$K^{\pi}=8^{-}$ rotational band and its fragmented decay through the $K^{\pi}=6^{+}$ intrinsic state in ^{170}Hf

D. M. Cullen, D. E. Appelbe,* and A. T. Reed
Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom

C. Baktash
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6371

I. Y. Lee and A. O. Macchiavelli
Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 12 May 1999; published 15 October 1999)

A $K^{\pi}=8^{-}$ strongly coupled rotational band, which is built upon a 23 ns isomeric state, has been established in ^{170}Hf. The single-particle configuration of the band has been determined from the in-band to out-of-band branching ratios and associated $|(g_K-g_R)|/Q_0$ values. The γ-ray decay of the $K^{\pi}=8^{-}$ isomeric state proceeds through a $K^{\pi}=6^{+}$ intrinsic state, in accordance with the K-selection rule. A complex array of delayed γ-ray transitions have been observed to link this $K^{\pi}=6^{+}$, intrinsic bandhead state into the yrast states. In particular, a new $\Delta K=8$, 1141 keV, $E1$ transition links the $K^{\pi}=8^{-}$ isomeric state directly to the ground-state band. The γ-ray reduced hindrance factor for this $E1$ decay in ^{170}Hf is the smallest $\Delta K=8$ transition observed in the Hf nuclei. However, its value is consistent with that expected on the basis of the increased Coriolis mixing which occurs in the lighter Hf isotopes. [S0556-2813(99)01911-1]

PACS number(s): 23.20.Lv, 21.10.Re, 27.70.+q

Low-lying multiquasiparticle isomeric states have been established in all of the heavy, odd- and even-mass hafnium isotopes from ^{170}Hf to ^{180}Hf. The systematic properties of these isomers have been discussed in Refs. [1,2]. In the even-mass Hf isotopes, the two-quasiparticle high-K states are built upon either the $K^{\pi}=8^{-}$ configuration (from the coupling of the two proton $\pi([514]9/2\otimes[404]7/2)_{8^{-}}$ states) or the $K^{\pi}=6^{+}$ configuration (from the two proton $\pi([404]7/2\otimes[402]5/2)_{6^{+}}$ states with some mass-dependent admixtures of the two neutron $\nu([514]7/2\otimes[512]5/2)_{6^{+}}$ states). Confirmation of the isomer configuration is generally obtained from the measurement of the in-band to out-of-band branching ratios for the associated high-K rotational band. For example, these high-K rotational bands have been used to establish configurations for the two-quasiparticle $K^{\pi}=6^{+}$ and 8^{-} states in ^{172}Hf [3], ^{174}Hf [4], ^{176}Hf [5], ^{178}Hf [6,7], ^{180}Hf [8], and ^{182}Hf [8]. However, in ^{170}Hf, only the two-quasiparticle $K^{\pi}=6^{+}$ and $K^{\pi}=8^{-}$ bandhead states were previously observed [9] and the configurations were, therefore, not unambiguously assigned. This paper presents the first observation of the $K^{\pi}=8^{-}$ rotational band and its associated $|(g_K-g_R)|/Q_0$ values which confirm its configuration. In addition, a complex array of delayed γ-ray transitions have been established which link the known $K^{\pi}=6^{+}$, intrinsic bandhead state [9], through a highly fragmented decay path, into the yrast states. Of particular interest, a $\Delta K=8$, 1141-keV, $E1$ transition has been established which links the $K^{\pi}=8^{-}$ isomeric state directly to the ground-state band. The γ-ray hindrance factors for these decays are discussed and compared with those of the systematics of the region.

High-spin states were populated in ^{170}Hf with the ^{48}Ca $+^{128}$Te reaction. The 200-MeV beam was supplied by the 88-in. cyclotron at the Lawrence Berkeley National Laboratory. A single thick target of ^{128}Te with thickness ≈ 1 mg/cm^2 was used on a 15 mg/cm^2 backing of ^{197}Au. A total of 70×10^9 unpacked triple-coincident events were collected with the sixty-four Compton-suppressed germanium detectors of the GAMMASPHERE array [10]. The main product of this reaction was ^{172}Hf [11] from the $4n$ exit channel. However, ^{170}Hf was produced via the $6n$ exit channel with an intensity $\approx 6\%$ that of the $4n$ exit channel.

Figure 1 shows a partial level scheme for ^{170}Hf illustrating the newly-established two-quasiparticle $K^{\pi}=8^{-}$ rotational band and its decay. A spectrum which is double-gated on the *prompt* transitions in this band is shown in Fig. 2(a). Two other transitions, 247 and 254 keV, were also observed to be in prompt coincidence with the lower-spin transitions in the $K^{\pi}=8^{-}$ band, however, they were not placed in the present work. In order to establish the decay of the $K^{\pi}=8^{-}$ isomeric state a matrix was constructed which was gated on those events which occurred 20–63 ns after each cyclotron beam pulse. These *delayed* matrices revealed a multitude of new γ-ray transitions which carry the highly fragmented decay intensity of the $K^{\pi}=6^{+}$ intrinsic state to the yrast band, see Fig. 1. Figure 2(b) shows a typical delayed spectrum which was double gated on the 217 keV, $8^{-}\rightarrow 7^{+}$, transition and the 221-keV yrast, $4^{+}\rightarrow 2^{+}$, transition. One of these new delayed transitions, the 1051-keV γ ray which deexcites the (6^{+}) state at 1373-keV to the yrast 4^{+} state, was previously observed in Ref. [12]. A new $\Delta K=8$, 1141-keV, $E1$ transition has been established which links the $K^{\pi}=8^{-}$ isomeric state directly to the ground-state band. This weak transition is shown in Fig. 2(c) relative to the 1131-keV $\Delta K=6$ linking transition.

*Present address: Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1.

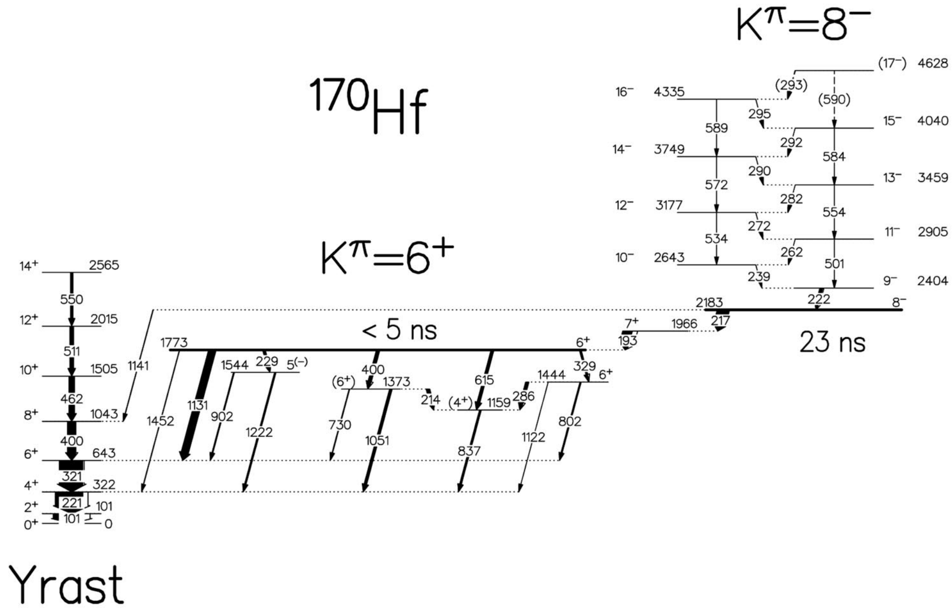

FIG. 1. Partial level scheme for ^{170}Hf showing the $K^{\pi}=8^{-}$ two-quasiparticle rotational band and its decay through the $K^{\pi}=6^{+}$ intrinsic state.

The multipolarities of the new γ-ray transitions have been deduced from an angular correlation analysis [using the directional correlation from oriented states (DCO) method [13]], see Table I. In addition Table I shows the intensities of the transitions which deexcite the $K^{\pi}=6^{+}$ intrinsic state. These DCO ratios are consistent with the configuration of the bandhead state having spin and parity, $K^{\pi}=8^{-}$.

In order to confirm the configuration assignments, for the $K^{\pi}=8^{-}$ rotational band in ^{170}Hf, $|(g_K-g_R)|/Q_0$ ratios have been calculated from the $(\Delta I=1)/(\Delta I=2)$ intensity branching ratios. These ratios are shown in Fig. 3 along with those for the corresponding $K^{\pi}=8^{-}$ band in ^{172}Hf also deduced from the same experiment. Table II shows the γ-ray energies, intensities and spin assignments for the transitions in the $K^{\pi}=8^{-}$ prompt rotational band in ^{170}Hf. From the systematics of the region, it is assumed that these $\Delta I=1$ transitions have positive mixing ratios and therefore, that (g_K

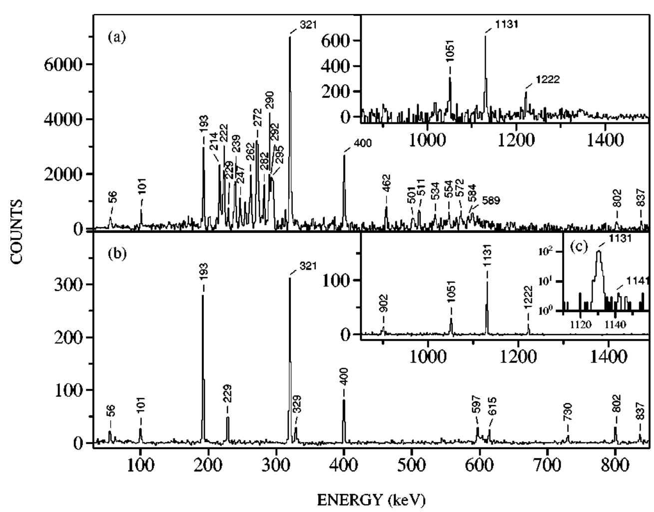

FIG. 2. (a) Double-gated spectrum for the new $K^{\pi}=8^{-}$ two-quasiparticle band in ^{170}Hf. The inset show the higher-energy part of the spectrum. The spectrum is from a sum of the 217-, 222-, 239-, 262-, and 282-keV transitions in a matrix which was gated on the 221- and 101-keV transitions in the yrast band. (b) Delayed spectrum double-gated on the 221-keV yrast and the 217-keV transitions showing the new γ-ray decays from the $K^{\pi}=6^{+}$ intrinsic state. (c) Delayed double-gated spectrum showing the new $\Delta K=8$, 1141 keV, E1 transition. The spectrum is a sum of the 101-, 321- and 400-keV transitions in a matrix which was gated on the delayed 221-keV yrast transition.

TABLE I. The γ-ray energies, intensities, DCO ratios, and assignments for the transitions which link the $K^{\pi}=8^{-}$ and $K^{\pi}=6^{+}$ states into the yrast states in ^{170}Hf.

E_{γ}(keV)	I_{γ}	DCO ratio	$J_f^{\pi}\to J_f^{\pi}$	Assignment
100.7(1)	9(1)	0.92(33)	$2^{+}\to 0^{+}$	$E2$
192.6(1)	34.2(2)	0.55(11)	$7^{+}\to 6^{+}$	$M1$
213.8(2)	1.6(8)		$(6^{+})\to(4^{+})$	$(E2)$
216.6(1)	49.0(24)	0.72(13)	$8^{-}\to 7^{+}$	$E1$
220.9(1)	80(8)		$4^{+}\to 2^{+}$	$E2$
229.2(1)	9.0(6)	0.56(18)	$6^{+}\to 5^{(-)}$	Dipole ($E1$)
286.2(3)	0.9(3)		$6^{+}\to(4^{+})$	$(E2)$
320.5(1)	62(6)	1.02(23)	$4^{+}\to 2^{+}$	$E2$
329.3(1)	5.7(5)		$6^{+}\to 6^{+}$	$(M1,\Delta I=0)$
400.1(1)	22(2)		$8^{+}\to 6^{+}$	$E2$
400.4(1)	11.4(9)		$6^{+}\to(6^{+})$	$(M1,\Delta I=0)$
614.5(1)	10.1(13)		$6^{+}\to(4^{+})$	$(E2)$
730.1(3)	2.0(5)	0.97(26)	$(6^{+})\to 6^{+}$	$(M1,\Delta I=0)$
801.5(2)	4.3(9)	1.10(23)	$6^{+}\to 6^{+}$	$M1(\Delta I=0)$
837.1(2)	6.2(6)		$(4^{+})\to 4^{+}$	$(M1,\Delta I=0)$
901.5(2)	3.3(6)	1.14(24)	$5^{(-)}\to 6^{+}$	Dipole ($E1$)
1050.9(1)	9.2(13)	1.05(22)	$(6^{+})\to 4^{+}$	$E2$
1122.3(8)	0.5(4)	0.99(19)	$6^{+}\to 4^{+}$	$E2$
1130.7(1)	26.3(14)	0.99(19)	$6^{+}\to 6^{+}$	$M1(\Delta I=0)$
1141(1)	0.8(2)		$8^{-}\to 8^{+}$	$(E1,\Delta I=0)$
1222.3(1)	5.0(9)	0.75(15)	$5^{(-)}\to 4^{+}$	Dipole ($E1$)
1452.4(1)	0.8(1)		$6^{+}\to 4^{+}$	$E2$

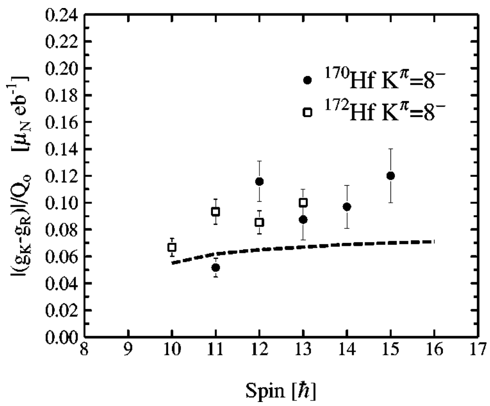

FIG. 3. $|g_K-g_R|/Q_o$ ratios for the $K^{\pi}=8^{-}$ two-quasiparticle bands in ^{170}Hf (circles) and ^{172}Hf (squares). The Dönau and Frauendorf estimate based on the $K^{\pi}=8^{-}$ configuration assignment is shown by the thick-dashed line; see text for details.

$-g_R$) is positive and also that the quadrupole moments of these bands are 7.1 e b [11]. Theoretical calculations, based on the geometric model of Dönau and Frauendorf [14], have been performed using the $K^{\pi}=8^{-}$ $(\pi([514]9/2 \otimes[404]7/2)_{8^-})$ configuration. This calculation, shown by the thick-dashed line in Fig. 3, is observed to be in good agreement with these new data and therefore, the $K^{\pi}=8^{-}$ configuration assignment.

In order to compare the new γ-ray decay transitions from the $K^{\pi}=6^{+}$ and $K^{\pi}=8^{-}$ bandhead states in ^{170}Hf, with other transitions in ^{170}Hf and those in the neighboring nuclei, it is instructive to consider the reduced hindrance factors. These are defined as $f_{\nu}=\{T^{\gamma}_{1/2}/T^{W}_{1/2}\}^{1/\nu}$ ($T^{\gamma}_{1/2}$ is the partial γ-ray half life, $T^{W}_{1/2}$ is the Weisskopf single-particle half-life estimate, and $\nu=\Delta K-\lambda$ is the degree of K forbiddeness where λ is the transition multipolarity). The reduced hindrance factors for the $K^{\pi}=8^{-}$ and $K^{\pi}=6^{+}$ bandhead states are given in Table III. The calculations were only performed for four of the decay transitions because the K^{π} configurations of the final states were only firmly established in these cases. From the table, it can be observed that all of these reduced hindrance factors are reasonably large (or have reasonably large upper limits) which implies that the decays are governed by the K-selection rule. It is worth noting that the short half-life of the $K^{\pi}=6^{+}$ intrinsic state in ^{170}Hf is consistent with that expected from the K-hindrance systematics, [15].

Recently, Walker *et al.* [2] made a survey of reduced hindrance factors for $\Delta K=8$, $E1$ transitions, to the 8^{+} state in the ground-state bands, for the even-even $^{172-178}$Hf nuclei. In the present work the corresponding $\Delta K=8$, 1141-keV $E1$ transition in ^{170}Hf is observed to be very weak, see Fig. 2(c). However, its reduced hindrance factor, 26.5 see Table III, it is remarkably close to that expected on the basis of the extrapolated systematics of Walker *et al.*, see Fig. 4. Although this reduced hindrance factor is the smallest observed for a $\Delta K=8$, $E1$ transition in the Hf nuclei it is consistent with the increased Coriolis mixing [2] in the lighter mass Hf nuclei.

TABLE II. The γ-ray energies, intensities, and assignments for the prompt transitions in the $K^{\pi}=8^{-}$ rotational band in ^{170}Hf. The γ-ray intensities are normalized to the intensity of the 238.7-keV transition.

E_{γ}(keV)	I_{γ}	$J^{\pi}_{f}\rightarrow J^{\pi}_{f}$
222.1(1)	126(10)	$9^{-}\rightarrow 8^{-}$
238.7(1)	100(9)	$10^{-}\rightarrow 9^{-}$
262.1(6)	58(7)	$11^{-}\rightarrow 10^{-}$
272.1(6)	69(6)	$12^{-}\rightarrow 11^{-}$
281.9(4)	37(6)	$13^{-}\rightarrow 12^{-}$
289.7(9)	47(7)	$14^{-}\rightarrow 13^{-}$
291.6(9)	47(7)	$15^{-}\rightarrow 14^{-}$
294.8(5)	42(7)	$16^{-}\rightarrow 15^{-}$
501.2(2)	33(8)	$11^{-}\rightarrow 9^{-}$
534.0(7)	32(8)	$12^{-}\rightarrow 10^{-}$
554.3(8)	22(7)	$13^{-}\rightarrow 11^{-}$
572.1(3)	16(5)	$14^{-}\rightarrow 12^{-}$
584.1(5)		$15^{-}\rightarrow 13^{-}$
588.7(2)		$16^{-}\rightarrow 14^{-}$

TABLE III. Reduced hindrance factors for the $K^{\pi}=6^{+}$ (<5 ns) and $K^{\pi}=8^{-}$ (23 ns) states in ^{170}Hf.

K^{π}	E_{γ} (keV)	I_{γ}	τ_{partial} (ns)	$M\lambda$	ΔK	$\nu=\Delta K-\lambda$	Reduced hindrance factor, f_{ν}
$K^{\pi}=8^{-}$	216.6	39.0	23.4	$E1$	2	1	1.09×10^{6}
$K^{\pi}=8^{-}$	1141	0.67	1361.8	$E1$	8	7	26.5
$K^{\pi}=6^{+}$	1130.7	24.5	<24.5	$M1$	6	5	<12.8
$K^{\pi}=6^{+}$	1452.4	0.7	<180	$E2$	6	4	<18.6

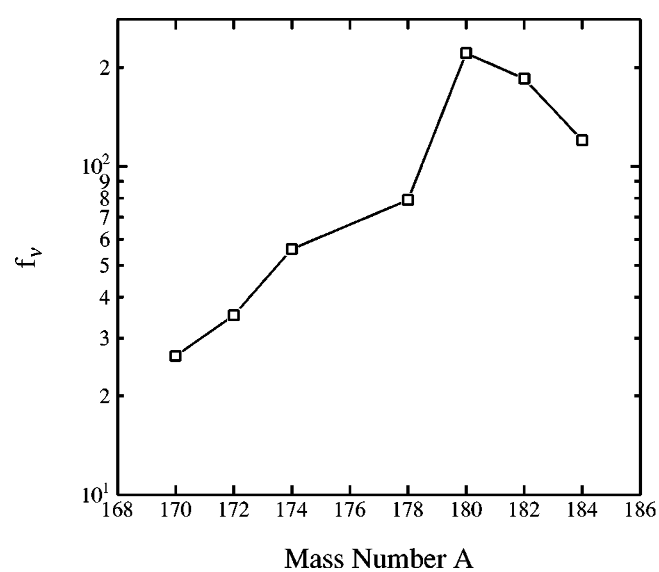

FIG. 4. Reduced hindrance factors for the $\Delta K=8$, $E1$ transitions for the $Z=72$ Hf nuclei. The value for ^{170}Hf is in excellent agreement with that predicted from the systematics of these decays [2]. The data point for ^{184}Hf is from Ref. [16].

D.M.C. and D.E.A. acknowledge financial support from the EPSRC, and A.T.R. acknowledges support from the University of Liverpool during the course of this work. Useful discussions with P.M. Walker are gratefully acknowledged. Oak Ridge National Laboratory is managed for the U.S. Department of Energy by Lockheed Martin Energy Research Corporation under Contract No. DE-AC05-96OR22464.

[1] P.M. Walker, Phys. Scr. **T5**, 29 (1983), and references therein.
[2] P.M. Walker, G.D. Dracoulis, A.P. Byrne, T. Kibédi, and A.E. Stuchbery, Phys. Rev. C **49**, 1718 (1994).
[3] P.M. Walker, G.D. Dracoulis, A. Johnson, and J.R. Leigh, Nucl. Phys. **A293**, 481 (1977).
[4] N.L. Gjørup, P.M. Walker, G. Sletten, M.A. Bentley, B. Fabricius, and J.F. Sharpey-Schafer, Nucl. Phys. **A582**, 369 (1995).
[5] R.G.H. Robertson and R.G. Summers-Gill, Can. J. Phys. **49**, 1186 (1971).
[6] T.L. Khoo and F. Løvhøiden, Phys. Lett. **67B**, 271 (1977).
[7] S.M. Mullins, G.D. Dracoulis, T.R. McGoram, S. Bayer, W.A. Seale, and F.G. Kondev, Phys. Lett. B **393**, 279 (1997).
[8] R. D'Alarcao *et al.*, Phys. Rev. C **59**, R1227 (1999).
[9] G.D. Dracoulis, P.M. Walker, and K.F. Yee, J. Phys. G **5**, L19 (1979).
[10] I.Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[11] D.M. Cullen, A.T. Reed, D.E. Appelbe, A.N. Wilson, E.S. Paul, R.M. Clark, P. Fallon, I.Y. Lee, A.O. Macchiavelli, and R.W. MacLeod, Nucl. Phys. **A638**, 662 (1998).
[12] C. Baktash, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, J. M. McConnell, F. K. McGowan, C. M. Steele, M. P. Carpenter, V. P. Janzen, and L. L. Reidinger, 1988, Oak Ridge National Laboratory, Annual report, 72 P.
[13] K.S. Krane, R.M. Steffan, and R.M. Wheeler, Nucl. Data Sheets **11**, 351 (1973).
[14] F. Dönau and S. Frauendorf, *Proceedings of the Conference on High Angular Momentum Properties of Nuclei*, Oak Ridge, 1982, edited by N. R. Johnson (Harwood Academic, New York, 1983); F. Dönau, Nucl. Phys. **A471**, 469 (1987).
[15] P.M. Walker, J. Phys. G **16**, L233 (1990).
[16] K. Krumbholz *et al.*, Z. Phys. A **351**, 11 (1995).