Low-energy one-quasiparticle bands in neutron-rich ^{181}Hf

C. Günther,[1] J. Jolie,[2,*] A. I. Levon,[3] S. Mannanal,[2] N. Warr,[2,*] and T. Wendel[1]
[1]Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany
[2]Institut de Physique, Université de Fribourg, Perolles, CH-1700 Fribourg, Switzerland
[3]Institute for Nuclear Research, 252028 Kiev, Ukraine
(Received 16 October 2001; published 12 March 2002)

Excited states in ^{181}Hf, populated in the ^{180}Hf(d,p) deuteron breakup reactions, were investigated by in-beam γ-ray spectroscopy. The $1/2^-[510]$ ground band and the $3/2^-[512]$ and $7/2^-[503]$ excited bands are extended to higher spins than previously known. The Coriolis coupling of the $1/2^-[510]$ and $3/2^-[512]$ bands is found to be consistent with that derived for the same bands in the classic case of ^{183}W.

DOI: 10.1103/PhysRevC.65.047301 PACS number(s): 21.60.Ev, 23.20.Lv, 27.70.+q

The isotope ^{181}Hf is located at the neutron-rich side of the nuclear valley of stability and therefore cannot easily be studied with in-beam γ-ray spectroscopy. Information on the low-energy structure of this nucleus has been obtained primarily from studies of the β^- decay of 3.5 m ^{181}Lu and from nuclear transfer reactions. From these investigations only three intrinsic states were known below ≈ 1 MeV with the $7/2^-$ member of the $1/2^-[510]$ ground band as the highest rotational excitation [1,2]. Only recently some additional experimental information was obtained in an investigation of ^{181}Hf via inelastic excitation and transfer by D'Alarcao *et al.* [3]. These authors confirmed the isomeric character of the $9/2^+[624]$ level proposed earlier [4] and extended the ground band to $I=11/2$.

The results presented in this brief report were obtained as a by-product during our investigation of ^{180}Ta which was in part performed with the ^{180}Hf$(d,2n)^{180}$Ta reaction [5]. During this investigation we found that the isotopes ^{181}Hf, ^{180}Hf, and ^{179}Hf are produced with appreciable cross sections by deuteron breakup reactions. While the observed results for the isotopes ^{180}Hf and ^{179}Hf did not provide new nuclear structure information we obtained new high-precision data for ^{181}Hf which justify a short note. During the preparation of this report we obtained information on a new investigation of ^{181}Hf through (n,γ) and (d,p) reactions [6] which will be compared with our results below.

A target of 8 mg/cm^2 HfO_2 enriched to 94.3% in ^{180}Hf was bombarded with 12.4 MeV deuterons at the cyclotron of the PSI (Villigen, Switzerland). Gamma-gamma coincidences were measured using the setup described by Warr *et al.* [7]. The data were recorded in list mode and sorted with an appropriate time window into a $4k\times 4k$ matrix which was analyzed with the interactive RADWARE package [8]. A total of 5.8 million twofold coincidences contained approximately 15 000 photopeak-photopeak coincidences of γ rays assigned to ^{181}Hf.

As an illustration of the quality of our data we show two γ-ray spectra in Fig. 1. The γ rays assigned to ^{181}Hf are listed, together with the levels which they depopulate, in Table I. The proposed assignments are based on coincidences with γ rays known from the ^{181}Lu$\rightarrow^{181}$Hf radioactive decay and can be considered as established except when otherwise noted.

The γ-ray intensities listed in the second to the last column of Table I were derived, when possible, from the γ-ray spectra in coincidence with γ rays populating a given level. For those levels, for which we do not observe populating γ rays, intensities were determined from the $\gamma\gamma$ coincidence counts with reasonable assumptions for the depopulation of the intermediate levels.

The levels listed in Table I up to the $11/2^-$ member of the ground band and the $9/2^\pm$ states of the excited bands were also identified by Bondarenko *et al.* [6] in the (n,γ) experiments. All level energies agree within 0.1 keV. The γ-ray intensities reported in Ref. [6] are listed in the last column of Table I. The agreement with our values is reasonable, taking into account the large experimental uncertainties of both data sets, except for a few transitions which are placed doubly in the level scheme (e.g., the 136 and 205 keV γ rays).

The high-spin levels listed in Table I are also assigned by Bondarenko *et al.* from the (d,p) reaction. The agreement between the two data sets is only moderate, with discrepancies between five and ten times the errors quoted for the level energies in Ref. [6].

One open question is the nuclear structure of the $9/2^+[624]$ band. The $9/2^+$ ground state is populated quite strongly in the deuteron breakup reaction (see Fig. 1), but the populating γ rays cannot be identified by direct $\gamma\gamma$ coincidences because of the long half-life of the 595 keV $9/2^+$ level [3,6]. Bondarenko *et al.* adopt a hypothesis made earlier by Burke *et al.* [4], in which the high-spin members of the $9/2^+[624]$ band are pushed to higher energies by the Coriolis coupling of this band with the $11/2^+[615]$ band, and suggest the $11/2^+$ and $13/2^+$ levels are at 802 and 1010 keV, respectively. We observe a coincidence between γ rays with energies of 203.5 and 210.3 keV which we cannot assign to other isotopes populated in the reaction of the 12.4 MeV deuterons with ^{180}Hf. If these γ rays result from the $13/2^+\rightarrow 11/2^+\rightarrow 9/2^+$ cascade it would place the $11/2^+$ level at 798.7 or 805.5 keV and the $13/2^+$ level at 1009.0 keV. Unfortunately, due to the complex γ-ray spectra observed in the present work we cannot even assign these coincident γ rays unambiguously to hafnium isotopes.

*Present address: Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany.

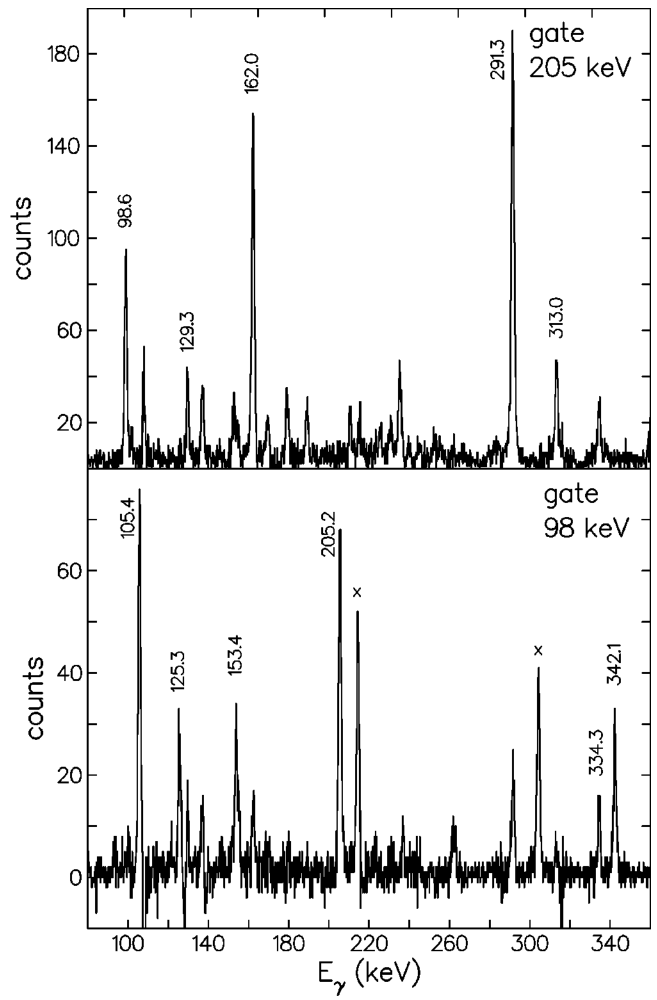

FIG. 1. Gamma-ray spectra in coincidence with the 98.6 keV $5/2^- \rightarrow 1/2^-$ and 205.2-keV $9/2^- \rightarrow 5/2^-$ transitions. The peaks marked by × result from the 98.4-304.0-214.3 keV cascade in ^{179}Hf.

The first two members of the $11/2^+[615]$ band are proposed by Bondarenko *et al.* at 622 and 759 keV. We observe a level at 617 keV, which decays by a 313 keV γ ray to the $9/2^-$ member of the ground band as might be expected for the $11/2^+$ level. However, the intensity of the 313 keV γ ray suggests the interpretation of the 617 keV level as $13/2^-$ member of the ground band (see also the discussion of the ground band given below). We also observe a very weak 205.4–315.4 keV $\gamma\gamma$ coincidence which could result from the decay of a 619.2 keV level to the $9/2^-$ member of the ground band in ^{181}Hf. Unfortunately, the 315.4 keV γ-ray energy coincides with a 315.6 keV γ ray in ^{180}Ta which appears most strongly in the dominant $(d,2n)$ reaction [5] making the association of the 205.4–315.4 keV $\gamma\gamma$ coincidence to ^{181}Hf uncertain. We do not observe a γ ray from the propsed $13/2^+$ level at 759 keV to the $11/2^-$ member of the ground band, which might not be significant since the $13/2^+$ level is expected to decay predominantly to the lower-lying members of the $K^\pi = 9/2^+$ and $11/2^+$ bands.

Alternatively, we observe coincident γ rays with energies of 127.5, 152.1, 178.7, and 331.0 keV which could be the

TABLE I. Levels and transitions assigned to ^{181}Hf.

Neutron orbital	Initial level[a] E_{exc}	I^π	Final level E_{exc}	I^π	Transition[a] E_γ	I_γ[b]	
$1/2^-[510]$	98.6	$5/2^-$	0.0	$1/2^-$	98.6		
	204.0	$7/2^-$	45.7	$3/2^-$	158.4	27	28
			98.6	$5/2^-$	105.4	100	100
	303.8	$9/2^-$	98.6	$5/2^-$	205.2	100	100
			204.0	$7/2^-$	100.0	13	6
	465.9	$11/2^-$	204.0	$7/2^-$	261.9	100	100
			303.8	$9/2^-$	162.0	72	87
	616.9	$13/2^-$	303.8	$9/2^-$	313.1		
	830.9[c]	$15/2^-$	465.9	$11/2^-$	365.0		
$3/2^-[512]$	251.9	$3/2^-$	0.0	$1/2^-$	252.0	30	9
			45.7	$3/2^-$	206.1	100	100
			98.6	$5/2^-$	153.4	24	13
	329.3	$5/2^-$	0.0	$1/2^-$	329.3	100	100
			45.7	$3/2^-$	283.7	9	12
			98.6	$5/2^-$	230.7	7	7
			204.0	$7/2^-$	125.3	55	65
			251.9	$3/2^-$	77.4	≈6	6
	440.7	$7/2^-$	45.7	$3/2^-$	395.0	14	16
			98.6	$5/2^-$	342.1	100	100
			204.0	$7/2^-$	236.7	28	23
			303.8	$9/2^-$	136.7	6	2
			251.9	$3/2^-$	188.9	9	11
			329.3	$5/2^-$	110.9	≈5	5
	573.7	$9/2^-$	204.0	$7/2^-$	369.7	86	
			329.3	$5/2^-$	244.2	100	100
			440.7	$7/2^-$	133.2	30	42
	749.4	$11/2^-$	303.8	$9/2^-$	445.5	100	
			465.9	$11/2^-$	283.5	33	
			440.7	$7/2^-$	308.6	37	
			573.7	$9/2^-$	175.7	24	
	930.0[c]	$13/2^-$	465.9	$11/2^-$	464.0		
			616.9	$13/2^-$	312.6		
			573.7	$9/2^-$	356.7		
$9/2^+[624]$	595.2	$9/2^+$	204.0	$7/2^-$	391.3	42	41
			303.8	$9/2^-$	291.3	100	100
			465.9	$11/2^-$	129.3	28	68
			440.7	$7/2^-$	154.5	30	24
$7/2^-[503]$	663.6	$7/2^-$	98.6	$5/2^-$	564.9	36	26
			204.0	$7/2^-$	459.6	40	32
			303.8	$9/2^-$	359.7	21	12
			251.9	$3/2^-$	411.8	36	29
			329.3	$5/2^-$	334.3	100	100
			440.7	$7/2^-$	222.8	29	22
	800.0	$9/2^-$	663.6	$7/2^-$	136.4		
	965.0	$11/2^-$	663.6	$7/2^-$	301.5	45	
			800.0	$9/2^-$	165.0	100	
$7/2^-[514]$	904.1[d]	$7/2^-$	251.9	$3/2^-$	652.2	100	100
			663.6	$7/2^-$	240.5	40	10

[a]All energies in keV; estimated accuracy ±0.1 keV.

[b]First column: present work; estimated accuracy ±20%. Second column: Ref. [6]; typical errors between ±20% and ±30%.

[c]Tentative assignment.

[d]Assignment proposed by Bondarenko *et al.* [6].

TABLE II. Energy parameters resulting from least-squares fits to the experimental energies of the $1/2^-[510]$ and $3/2^-[512]$ bands.

Parameter	Fitted value[a] ^{181}Hf I	II	^{183}W I	II
h_1 (keV)	21.7	23.0	21.71	22.74
$A_{3/2}$ (keV)	13.19	13.40	14.02	13.75
$B_{3/2}$ (keV)		−0.020		−0.007
$A_{1/2}$ (keV)	15.28	15.30	15.84	16.08
$B_{1/2}$ (keV)		+0.011		+0.009
a	0.1532	0.1564	0.1719	0.1706

[a]Derived from the rotational bands in ^{181}Hf and ^{183}W up to the $11/2^-$ and $9/2^-$ states, respectively.

$11/2^+ \rightarrow 9/2^+$, $13/2^+ \rightarrow 11/2^+$, $15/2^+ \rightarrow 13/2^+$, and $15/2^+ \rightarrow 11/2^+$ transitions, respectively, of an unperturbed $9/2^+[624]$ band. This assignment would be in agreement with the systematics of this band which is known in ^{177}Hf and ^{179}Hf, but again the assignment of these γ rays to ^{181}Hf is not experimentally established.

In a very recent study of high-K orbitals in ^{181}Hf, which came to our attention after submission of the present report, the $11/2^+[615]$ band is proposed with the bandhead at 617 keV [9]. However, this 617-keV level is not reported to decay to the $9/2^-$ member of the $1/2^-[510]$ band and therefore its relation to the 616.9 keV level proposed in the present work is unclear.

The ground and first-excited bands, with the configuration $1/2^-[510]$ and $3/2^-[512]$, respectively, are expected to be mixed due to Coriolis coupling. This mixing has been studied in the isotone ^{183}W, where these bands have an almost identical structure as in ^{181}Hf [10,11]. In order to test the similarity of the Coriolis coupling in the two isotopes we have performed a simple two-band mixing analysis of the bands in ^{181}Hf analogous to that described by Brockmeier *et al.* [10] for ^{183}W.

The unperturbed rotational energies and the matrix element of the Coriolis interaction H_c are given by

$$E_{rot}(K,I) = E_0 + A_K[I(I+1) + a(-)^{I+1/2}(I+1/2)\,\delta(K,1/2)] + B_K[I(I+1) + a(-)^{I+1/2}(I+1/2)\,\delta(K,1/2)]^2 \quad (1)$$

and

$$\langle I,3/2|H_c|I,1/2\rangle = h_1\sqrt{(I-1/2)(I+3/2)}. \quad (2)$$

The results of the two-band analysis with the above equations are compared in Table II with the corresponding results given in Ref. [10] for ^{183}W.

The fitted values for the Coriolis parameter h_1 for ^{181}Hf and ^{183}W are in remarkable agreement. The rotational parameters A_K can be compared with the values $E(2^+)/6 = 15.55$ and 16.68 keV of the core nuclei ^{180}Hf and ^{182}W, respectively. The small values for the $3/2^-$ bands are perhaps due to the influence of higher-lying bands: Brockmeier *et al.* [10] discuss the coupling of seven additional bands and find a significant improvement by including these bands.

TABLE III. Deviations of calculated from experimental energies in ^{181}Hf.

Quantity[a]	Values in keV $h_1=0$	Fit I	Fit II
$\Delta E_{max}(K=1/2)$	1.31	0.50	0.32
$\Delta E_{av}(K=1/2)$	0.67	0.22	0.14
$\Delta E_{max}(K=3/2)$	3.73	1.38	0.29
$\Delta E_{av}(K=3/2)$	1.66	0.56	0.15

[a]$\Delta E = |E_{exp} - E_{calc}|$ for the rotational levels up to the $11/2^-$ states in ^{181}Hf.

In Table III we list the maximum and average deviations of the calculated level energies from the experimental ones. The large improvement of the description of the $3/2^-$ band by including the quadratic term in $I(I+1)$ in the rotational energy indicates again the importance of the coupling of this band to higher-lying bands.

In Table I we assign the 616.9 and 830.9 keV levels as the $13/2^-$ and $15/2^-$ members of the $1/2^-$ band. The energies calculated for these levels are 614.4 and 832.5 keV for fit I, and 611.4 and 814.9 keV for fit II. This disagreement is in contrast to ^{183}W where the energies calculated with the parameters of fit II for the $11/2^-$, $13/2^-$, and $15/2^-$ members of the $1/2^-$ band agree with the experimental values reported in Ref. [11] within ≈ 1 keV. However, Brockmeier *et al.* mention already that fit II is unsatisfactory because of the inconsistent signs of the B parameters, and that an improved fit is obtained by including additional higher-lying bands instead. In the present case the levels are already strongly mixed for moderate spins (e.g., in fit II the lower-lying $13/2^+$ level is composed of 58% $K=1/2$ and 42% $K=3/2$) and one has to expect appreciable energy shifts by the additional admixed bands. The large mixing also makes an interpretation of the γ-ray intensities difficult. In view of the large experimental uncertainties of the few observed branching ratios we have therefore made no attempt of such an interpretation.

We would like to acknowledge the help of M. Dorthe, P. E. Garrett, J. Kern, H. Lehmann, J. L. Schenker, and T. Weber during some of the experiments. We are grateful to V. Bondarenko and T. von Egidy for making available their work prior to its publication. This work was supported by the Deutsche Forschungsgemeinschaft (grants Gu 179/3 and 436 UKR 17/17/98), the Paul Scherrer Institute, and the Swiss National Science Fund.

[1] R.B. Firestone, Nucl. Data Sheets **62**, 101 (1991).
[2] *Table of Isotopes*, edited by R. B. Firestone and V. S. Shirley, 8th ed. (Wiley, New York, 1996).
[3] R. D'Alarcao *et al.*, Phys. Rev. C **59**, R1227 (1999).
[4] D.G. Burke, J.C. Waddington, G. Løvhøiden, and T.F. Thorsteinsen, Can. J. Phys. **62**, 192 (1984).
[5] T. Wendel *et al.*, Phys. Rev. C **65**, 014309 (2002).
[6] V. Bondarenko *et al.*, Nucl. Phys. (submitted).
[7] N. Warr, S. Drissi, P.E. Garrett, J. Jolie, J. Kern, S.J. Mannanal, J.-L. Schenker, and J.-P. Vorlet, Nucl. Phys. **A620**, 127 (1997).
[8] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[9] I. Shestakova *et al.*, Phys. Rev. C **64**, 054307 (2001).
[10] R.T. Brockmeier, S. Wahlborn, E.J. Seppi, and F. Boehm, Nucl. Phys. **63**, 102 (1965).
[11] T.R. Saitoh, N. Saitoh-Hashimoto, G. Sletten, R.A. Bark, M. Bergström, P. Regan, S. Törmänen, P.G. Varmette, P.M. Walker, and C. Wheldon, Nucl. Phys. **A660**, 171 (1999).