gamma(79°)} \quad (1)$$

has been determined, where $I_\gamma(37°)$ is the intensity of a transition measured by a detector at 37°, after gating on an $E2$ transition on the other axis of the asymmetric matrix, and $I_\gamma(79°)$ is the intensity measured in the inverse projection following the same gating conditions. Using this method, γ-rays known to be stretched quadrupole transitions give an average ratio close to unity, while known stretched dipole transitions yield a considerably lower value ($R_{DCO} \approx 0.6$). Using this information, together with relative intensity measurements and coincidence relations, the level scheme of figure 2 has been deduced.

Band 1 has previously been interpreted [9–13] as the favoured signature ($\alpha = +\frac{1}{2}$) of the decoupled $\nu i_{13/2}$ sequence, and was known to exist up to a spin of $\frac{49}{2}^+$. The band has now been extended by the addition of seven new transitions at high spin, up to $(\frac{77}{2})\hbar$. Band 2 we propose to be the unfavoured component of the $\nu i_{13/2}$ sequence upon which band 1 is based. Previous studies had identified only the $\frac{19}{2}^+$ and $\frac{15}{2}^+$ states associated with this sequence, the latter observed to decay to the $\frac{13}{2}^+$ bandhead of the favoured configuration. A rotational cascade of nine γ-rays has now been established, extending to a spin of $(\frac{47}{2}^+)$ and including the $\frac{15}{2}^+ \rightarrow \frac{11}{2}^+$ transition. Furthermore, states in band 2 with $\frac{15}{2} \leq I \leq \frac{31}{2}$ are observed to decay directly into band 1.

The sequences based on the $\nu[523]5/2^-$ ground state of ^{167}Hf were previously known up to a spin of $\frac{25}{2}^-$ for the favoured signature (band 3), and to spin $\frac{19}{2}^-$ for the unfavoured component (band 4). Prior to this work, only two transitions between the two signatures had been observed ($\frac{9}{2}^- \rightarrow \frac{7}{2}^-$ and $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$). We have now identified in-band transitions for the favoured sequence up to $\frac{33}{2}\hbar$ and also observe interband transitions de-exciting all states up to $\frac{21}{2}\hbar$, thus establishing the strongly-coupled nature of the two signatures. Decay out of band 3 is also observed from the $\frac{25}{2}^-$ level, via a new 543 keV γ-ray, to the $\frac{23}{2}^+$ state of band 2. In the previous studies, two transitions (447 keV and 451 keV) were seen above the $\frac{25}{2}^-$ state of band 3; these transitions we now suggest involve the lowest observed state, with $I^\pi = \frac{29}{2}^-$, of a newly-established rotational sequence (band 5). A coincidence spectrum of band 5, produced by gating on the in-band 451 keV, 512 keV and 715 keV γ-rays, is shown in Figure 1(a). Ten in-band transitions have been observed above the $\frac{29}{2}^-$ state, extending to a spin of $\frac{69}{2}\hbar$. Band 5 is also seen to feed into band 2, by way of a 412 keV ($\frac{29}{2}^- \rightarrow \frac{27}{2}^+$) γ-ray. Angle-dependent intensity ratios for the 412 and 447 keV transitions de-exciting band 5 have been measured as $R_{DCO} = 0.64 \pm 0.10$ and $R_{DCO} = 0.91 \pm 0.10$ respectively. The I^π assignments for band 5 shown in Fig. 2 are based on these R_{DCO} values. A second new band, band 6, has been established and is observed to feed directly into band 4 via a 441 keV transition. The cascade consists of ten transitions, extending to a spin of $\frac{63}{2}\hbar$. Figure 1(b) shows the coincidence spectrum resulting from gates on the 447 keV, 496 keV and 640 keV band members. Clearly this band decays into the yrast band, as well as into band 4, and evidence is found for three transitions feeding band 1 from the lowest spin states of band 6. The intensity ratios for the 441 keV and 737 keV γ-rays de-exciting band 6 have been measured as $R_{DCO} = 0.96 \pm 0.19$ and $R_{DCO} = 0.43 \pm 0.19$ respectively. Based on this information, the band is assigned negative parity.

A further new band, band 7, is observed and consists of seven transitions. This sequence feeds directly into band 1 via five linking transitions de-exciting the lowest spin states. A value of $R_{DCO} = 0.98 \pm 0.42$ has been determined for the 867 keV transition feeding out of the band; the ratio could not be measured for any of the other linking γ-rays due to their low intensity. The multipolarity of the 867 keV γ-ray could thus not be determined since, within

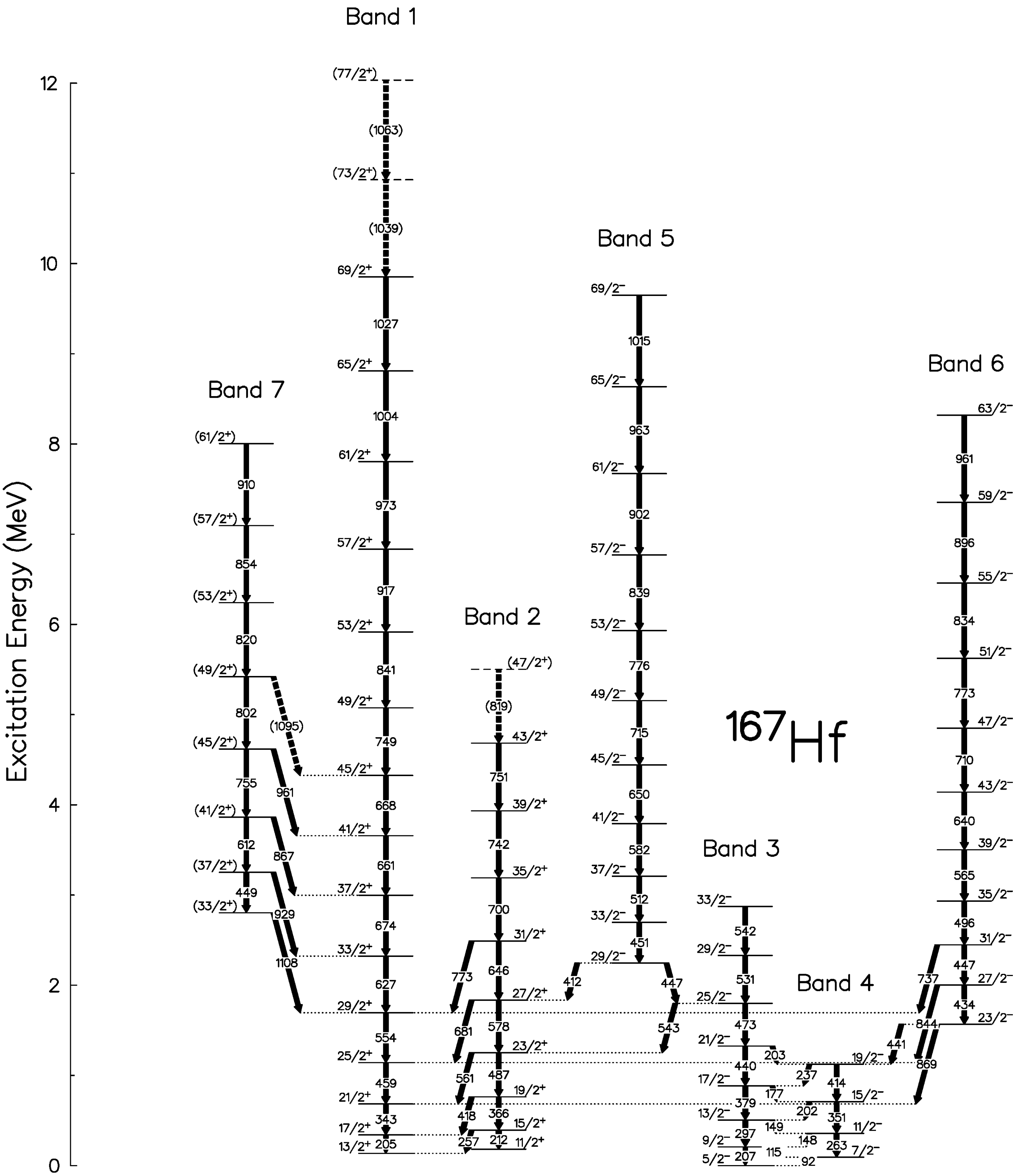

Fig. 2. The deduced level scheme for ^{167}Hf from the current work. Tentative levels are indicated by dashed lines and tentative transitions by dashed arrows

Table 1. The convention used to label the quasiparticle orbitals close to the Fermi surface according to their signature α and parity π. The subscripts n and p denote quasineutrons and quasiprotons respectively and the subscript m denotes the mth lowest excitation with that parity and signature. Also shown are the corresponding shell-model states and asymptotic Nilsson labels at $\hbar\omega = 0$ MeV

Shell-model state	Nilsson label	Label $(\pi, \alpha)_m$
$\nu i_{13/2}$	$\nu[642]5/2^+$	$A_n\ (+,+\frac{1}{2})_1$ $B_n\ (+,-\frac{1}{2})_1$
$\nu i_{13/2}$	$\nu[633]7/2^+$	$C_n\ (+,+\frac{1}{2})_2$ $D_n\ (+,-\frac{1}{2})_2$
$\nu f_{7/2}$	$\nu[523]5/2^-$	$E_n\ (-,+\frac{1}{2})_1$ $F_n\ (-,-\frac{1}{2})_1$
$\pi i_{13/2}$	$\pi[660]1/2^+$	$A_p\ (+,+\frac{1}{2})_1$ $B_p\ (+,-\frac{1}{2})_1$
$\pi h_{11/2}$	$\pi[514]9/2^-$	$E_p\ (-,+\frac{1}{2})_1$ $F_p\ (-,-\frac{1}{2})_1$
$\pi h_{9/2}$	$\pi[541]1/2^-$	$G_p\ (-,+\frac{1}{2})_2$ $H_p\ (-,-\frac{1}{2})_2$

the uncertainties of the R_{DCO} measurement, it could be either a quadrupole or dipole transition. Therefore, the spins and parities of states in band 7 cannot be deduced experimentally. However, we argue that the band is most likely to be based on a state of $I = \frac{33}{2}\hbar$ since the only other likely spin, $I = \frac{31}{2}\hbar$, would result in the state being too far above yrast to explain the population intensity of the band. Based on this assumption, the linking transitions to the yrast band are of $E2$ multipolarity, and the band is of positive parity. The quasiparticle configurations associated with all the decay sequences are discussed in the next section, and further support the suggestion that band 7 corresponds to a positive parity structure.

4 Discussion

The rotational sequences have been interpreted within the framework of cranked Woods-Saxon calculations [17]. Quasiparticle orbitals close to the Fermi surface have been labelled using the Stockholm convention, as summarised, for ^{167}Hf, in Table 1, with the subscripts n and p used to denote quasineutrons and quasiprotons respectively. The unpaired single-particle levels are labelled using the Nilsson notation [18]. Figure 3 shows (a) the experimental Routhians and (b) the aligned angular momentum for bands 1 − 7 of ^{167}Hf, plotted as a function of rotational frequency $\hbar\omega$. A reference has been subtracted, with Harris parameters [19] $\mathcal{J}^{(0)} = 18$ MeV$^{-1}\hbar^2$ and $\mathcal{J}^{(1)} = 30$ MeV$^{-3}\hbar^4$. Figure 4 shows the Routhians for both quasiprotons and quasineutrons, calculated using a universal Woods-Saxon potential with the deformation parameters $\beta_2 = 0.245$, $\beta_4 = 0$ and $\gamma = 0°$. These deformation parameters are predicted for the ground-state configuration of ^{167}Hf in reference [20]. For all calculations, Routhians (e') are plotted according to their parity and

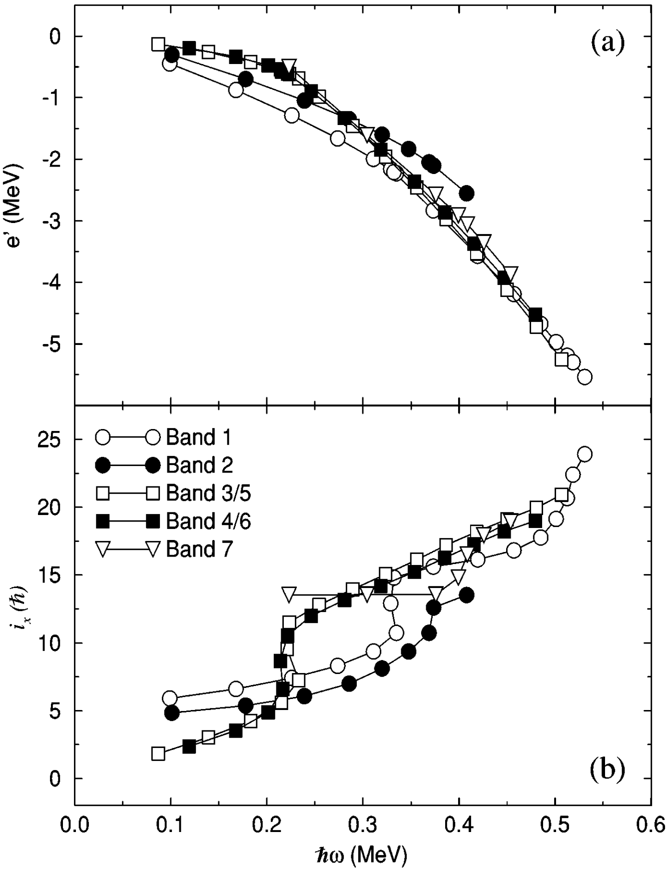

Fig. 3. (a) experimental Routhians and (b) alignment i_x for bands in ^{167}Hf, plotted as a function of rotational frequency. The reference Harris parameters used are $\mathcal{J}^{(0)} = 18$ MeV$^{-1}\hbar^2$ and $\mathcal{J}^{(1)} = 30$ MeV$^{-3}\hbar^4$

signature (π, α) as follows: $(+,+\frac{1}{2})$ solid line, $(+,-\frac{1}{2})$ dotted line, $(-,+\frac{1}{2})$ dot-dashed line and $(-,-\frac{1}{2})$ dashed line.

For band 1, a backbend is observed at a crossing frequency ($\hbar\omega_c$) of 0.33 MeV. By comparison of the experimental crossing frequency (Fig. 3) with the calculated quasineutron Routhians (Fig. 4(a)), the first backbend of band 1 is thought to correspond to the B_nC_n crossing; the first predicted interaction, the A_nB_n crossing, is blocked for band 1 since the A_n orbital is occupied below the first backbend. The configuration of the band thus changes from one-quasineutron A_n to three-quasineutron $A_nB_nC_n$. Band 2 undergoes a similar backbend at the slightly higher frequency of $\hbar\omega_c = 0.34$ MeV. This is attributed to the A_nD_n crossing (the A_nB_n crossing again being impossible due to Pauli blocking arguments) and the structure of band 2 similarly changes from B_n to the three-quasineutron configuration $B_nA_nD_n$. At higher rotational frequencies, around $\hbar\omega = 0.5$ MeV, band 1 is observed to undergo a second band crossing, which gives rise to an alignment gain of at least $5\hbar$. From inspection of the calculated quasineutron Routhians, there appears to be no suitable crossing which could explain such an effect. However, Fig. 4(b), which shows the corresponding quasiproton energies, suggests an E_pF_p crossing at approximately

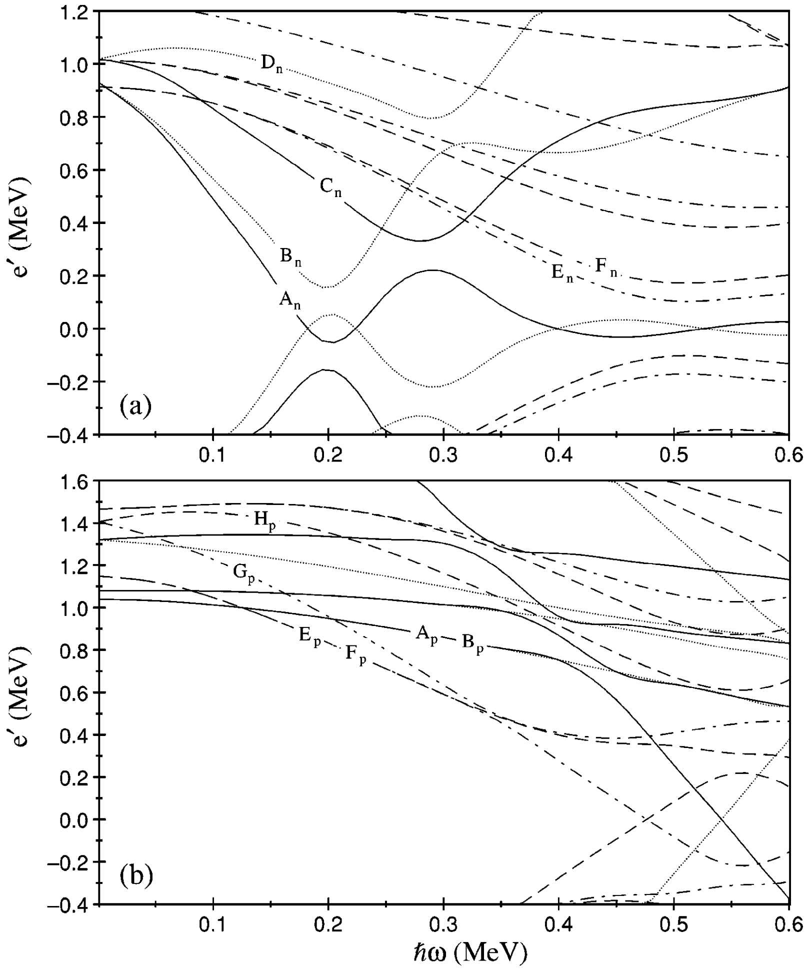

Fig. 4. Quasiparticle energy levels, calculated with $\beta_2 = 0.245$, $\beta_4 = 0$ and $\gamma = 0°$ for (a) neutrons and (b) protons. Orbitals are labelled by the Stockholm convention as discussed in the text

the right frequency. The alignment gain predicted by this interaction is very small and is not sufficient to explain the observed upbend in the alignment plot of band 1. At high rotational frequencies the $\pi h_{11/2}$ and $\pi h_{9/2}$ orbitals are known to be strongly admixed, and a crossing between two such mixed orbitals (E_p and G_p) is predicted at a frequency of $\hbar\omega = 0.56$ MeV. Such mixed crossings have previously been discussed in the osmium-iridium region [21] and the same orbitals have been used to explain a similar high-frequency band crossing in neighbouring ^{169}Hf [6]. We propose that the second upbend in band 1 is caused by the alignment of a pair of $h_{11/2}$ protons or a pair of mixed $h_{11/2}$ and $h_{9/2}$ protons or some combination of both. At the highest rotational frequencies band 1 thus corresponds to at least a five-quasiparticle configuration.

Both band 3 and band 4 clearly undergo a band crossing at the point where they are fed, respectively, by band 5 and band 6. At this crossing frequency, band 5 becomes the three-quasiparticle continuation of band 3 and, similarly, band 6 becomes the three-quasiparticle extension of band 4. This crossing occurs at a frequency of around 0.22 MeV, considerably lower than the first crossing frequency observed for bands 1 and 2. The two signatures based on the $\nu[523]5/2^-$ ground state have the configurations E_n (band 3) and F_n (band 4) below the first crossing. From the calculated quasineutron energies of Fig. 4(a) the interaction predicted at the appropriate frequency is the A_nB_n crossing, which is not blocked for either the positive or negative signature. Both the three-quasineutron $E_nA_nB_n$ band and the continuation of the E_n sequence are observed above the crossing. We propose that the $E_nA_nB_n$ structure corresponds to the new sequence, band 5, which decays into the E_n band at the band crossing. Similarly, we propose that band 6, which feeds into band 4 at the crossing, corresponds to the $F_nA_nB_n$ configuration. Band 6 clearly undergoes the A_nB_n crossing and the spin sequence assigned to the band $(\frac{23}{2}^-, \frac{27}{2}^-, \frac{31}{2}^-, \ldots)$ suggests that the structure has overall signature $\alpha = -\frac{1}{2}$, and thus corresponds to the $F_nA_nB_n$ configuration. We thus suggest that bands 5 and 6 are signature partners. This suggestion is supported by the close similarities in the experimental Routhians and quasiparticle alignments (Figs. 3(a) and 3(b) respectively) for the two decay sequences.

Based on the assumption that band 7 is a positive parity sequence, its structure is most likely to be based on the C_n orbital, since the A_n and B_n orbitals provide the basis for bands 1 and 2. The initial alignment ($\approx 13\hbar$) of the band is most likely due to the A_nB_n crossing, as for bands 5 and 6. However, the band would then have the $C_nA_nB_n$ configuration above the initial crossing, which duplicates the structure of the $A_nB_nC_n$ yrast band. We suggest

Table 2. Experimental and calculated crossing frequencies for quasiparticle configurations in ^{167}Hf, together with observed and calculated alignment gains. Also shown is the experimental crossing frequency and alignment increase for the first crossing observed in ^{168}Hf

	Experiment		Theory	
Crossing	$\hbar\omega_c$ (MeV)	$\Delta i_x(\hbar)$	$\hbar\omega_c$ (MeV)	$\Delta i_x(\hbar)$
^{167}Hf				
A_nB_n	0.22	8	0.20	10.6
B_nC_n	0.33	5	0.29	7.6
A_nD_n	0.34	4	0.31	6.6
C_nD_n	0.40	5	0.43	2.8
E_pF_p	≥ 0.46	≥ 5	0.45	1.8
E_pG_p			0.56	5.5
^{168}Hf				
A_nB_n	0.26	8		

that band 7 corresponds to the $C_nA_nB_n$ only for the two lowest-spin ($\frac{33}{2}^+$ and $\frac{37}{2}^+$) states, with band 1 assuming the $A_nB_nC_n$ configuration above $I = \frac{37}{2}^+$ and band 7 then becoming the continuation of the A_n sequence. At higher rotational frequency, around $\hbar\omega = 0.4$ MeV, band 7 clearly undergoes another alignment gain, which we suggest is due to the C_nD_n crossing. We thus propose that band 7 corresponds to the three-quasiparticle $A_nC_nD_n$ configuration at the highest spins.

A comparison of the crossing frequencies observed in the yrast bands of ^{167}Hf and even-even ^{168}Hf shows directly the blocking effect of the odd neutron. Table 2 shows the experimental and calculated crossing frequencies observed for ^{167}Hf in this work, compared to that of the yrast band in ^{168}Hf [5]. Experimental and theoretical alignment gains Δi_x are also presented for each band crossing. The experimental and predicted frequencies for the A_nB_n crossing in ^{167}Hf are in very good agreement; however the predictions for the B_nC_n, A_nD_n and C_nD_n crossings are slightly higher or lower than the observed frequencies. The experimental alignment increase for each crossing is generally lower than the value predicted by the calculations; the C_nD_n crossing, however, generates slightly more alignment than the predictions suggest. Clearly the A_nB_n crossing is considerably lower for ^{167}Hf ($\hbar\omega_c = 0.22$ MeV) than for ^{168}Hf (0.26 MeV), although the interaction gives the same increase in alignment in each case. This effect is due to the lower pairing field associated with the odd-N ^{167}Hf nucleus. Such an effect has been observed in many odd-N nuclei when compared to their even-N neighbours [22,23]. The effect has been interpreted [22] as a pairing decrease, a consequence of a blocking of the pairing contributions from the valence configuration in the odd-N nuclei.

5 Conclusions

Three rotational cascades in the ^{167}Hf nucleus have been observed for the first time and the previously-known sequences have been extended to higher spin. The bands have been assigned to multi-quasiparticle configurations and band-crossing effects, including the first observation of a quasiproton crossing, are found to be in good agreement with Woods-Saxon cranking calculations.

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