$K^\pi = 6^+$ and 8^- isomer decays in ^{172}Hf and $\Delta K = 8$ $E1$ transition rates

P. M. Walker,* G. D. Dracoulis, A. P. Byrne, T. Kibèdi, and A. E. Stuchbery
Department of Nuclear Physics, Research School of Physical Sciences and Engineering,
The Australian National University, Canberra ACT 0200, Australia
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A recoil-shadow measurement of isomer decays in ^{172}Hf has revealed many weak γ-ray transitions. One of these is a sevenfold K-forbidden $E1$ transition from the $K^\pi = 8^-$ isomer ($T_{1/2} = 163$ ns) to the $K^\pi = 0^+$ ground-state band. The low hindrance factor for this transition in ^{172}Hf is compared with the hindrance factors for other $\Delta K = 8$ $E1$ transitions.

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The well-deformed hafnium ($Z = 72$) isotopes contain multiquasiparticle K isomers, with half-lives ranging from nanoseconds to years [1]. $K^\pi = 6^+$ and 8^-, two-quasiparticle isomers are observed systematically from ^{170}Hf to ^{182}Hf, and there are related three-quasiparticle isomers in the intervening odd-N isotopes [2,3]. The γ-ray transition-rate hindrance factors correlate strongly [4] with the degree of K forbiddenness, $\nu = \Delta K - \lambda$ (where λ is the transition multipolarity), but the hindrance factors also have a significant neutron (and proton) number dependence, as discussed recently for $M1$ and $E2$ transition rates [5].

Some form of K mixing must exist to enable K-forbidden transitions. The mixing could take place in the ground-state band (g.s.b.), in the isomer itself, or in both. Systematic studies of K-forbidden transition rates give the possibility of determining the important degrees of freedom. The objective of the present study was to identify weak γ-ray transitions from known [6] isomeric states in ^{172}Hf, in order to be able to make comparisons with transition rates in the heavier isotopes, and to search for new isomers. Many new γ-ray decay branches were found, but no new isomers.

A recoil-shadow experiment was performed, with a 700 μg cm^{-2} isotopically enriched ^{160}Gd target placed between tungsten alloy collimators, 53 mm upstream of the center of the CAESAR detector array (which consisted, for this experiment, of six Compton-suppressed germanium γ-ray detectors, in close geometry [7]). A bunched and chopped beam of 75 MeV ^{16}O (with 1 ns beam bursts, 648 ns apart) from the ANU 14UD accelerator was incident on the ^{160}Gd target. Evaporation residues recoiling from the target were caught on a 7 mg cm^{-2} bismuth foil in the center of the detector array, and γ-γ coincidences were recorded event by event, including the time of each γ-ray signal relative to the beam pulses. Events occurring during beam pulses were vetoed by the fast electronics. The arrangement gave high sensitivity to radiations occurring > 15 ns after the beam pulses.

A sample γ-ray coincidence spectrum is shown in Fig. 1, gated by the 409 keV $8^+ \to 6^+$ transition of the g.s.b., illustrating one of the lowest intensity isomer decay paths. Although $K^\pi = 6^+$ and 8^+ isomers were already known [6] in ^{172}Hf, with half lives of 5 ns and 163 ns, respectively, the decays assigned previously populated only up to the $I^\pi = 6^+$ member of the g.s.b. Figure 1 demonstrates that the $I^\pi = 8^+$ g.s.b. state is also populated, though weakly, with two new feeding transitions, 647 and 968 keV, which come directly from the $K^\pi = 6^+$ and 8^- isomers. The full list of transitions connected with these isomer decays is given in Table I, and the associated level scheme is shown in Fig. 2.

All but one of the populated levels was already known [6,8]. The new level is at 1621 keV, and is tentatively placed as the $I^\pi = 6^+$ member of the γ-vibrational band. The 63 keV transition into this state is not itself observed due to its low energy (with consequently large electron conversion coefficient), but its existence is required by the coincidence relationships. Apart from the 1621 and 1857 keV levels, the spin and parity assignments are taken from previous work [6,8]. The 1857 keV level was previously [6] assigned $I = (5)$, but this is incompatible with the new observation of a 149 keV transition from the $I(= K)^\pi = 8^-$ isomer. With the present tentative $I^\pi = (6^-)$ assignment for the 1857 keV level, the most likely structure of this state is the two-quasineutron $\{\nu 7/2^+[633] \otimes \nu 5/2^-[512]\}$ $K^\pi = 6^-$ configuration, which is also observed at low excitation energy in neighboring even-even nuclei.

Many of the γ-ray transitions assigned to ^{172}Hf are new. Of principal interest are the 149, 278, 408, and 968

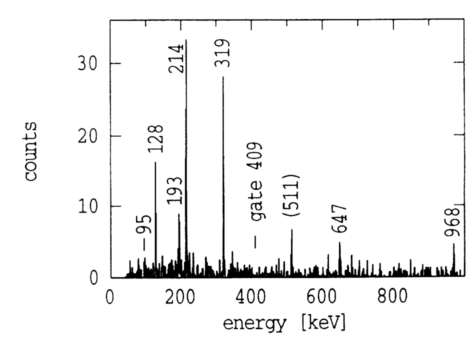

FIG. 1. Gamma-ray spectrum showing coincidences with the 409 keV, $8^+ \to 6^+$ transition.

*On leave from Department of Physics, University of Surrey, Guildford, UK.

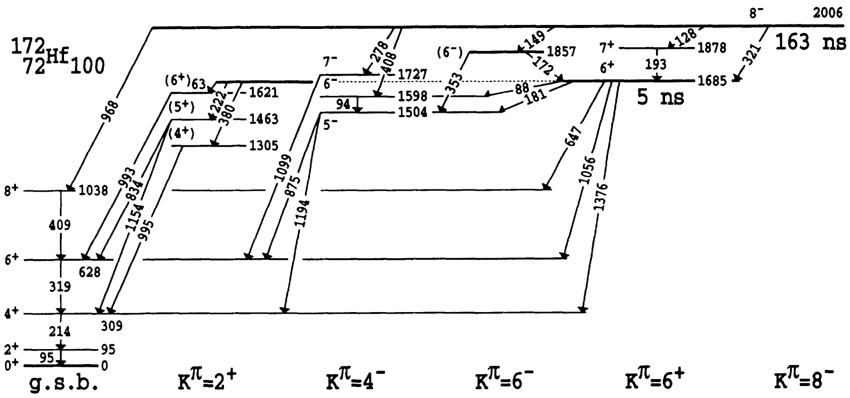

FIG. 2. Partial level scheme for ^{172}Hf, showing levels and transitions identified following the $K^{\pi} = 8^{-}$ and 6^{+} isomer decays.

TABLE I. Out-of-beam ^{172}Hf γ-ray intensities in coincidence with the 214 keV $4^{+} \to 2^{+}$ transition.

E_{γ} (keV)	I_{γ} [a]	E_i	E_f
63.2	b	1685	1621
87.5	36±12	1685	1598
94.2	c	1598	1504
95.2	190±60	95	0
127.7	954±95	2006	1878
149.4	6±3	2006	1857
172.4	8±3	1857	1685
180.9	38±6	1685	1504
193.4	752±60	1878	1685
214.0	d	309	95
221.6	16±4	1685	1463
278.2	19±5	2006	1727
319.1	1000[a]	628	309
321.0	22±6[e]	2006	1685
353.4	18±5	1857	1504
380.0	22±5	1685	1305
408.4	31±10	2006	1598
409.2	50±10	1038	628
647.4	33±7	1685	1038
834.3	12±4[e]	1463	628
875.4	51±9	1504	628
968.2	12±4[e]	2006	1038
993.1	44±8[e]	1621	628
995.4	39±10	1305	309
1056.3	820±43	1685	628
1099.1	22±7	1727	628
1153.5	14±5	1463	309
1194.3	51±11	1504	309
1375.5	444±32	1685	309

[a]Intensities are normalized to 1000 units for the 319 keV transition.

[b]The existence of the 63.2 keV transition is required by the coincidence relationships, but the transition itself is not observed.

[c]The 94.2 keV transition cannot be resolved; its existence is required by the coincidence relationships, and it is known from previous work [6].

[d]The 214 keV transition is the gating transition, from which the other transition intensities are obtained (unless otherwise noted).

[e]Intensity obtained from coincidences with the 319 keV transition, appropriately renormalized.

keV transitions from the $K^{\pi} = 8^{-}$ isomer, and the 88, 181, and 647 keV transitions from the $K^{\pi} = 6^{+}$ isomer. The branching ratios for the transitions from the isomers are given in Table II, together with the values of the hindrance per degree of K forbiddenness (hereafter called the *reduced hindrance*) defined as $f_{\nu} = [T^{\gamma}_{1/2}/T^{W}_{1/2}]^{1/\nu}$, where $T^{\gamma}_{1/2}$ is the partial γ-ray half-life, and $T^{W}_{1/2}$ is the Weisskopf single-particle estimate.

The 1056 and 1376 keV, $\Delta K = 6$, $M1$ and $E2$ transitions from the $K^{\pi} = 6^{+}$ isomer to the g.s.b. were already known [6], and their transition rates have been discussed [5]. Generally, the $M1$ and $E2$ reduced hindrance factors scale with N_pN_n, the product of the valence nucleon numbers.

It is now interesting to compare the reduced hindrance factor of the new $E1$, 968 keV, $\Delta K = 8$ transition with that of equivalent transitions in the $A \approx 180$ region of nuclei. These transitions are known [3] for all the even-even hafnium ($Z = 72$) isotopes from ^{172}Hf to ^{182}Hf (except for ^{176}Hf) with the ^{174}Hf transition being identified recently [9]. There is a substantial increase in the reduced hindrance factor with neutron number (except for between ^{180}Hf and ^{182}Hf—see below) as illustrated in Fig. 3(a). The reduced hindrance for ^{172}Hf, $f_{\nu} = 35$, is the smallest yet found for a $\Delta K = 8$ transition in a well-deformed nucleus. (The only known smaller value is for the transitional nucleus ^{134}Nd [10] with $f_{\nu} = 26$.) The corresponding reduced hindrance factors for the $N = 106$ isotones [3] ($Z = 70$–78) are included in Fig. 3(a). The states are formed from [1] the $\{\nu 7/2^{-}[514] \otimes \nu 9/2^{+}[624]\}$ (ν^2) configuration for $N = 106$, and from the $\{\pi 7/2^{+}[404] \otimes \pi 9/2^{-}[514]\}$ (π^2) configuration for $Z = 72$. In ^{178}Hf, with $N = 106$ *and* $Z = 72$, there are two $K^{\pi} = 8^{-}$ states 332 keV apart. The neutron and proton configurations mix, and the lower (isomeric) level is [11] 64% ν^2 and 36% π^2.

For the $Z = 72$ hafnium isotopes, the product N_pN_n maximizes at ^{176}Hf ($N = 104$), and it is evident that the $E1$ reduced hindrance factors would not form a smooth function of that variable (e.g., ^{172}Hf and ^{180}Hf each have $N_pN_n = 180$, yet their hindrance factors are very different). Although $E1$ transition rates are generally sensitive to small admixtures of other wave functions, particularly vibrations [4], in the present case the high K, and the

TABLE II. (a) $K^\pi = 8^-$ decay branches ($T_{1/2} = 163$ ns) and (b) $K^\pi = 6^+$ decay branches ($T_{1/2} = 5$ ns).

E_γ (keV)	Multipolarity	I_γ (%)[a]	ν	f_ν
		(a)		
127.7	$E1$	76.4	1	2.0×10^6
149.4	($E2$)	0.5	-	-
278.2	($M1$)	1.5	3	221
321.0	$M2$	1.8	-	-
408.4	$E2$	2.5	2	86
968.2	$E1$	1.0	7	35
		(b)		
63.2	($M1$)	0.3[b]	3	27
87.5	$E1$	2.4	1	6.4×10^5
180.9	$E1$	2.6	1	5.2×10^6
221.6	($M1$)	1.1	3	61
380.0	($E2$)	1.5	2	16
647.4	$E2$	2.2	4	7.2
1056.3	($M1$)	55.3	5	14
1375.5	$E2$	30.0	4	9.6

[a]The total γ-ray intensity is less than 100% due to electron conversion.
[b]The γ-ray intensity for the 63.2 keV transition is inferred from the 993 keV transition intensity, after allowing for electron conversion.

necessity to consider only two different two-quasiparticle configurations, might be expected to result in simple behavior.

The dependence of the reduced hindrance on mass number, revealed in Fig. 3(a), is presumably due to a variation in K mixing. Consider first the possibility of

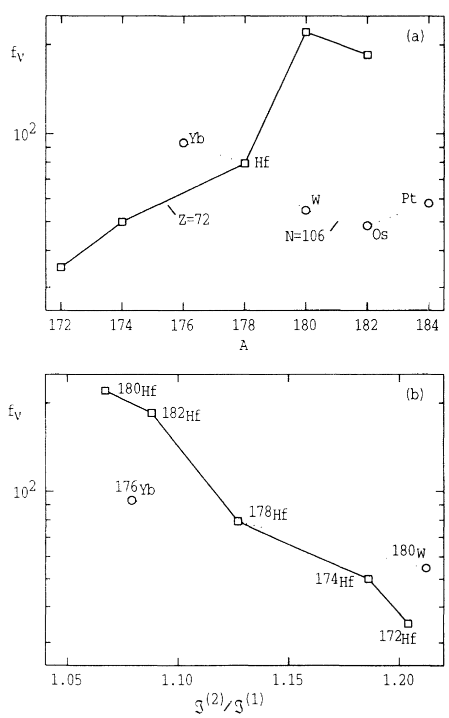

FIG. 3. Reduced hindrance factors for $\Delta K = 8$ $E1$ transitions, (a) as a function of mass number, and (b) as a function of the ratio of the dynamic and kinematic moments of inertia. The error bars are smaller than (or about the same size as) the data points.

K mixing in the g.s.b. The rate of increase (with angular momentum) of the moment of inertia gives a measure of the degree of rotational perturbation, which should be related to the degree of K mixing. A convenient way of quantifying this is through the ratio of the dynamic moment of inertia, $J^{(2)}$, to the kinematic moment of inertia, $J^{(1)}$. A value of $J^{(2)}/J^{(1)} > 1$ corresponds to an increasing kinematic moment of inertia, as is always found experimentally at low spin in the g.s.b.'s of even-even nuclei. In the $A \approx 180$ region, a large part of this effect comes from Coriolis forces, which begin to align intrinsic angular momentum with the rotation. There is mixing with a structure based on two $i_{13/2}$ neutrons, usually assumed to have $\langle K \rangle \approx 1$, forming the "$s$ band." However, the discovery [12,13] that for $N = 106$ an $i_{13/2}$ neutron pair can couple to $\langle K \rangle \approx 8$, forming a "$t$ band" that also mixes with the g.s.b., makes it clear that Coriolis forces can introduce *high-K components* into the yrast bands of even-even nuclei, at least in the $N \approx 106$ region.

The reduced hindrance factors are shown as a function of $J^{(2)}/J^{(1)}$ in Fig. 3(b). The values of $J^{(2)}/J^{(1)}$ are obtained from the experimental $8^+ \to 6^+$ and $6^+ \to 4^+$ γ-ray transition energies, with $J^{(1)} = (2I-1)/E_\gamma$ and $J^{(2)} = 4/\Delta E_\gamma$. From Fig. 3(b) it can be seen that, for the $Z = 72$ hafnium isotopes, the reduced hindrance decreases monotonically as $J^{(2)}/J^{(1)}$ increases, in accordance with what would be expected if rotational K mixing is important in the g.s.b.'s. It should be noted that the larger reduced hindrance for ^{180}Hf, compared to ^{182}Hf, conforms with this systematic behavior. The special case of ν^2-π^2 mixing in ^{178}Hf is discussed below.

The behavior of the $N = 106$ isotones appears to be more complex. For ^{182}Os and ^{184}Pt, with values of $J^{(2)}/J^{(1)}$ (1.43 and 1.65, respectively) off the scale of Fig. 3(b), there is increasing tendency to axially asymmetric distortions, and "softness" in the axially asymmetric direction. The observation that the reduced hindrance values become larger with the approach of the $Z = 82$ closed proton shell is similarly seen in the decay of the $K^\pi = 8^-$ isomers in the $N = 74$ isotones, above the $Z = 50$ closed shell [3]. The effect could possibly arise because the two-quasiparticle excitation changes the equilibrium nuclear shape, so that the decay has an element of *shape isomerism*, as well as K isomerism. There is at present no independent information about $K^\pi = 8^-$ isomer shape differences, though this could, in principle, be obtained from laser measurements of hyperfine structure and isomer shifts.

When seen as a function of $J^{(2)}/J^{(1)}$ [Fig. 3(b)] the reduced hindrance for ^{176}Yb appears surprisingly low, compared with ^{180}Hf and ^{182}Hf. This may be related to the involvement of an $i_{13/2}$ neutron in the ν^2 configuration of ^{176}Yb, which introduces K mixing in the isomeric state itself. Coriolis coupling calculations indicate that the $i_{13/2}$ neutron could well be responsible for this effect, but it is difficult to determine reliably the parameters of the calculation without experimental knowledge of the rotational band above the isomer. It would also be interesting to investigate K-mixing effects in the π^2 configuration, but the limited knowledge of the associated rotational bands means that systematic comparisons are not yet possible.

Returning to consideration of the ν^2-π^2 mixing in ^{178}Hf, it is significant that the reduced hindrance for ^{178}Hf, as shown in both Figs. 3(a) and 3(b), is smaller than the systematic trend for the $Z = 72$ isotopes, and slightly larger than the systematic trend for the $N = 106$ isotones. If a straight-line interpolation is used [in Fig. 3(b)] between the ^{174}Hf and ^{182}Hf values, $f_\nu \approx 110$ is predicted for the π^2 component in ^{178}Hf. Correspondingly, $f_\nu \approx 78$ is predicted for the ν^2 component in ^{178}Hf. These values may be combined according to their relative contributions to the transition rate, so that $f_\nu^{\text{mixed}} = [a_1(f_{\nu 1})^{-\nu} + a_2(f_{\nu 2})^{-\nu}]^{-1/\nu}$. Assuming $a_1 = 0.64$ and $a_2 = 0.36$, for the neutron and proton contributions, respectively [11], the result is $f_\nu^{\text{mixed}} = 80$, which is in agreement with the experimental value. It should be noted, however, that the result is dominated by the lower f_ν value (for the neutron component) and has little sensitivity to the f_ν value for the proton component.

In summary, a recoil-shadow experiment has revealed many new γ-ray transitions in ^{172}Hf, associated with known two-quasiparticle isomers. A new $\Delta K = 8$ $E1$ transition has the smallest hindrance factor for such a transition in a well-deformed nucleus. For the decays of the $K^\pi = 8^-$ isomers in the hafnium isotopes, the reduced hindrance values vary smoothly as a function of the $J^{(2)}/J^{(1)}$ moment-of-inertia ratio, especially when the neutron-proton mixing in ^{178}Hf is taken into account.

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