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Rotational band on the 31 yr 16^+ isomer in ^{178}Hf

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Abstract

High-spin states in ^{178}Hf have been identified using particle-γ-γ-time techniques and the incomplete fusion reaction, ^{176}Yb(^{9}Be,α3n)^{178}Hf. The rotational band associated with the four-quasiparticle $T_{1/2}$ = 31 year, $K^\pi = 16^+$ isomer in ^{178}Hf has been established. The g_K–g_R values obtained from the in-band decay properties confirm the configuration of the isomer as does its alignment which matches the sum of the alignments of the two $K^\pi = 8^-$ two-quasiparticle bands that contain the components of the 16^+ configuration. New information has also been obtained on the four-quasiparticle 14^- band and on the two-quasiparticle 6^+ and 8^- bands.

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The phenomenon of high-K isomerism is common in the A $\sim$ 180 region of the nuclear chart. It arises when a few nucleons couple and align their angular momenta along the nuclear symmetry axis so that K $= \Sigma\Omega_i$. This is a favourable process for formation of the yrast line if orbits (preferably both proton and neutron) with high values of the projection Ω_i are available near the Fermi surface. Perhaps the most celebrated example is the $K^\pi = 16^+$ isomer in ^{178}Hf [1] (commonly referred to as ^{178m2}Hf), which has a half-life of 31 years [2]. The remarkably long lifetime comes about not only because of its high K-value and the effect of the K-selection rule, but also because its excitation energy is so low that it resides below any states of spin 14 or higher. Hence, it can decay neither by low multipolarity transitions, nor by small changes in K.

The exotic nature of ^{178m2}Hf has stimulated a great deal of interest and associated experimental endeavour. Earlier studies concentrated on elucidating the decay and excitation energy of the isomer [3,4], while a number of recent studies have made use of a target in which nanogram amounts of ^{178m2}Hf were present [5–9]. The extraordinary effort that went into the production of this target reflects both the interest in the isomer, and the difficulties that are inherent in its study.

Conventional fusion-evaporation reactions capable of producing states in ^{178}Hf are limited to (α,2n) [10,11] which brings in a maximum angular momentum of $\sim$16$\hbar$, insufficient to populate strongly states

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of the rotational band which should be built on the isomer. Furthermore, the assignment of a prospective band to ^{178m2}Hf by delayed coincidence techniques is problematic, due to the long lifetime, but the associated rotational band is of prime importance for characterisation of the configuration of this and other such states.

In this letter, we report on an in-beam γ-ray experiment in which an incomplete fusion reaction was used. This had higher input angular momentum than the (α,2n) reaction, and its characteristics allowed the assignment of new isomeric bands to their nucleus of origin. Many new transitions were assigned to ^{178}Hf including a rotational band based on the 16^+ isomer extending to its 22^+ member. While the decay characteristics [3,4] and measured magnetic moment [12,7] of ^{178m2}Hf support the configuration originally suggested [1] for the isomer, the g_K–g_R values deduced here from the in-band branching ratios and the alignments provide clear independent evidence for the proposed two-quasineutron-two-quasiproton ($\nu^2\ \pi^2$) assignment.

The study was performed with ^{9}Be beams supplied at energies of 55 and 60 MeV by the ANU 14UD Pelletron accelerator. The beams, of ~0.75 pnA intensity, were directed onto a 4 mg/cm^2 ^{176}Yb target enriched to 96%. States in ^{178}Hf were populated via the $\alpha 3n$ exit channel. A small proportion of the α-particle yield is expected through evaporation from the compound nucleus but the main component is from breakup of the beam and subsequent fusion of the heavy fragment in the process termed "incomplete fusion" or "massive transfer" [13,14]. The mechanism can be viewed approximately as breakup into α + ^{5}He with subsequent fusion and evaporation of the form ^{176}Yb(^{5}He,3n)^{178}Hf. At 55 MeV, ^{178}Hf was populated with a strength of 20–30% relative to ^{180}W, which was the dominant fusion-evaporation residue. An array of 14 charged-particle detectors covering ~85% of 4π (fast/slow plastic scintillators using the phoswich technique [15]) was used to select α-γ-γ-time coincidences, which were collected at ~250 Hz for a detected-particle rate of ~30 KHz. Gamma rays were recorded with the six hyperpure n-type germanium detectors of the CAESAR array [16], for which the individual detector rate was typically ~6 KHz. The time conditions allowed recording of all events within 856 ns of the detected α-particle. A particle-γ-time measurement was also undertaken.

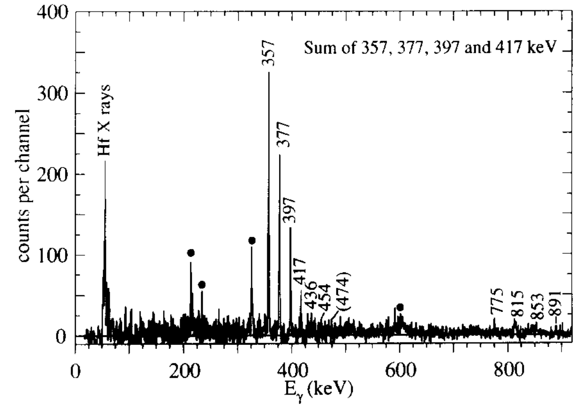

Fig. 1. Summed coincidence spectrum from projections made on the 357, 377, 397 and 417 keV transitions in the rotational band assigned to ^{178m2}Hf. Band members are labelled by their energy in keV, while contaminants are indicated by a •.

The γ-γ coincidence data were sorted offline into E_γ-E_γ correlation matrices with different time conditions. No new isomers in the range of sensitivity (10–1000 ns) were found and there was no delayed feeding of the states that were finally assigned. The main analysis was carried out with two matrices produced for each beam energy. One required that an α-particle was detected in the forward particle detectors, which subtended angles covering ~20° to 60° with respect to the beam axis, while the other required that an α-particle was detected at more backward angles, in either the middle (60° to 100°) or backward rings (100° to 140°) all with a condition of $\pm$ 140 ns for the γ-γ time differences. The final matrices that were generated from the 55 MeV data contained 11.9×10^6 counts (forward-α selected) and 2.8×10^6 counts (middle- or back-α selected). At 60 MeV, the number of counts in the matrices were 5.4×10^6 (forward) and 1.7×10^6 (middle or back).

Many previously known bands in ^{179}Hf [17], ^{178}Hf [11], and ^{177}Hf [18] were extended, results which will be published elsewhere. A number of new bands were discovered, all of which a) were characteristic of high-K structures, b) showed coincidences with Hf X-rays and c) were not connected to any of the known bands (in prompt or delayed coincidence). One of these bands is shown in Fig. 1, and it was assigned to ^{178m2}Hf, as will be discussed below.

Assignment to a particular hafnium isotope was

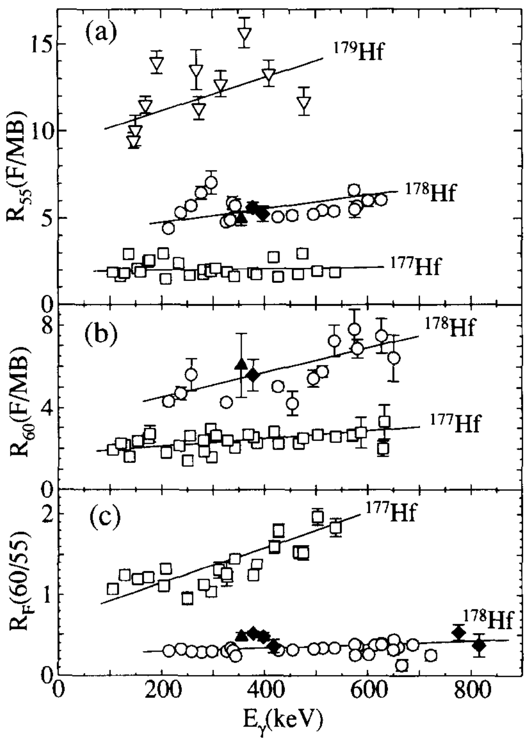

Fig. 2. Intensity ratios (see text) for γ-γ coincidences within known bands in ^{177}Hf, ^{178}Hf and ^{179}Hf (open symbols) together with those for the bands assigned to the 16^+ (^{178m2}Hf) and the 14^- four-quasiparticle isomers in ^{178}Hf (filled symbols). (a) R_{55}(F/MB) corresponds to "forward/middle-back" intensity ratios at 55 MeV, (b) R_{60}(F/MB) "forward/middle-back" intensity ratios at 60 MeV and (c) R_F(60/55) corresponds to ratio of "forward" intensities at 60 MeV and 55 MeV. No efficiency correction has been applied to the ratios. The lines are drawn to guide the eye.

made on the basis of the relative yields at the two beam energies (see Fig. 2(c)), and also from the yield in coincidence with forward or middle-backward emitted α-particles. As can be seen in Figs. 2(a), (b) there is a distinctive correlation between forward or middle-backward emission of the α-particle and the population of specific nuclei, with fewer neutrons apparently emitted if the α-particle is detected at forward angles [19]. The small proportion of the reaction that proceeds by evaporation of α-particles from the compound nucleus will lead to isotropic emission in the centre-of-mass.

The ratios of yields for different products of the ^{176}Yb(^{9}Be,αxn)$^{181-x}$Hf reactions were derived from the γ-γ coincidence matrices described above. The results are shown in Fig. 2, where the clear separation into regions with different numbers of neutrons emitted can be seen. This has allowed three of the new bands to be assigned to ^{179}Hf, while the yield ratios of the remaining two new bands lead to their unambiguous assignment to ^{178}Hf. In Fig. 2(a), one band is represented by the 377 and 397 keV transitions (filled diamonds), while the other is represented by the 355 keV transition (filled triangle).

New transitions assigned to the lowest 8^- band extend it to spin 18 $\hbar$, while the 18^+ level in the ground state band [20] has been confirmed and a tentative 20^+ level has been added. These observations confirm that higher spin is reached in this reaction than in the α-induced studies. Under these circumstances, relatively strong population of both the band based on the 16^+ isomer (which is lower by ~1 MeV than other spin 16 states) and to a lesser extent the four-quasiparticle 14^- isomer [11], should have occurred. The band associated with the 377 keV γ ray, for which a representative spectrum is shown in Fig. 1, was populated with twice the intensity of that related to the 355 keV γ ray. Hence the former is assigned to ^{178m2}Hf, the 16^+ isomer, the latter by default to the 14^- state. Both bands, together with the ground state band, are shown in the partial level scheme displayed in Fig. 3. The transitions assigned to the 16^+ band give states whose energies agree with those of 2802 keV for the 17^+ level and the tentative value of 3183(2) for the (18^+) level that were identified from (d,d′) of the isomer itself [8]. Also, the energy of the $17^+ \rightarrow 16^+$ transition agrees with that found from Coulomb excitation of the isomer [9].

The configuration originally suggested [1] for the isomer is $\nu^2 7/2^-[514]9/2^+[624] \otimes \pi^2 7/2^+[404]9/2^-[514]$, which is formed from the ν^2, 8^- and π^2, 8^- components, whose respective (but mixed) states are known at 1147 keV and 1479 keV, and whose bands have also been extended. Similarly, the 14^- isomer is formed by combining either the ν^2, 8^- component with the 6^+, $\pi^2 5/2^+[402]7/2^+[404]$ state, or the π^2, 8^- component with the 6^+ state from the $\nu^2 5/2^-[512]7/2^-[514]$configuration, as shown in Table 1. The π^2 $[6^+]$ band is known at 1554 keV [11].

The net alignments of all these bands including the ground state band are plotted in Fig. 4, with a common reference. It can be seen clearly that the alignment of

Table 1
Configurations and g_K factors for multiquasiparticle states in ^{178}Hf

Configuration [a]			g_K		
K^π	ν	π	Exp [b]	Nilsson [e]	empirical [f]
6^+		$7/2^+$, $5/2^+$	1.01(5) 1.06(7) [c]	1.00	1.06(7)
8_1^-	64% ν^2	36% π^2	0.37(1)	0.35	0.36(6)
8_2^-	36% ν^2	64% π^2	0.62(7)	0.64	0.66(5)
8^- π^2		$7/2^+$, $9/2^-$		1.00	
8^- ν^2	$7/2^-$, $9/2^+$			−0.02	
14^-	(i) $7/2^-$, $9/2^+$	$7/2^+$, $5/2^+$	0.6(1)	0.42	0.44(7)
	(ii) $7/2^-$, $5/2^-$	$7/2^+$, $9/2^-$		0.58	0.60(6)
16^+	$7/2^-$, $9/2^+$	$7/2^+$, $9/2^-$	0.54(4) 0.52(6) [d]	0.49	0.51(7) 0.50(7) [g]

[a] π: $7/2^+$: $7/2^+[404]$; $5/2^+$: $5/2^+[402]$; $9/2^-$: $9/2^-[514]$.
ν : $9/2^+$: $9/2^+[624]$; $7/2^-$: $7/2^-[514]$; $5/2^-[512]$.
[b] $(g_K-g_R)/Q_0$ is positive, Q_0 = 7.2(1) *e*b [7] and g_R = 0.3 [[c] and [d] as [b], but with g_R = 0.35(5) and g_R = 0.28(4), respectively (see text)].
[e] Nilsson wave functions, $g_s = 0.7g_{free}$ and deformations of $(\varepsilon_2, \varepsilon_4)$ = (0.254,0.053).
[f] Nilsson values for neutrons, empirical g_K values for proton orbitals taken from ^{179}Ta [23]; 0.78(5) ($7/2^+$), 1.44(5) ($5/2^+$), 1.24(4) ($9/2^-$).
[g] Combining present g_K-values for the two 8^- states.

the 16^+ band corresponds approximately to the sum of the alignments for the two 8^- bands. It can be also seen that the 14^- band is consistent with a sum of either of the two ν^2 8^- and the known π^2 6^+ bands. Without, however, experimental information on the ν^2 6^+ band, the alignment cannot be used to distinguish between the two 14^- configurations discussed in the previous paragraph.

Values of $(g_K-g_R)/Q_0$ were extracted from the observed γ-ray branching ratios using the well-known rotational model formulae. From intensities alone the sign of $(g_K-g_R)/Q_0$ is not determined, but it can be defined through the cascade transition mixing ratios which determine the γ-ray angular anisotropies. In the present cases, anisotropies were extracted from angular distributions that were obtained from the particle-γ-time data. Slightly positive anisotropies were determined for several of the cascade transitions, consistent only with a positive mixing ratio [21] and therefore a positive sign for $(g_K - g_R)/Q_0$. In order to extract the experimental g_K factors that are shown in Table 1, it was initially assumed that g_R = 0.3, consistent with other information in this region, although further comment will be made on this below. The intrinsic quadrupole moment was taken from the measured value for the 16^+ isomer of Q_0 = 7.2(1) *e*b [7], which differs only slightly from the measured value of 6.96(5) *e*b for the ground state [22]. The experimental values in Table 1 correspond to weighted averages of the branching ratios for the 18^+ to 21^+ states in the 16^+ band, the 8^+ to 13^+ states in the 6^+ band, the 10^-, 11^-, 13^- and 14^- states for the 8_2^- band, while the 8_1^- band and 14^- bands are represented by their 10^- and 16^- states, respectively. Shown for comparison are theoretical values obtained from the Nilsson model. A semi-empirical comparison is also made, with a combination of Nilsson values and experimental values for some orbitals.

The Nilsson prediction for the 16^+ state is in reasonable agreement with the experimental value; a slightly better agreement is obtained when the semi-empirical proton g_K factors are used. If g_K = 0.08(6) is taken for the $9/2^+[624]$ neutron [24], a value of 0.56(9) is obtained for the 16^+ state. It is also interesting to note that combining the present experimental values for the two 8^- bands results in g_K = 0.50(7).

The situation regarding the configuration of the proposed 14^- band is less clear, since only one relatively imprecise branching ratio could be extracted. Of the two possibilities shown in Ta-

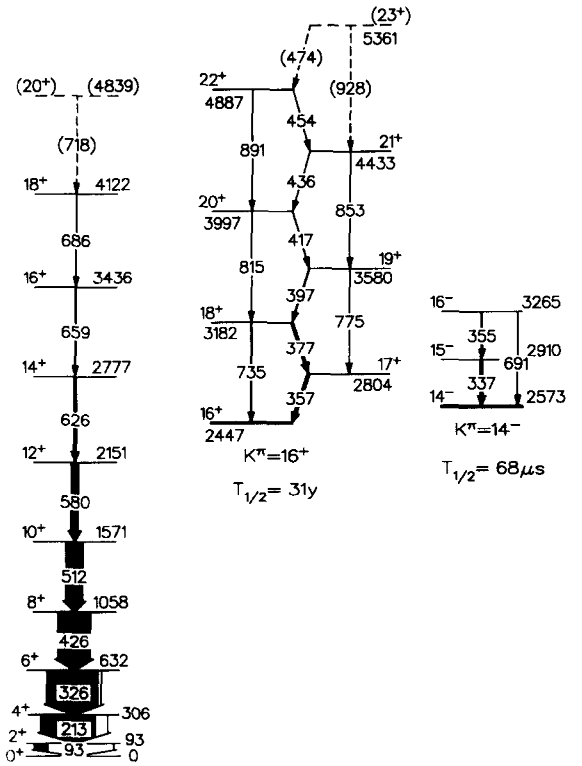

Fig. 3. Partial level scheme for ^{178}Hf, in which the two new bands built on the 16^+ (^{178m2}Hf) and 14^- four-quasiparticle isomers are shown. In the previously known 8_1^-, 8_2^- and 6^+ two-quasiparticle bands, the states above 14^-, 13^- and 11^+ are new, respectively. Transitions below the long-lived isomers are not shown.

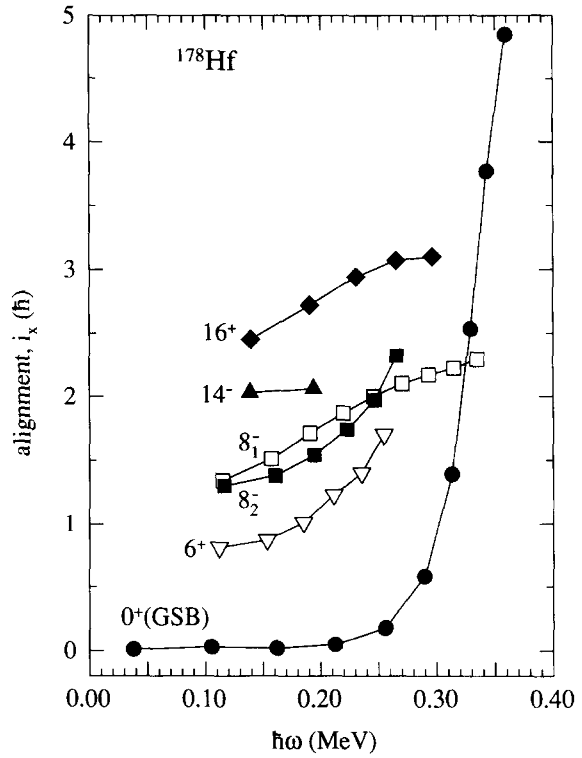

Fig. 4. Aligned angular momenta for bands in ^{178}Hf, extracted with K-values as shown in the figure. The Harris reference parameters used were $\mathcal{J}_0$ = 31.8 $\hbar^2$/MeV and $\mathcal{J}_1$ = 70 $\hbar^4$/MeV^3.

ble 1, comparison with the pure Nilsson model and the semi-empirical calculation suggests that the $\nu^2[7/2^-5/2^-] \otimes \pi^2[7/2^+9/2^-]$ configuration is slightly favoured, although again, these configurations would be expected to mix.

Some final points with respect to the collective moment g_R are worth noting. The g-factor of the 6^+ band had been measured by Faestermann et al. [25] which when combined with the branching ratio information of Ref: [11] and the formula

$$g = g_R + (g_K - g_R) \cdot \frac{K^2}{I(I+1)}$$

gave a surprisingly large value for the collective moment of $g_R \simeq 0.6$. (A later measurement gave a g-factor of 0.959(8) [26].) The value of the branching ratio of Ref. [11] used in that evaluation was $(g_K - g_R)/Q_0 = 0.0657(25)$. However the present branching ratios for the 6^+ band give $(g_K - g_R)/Q_0 = 0.099(7)$ which, when combined with the same g-factor, results in values of g_R = 0.35(5) and g_K = 1.06(7). Similarly, combining the mean value of $(g_K - g_R)/Q_0$ reported here for the 16^+ band, together with the g-factor of 0.510(3) derived from the more recent of the two magnetic moment measurements of the 16^+ isomer [7], gives $g_R = 0.28(4)$ and $g_K = 0.52(6)$.

The 8^- bands are known to be of mixed character [3], but branching information has only been available for the lower of the two. From the present data it was possible to extract branching ratios for the higher 8^- band. As shown in the table, the derived g_K factors are consistent with the proton and neutron admixtures proposed [3] for the 8_2^- state.

In summary, new states in ^{178}Hf have been identified using an incomplete fusion reaction, including a rotational band associated with the $T_{1/2}$ = 31 year, 16^+ isomer. Its alignment and g_K factor are consistent with the previous assertion that the isomer is a four-quasiparticle state that arises from the coupling of the two lower lying 8^- two-quasiparticle states in ^{178}Hf. Mixed configurations for the 8^- bands themselves have been confirmed, while the collective moment g_R extracted from a combination of the g-factor and the new branching ratios for the 6^+ band and for the 16^+ band, do not confirm the large values obtained previously.

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