single-particle rate to more than one hundred times single particle. The very large rates occur only for nuclei whose even neighbors have particularly large $B(E2)_{0+\to 2+}$ rates. The small rates are not so common, only about 30 of the 150 calculated cases being less than single particle. These cases occur only if the factor $(U_iU_f-V_iV_f)$ is quite small, corresponding to λ, the Fermi energy of pairing theory, being midway between the two single-particle energies in question. The exact isotope for which this occurs depends sensitively on the original choice of the single-particle energies. The experimental $B(E2)$ values for odd nuclei in this region also vary over a range of a factor of 1000. The agreement between theory and experiment is quite good, the large majority of the forty or so cases agreeing to within about a factor of 2 with the theoretical result.

This agreement shows that there is considerable truth in the picture of wave functions of odd spherical nuclei consisting of linear combinations of quasiparticles and quasiparticles coupled to phonons. Furthermore, the phonons have the same properties as those of the neighboring even nuclei, and the mixing coefficients of Eq. (2) may be computed as in Ref. 4. Further experimental investigation is desirable, and the calculated rates may serve as a guide to the expected rates. Fast cases might be used to investigate the phonon character of the wave functions in more detail. On the other hand, an observation of the $E2$ rate in cases for which a large retardation from the single particle rate is predicted might help to determine the validity of the single-particle energies used in the calculation and also to indicate possible wave-function components not included in Eq. (2).

ACKNOWLEDGMENT

The author wishes to thank Dr. L. Grodzins, who helped locate some of the experimental results.

PHYSICAL REVIEW VOLUME 133, NUMBER 2B 27 JANUARY 1964

Spin-23/2⁻ Isomer of Lu^{177}†

P. Alexander, F. Boehm, and E. Kankeleit
California Institute of Technology, Pasadena, California

(Received 3 September 1963)

Investigations of the decay of the three-particle state in Lu^{177} with spin $23/2^-$ performed with the crystal diffraction technique revealed evidence for three-particle states in Hf^{177} and rotational bands in Lu^{177} and in Hf^{177}. Levels with spins to 17/2 were found in the $K=7/2^+$ rotational band in Lu^{177} while the $K=7/2^-$ and $K=9/2^+$ bands in Hf^{177} were found to be excited up to spin 21/2 levels. From energy and intensity measurements of the cascade, crossover, and interband transitions, the values of a number of parameters pertinent to the collective model were derived. In particular, it was verified for each of the rotational bands that the quantity $(g_K-g_R)/Q_0$ was a constant within the experimental error.

INTRODUCTION

Recently, Jorgensen *et al.*[1] have observed a 155-day isomeric state in Lu^{177} in a neutron-bombarded lutetium sample. From considerations of the decay mode they conclude[2] that this isomer has a very high spin of 23/2. Only a three-particle configuration of the odd proton of Lu^{177} and an uncoupled neutron pair could give rise to this high spin. In particular, the configuration obtained by adding the [624]$9/2^+$ neutron and the [514]$7/2^-$ neutron to the [404]$7/2^+$ proton is most likely to explain the observed Lu^{177} isomer.

The large change in the intrinsic configuration reduces the speed of the electromagnetic isomeric transition from the three-particle state so that it can compete with β decay into the neighboring Hf^{177}. In Hf^{177} similar three-particle states are expected to appear. A configuration based on the [514]$7/2^-$ neutron coupled to a [514]$9/2^-$ proton and a [404]$7/2^+$ proton could result in a state of spin $23/2^+$. Two other configurations favored by energy considerations both resulting in spin $21/2^+$ are obtained by coupling the [514]$7/2^-$ neutron to the [514]$9/2^-$ and [402]$5/2^+$ protons, or by coupling together three neutrons in [624]$9/2^+$, [514]$7/2^-$, and [512]$5/2^-$ orbits. Other combinations resulting in three-particle states of spin $25/2^-$, $19/2^-$, $17/2^+$, $15/2^+$, $15/2^-$, and $13/2^-$ can be constructed, but their respective energies are expected to be somewhat higher than those of the $23/2^+$ and $21/2^+$ configurations.

In this article we report on a study of the decay of the Lu^{177} isomer into Lu^{177} and Hf^{177}. Evidence for two three-particle states in Hf^{177} with spin $23/2^+$ and $21/2^+$

---

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] M. Jorgensen, O. B. Nielsen, and G. Sidenius, Phys. Letters **1**, 321 (1962).

[2] O. B. Nielsen (private communication).

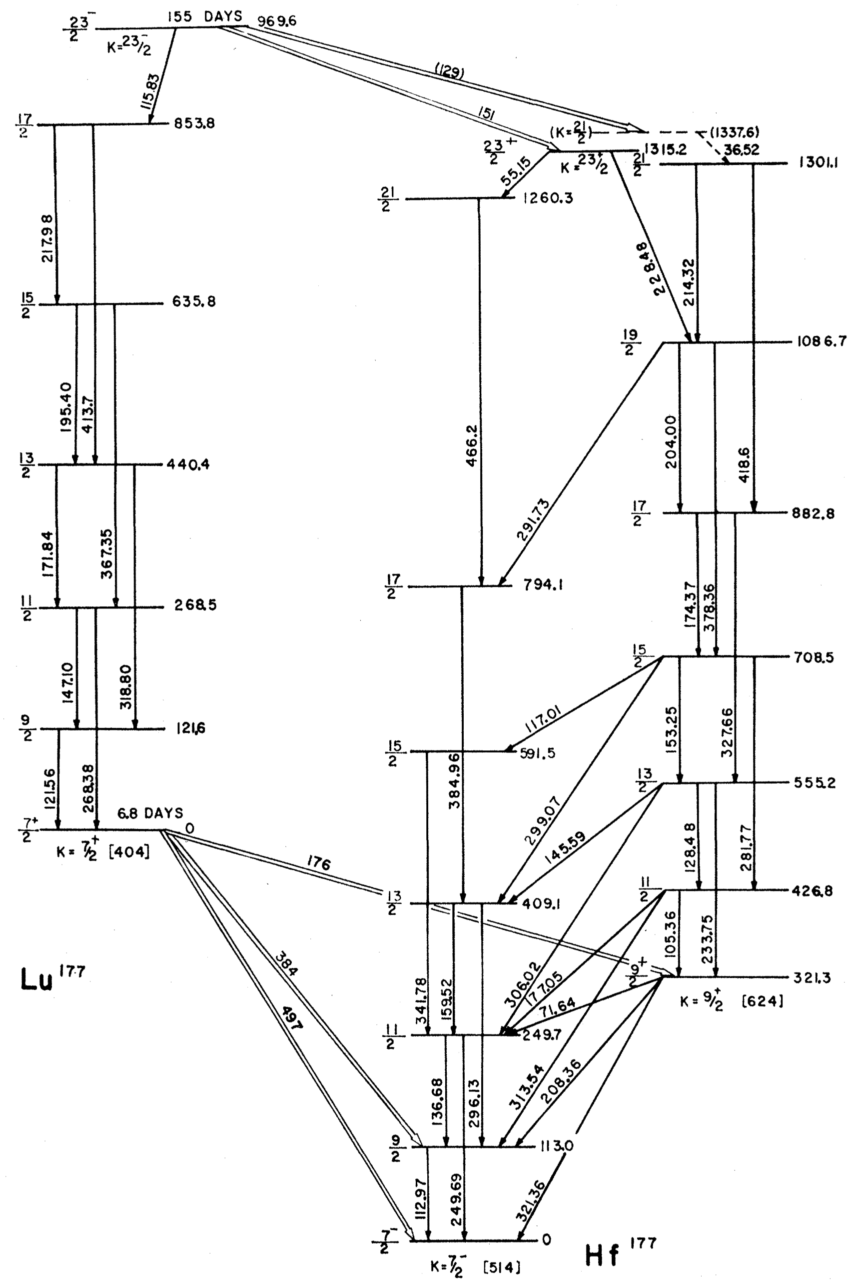

FIG. 1. Level scheme of Lu^{177} and Hf^{177} as observed in the decay of Lu^{177*}.

is found. A preliminary report on the magnetic transition rates in the rotational bands observed in this investigation has been given previously.[3]

RESULTS

Source Preparation

The Lu^{177} gamma-ray source was prepared from 1.5 mg of Lu_2O_3 enriched in Lu^{176} to 74.5%. This material was encapsulated in a quartz capillary of inner diameter 0.20 mm, outer diameter 0.62 mm, and length 2.0 cm and irradiated for two weeks with a neutron flux of 4×10^{14} in the MTR reactor at Arco, Idaho. The source strength at the onset of the measurements was about 100 Ci.

7-Day Lu^{177}

Precision energy and relative intensity measurements were made on the gamma-ray spectrum of 7-day Lu^{177} using the Caltech 2-m-radius, bent-crystal spectrometer. A description of the methods for performing these measurements has been detailed previously.[4] The rela-

[3] F. Boehm, P. Alexander, and E. Kankeleit, in Proceedings of the Conference on the Role of Atomic Electrons on Nuclear Transformations, Warsaw, Poland, 1963 (to be published).

[4] P. Alexander and F. Boehm, Nucl. Phys. 46, 108 (1963).

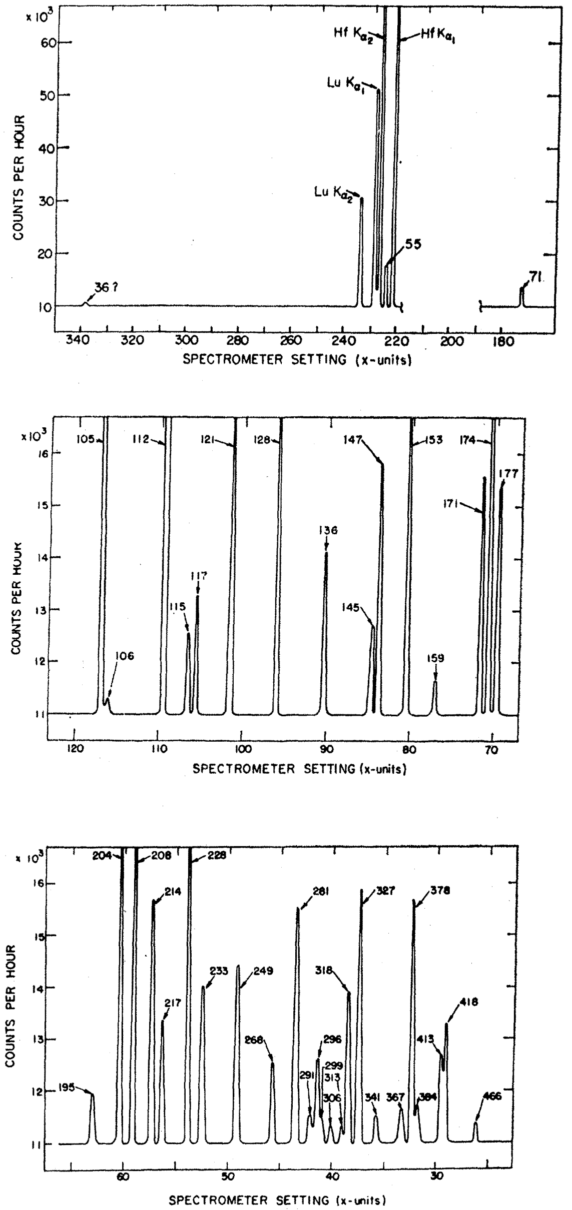

FIG. 2. Pictorial presentation of the gamma spectrum of Lu^{177*} as observed with the curved crystal spectrometer. The lines are identified by their respective energies in keV.

tive intensities of the gamma rays were measured to 5%. Table I contains our intensity data together with the energy and intensity values reported earlier by Marmier and Boehm.[5] The weak gamma ray at 136.68±0.02 keV was not observed by these authors, but was seen and assigned as transition between the 249.7-keV and 113.0-keV levels in Hf^{177} by others.[6] A decay scheme showing these levels is given in Fig. 1.

Using the relative intensity data we have derived the β-decay branching ratios from the Lu^{177} ground state to the 113.0-, 249.7-, and 321.3-keV levels in Hf^{177}. Our results are compared with those of El-Nesr and Bashandy[7] in Table II. For comparison we have normalized the feeding of the 321-keV level to 6.7. The two sets of data are in poor agreement. In particular, we find no evidence for β feeding of the 249.7-keV level.

[5] P. Marmier and F. Boehm, Phys. Rev. **97**, 103 (1955).

[6] *Nuclear Data Cards,* (U. S. Government Printing Office, Washington 25, D. C.).

TABLE I. Relative intensities of gamma rays in 7-day Lu^{177}.

Gamma energy (keV)	Relative intensity: This measurement[a]	Marmier and Boehm[b]
71.64	2.4	2
112.97	100	100
136.68[c]	.74	...
208.36	171	220
249.69	3.3	3
321.36	3.4	3.2

[a] Relative error ±5%.
[b] Relative error estimated to be ±20% (see Ref. 5).
[c] 136.68±0.02 keV.

155-Day Lu^{177*}

During the measurements of the 7-day lines with the bent-crystal spectrometer, a number of gamma rays, two to three orders of magnitude weaker than the 7-day Lu^{177} lines, were observed. These lines were found to have a considerably longer half-life and were attributed to the Lu three-particle excitation reported by Jorgensen *et al.*[1] The strength of this isomeric Lu^{177} activity was approximately 100 mCi. The present investigation of the isomeric activity started after the 7-day period had decayed and lasted about six months. Using the curved crystal spectrometer, some 44 gamma lines have been observed to follow the 155-day half-life of Lu^{177*}. In Table III we present a summary of our energy and relative intensity values for these gamma rays. A pictorial representation of the Lu^{177*} gamma-ray spectrum from 35 to 470 keV is presented in Fig. 2. From the energy relationship of the cascade and crossover transitions, the decay scheme of Fig. 1 was established. It is in close agreement with the scheme proposed by Nielsen *et al.*[2] Conversion electrons of most of these lines were studied in the homogeneous-field ring-focusing β spectrometer.

TABLE II. Relative β branchings from decay of 7-Day Lu^{177} into states of spin I in Hf^{177}.

I	K	Percent branching: This work	El-Nesr and Bashandy[b]
7/2⁻	7/2	...	90±4
9/2⁻		7 ±1	2.95±0.05
11/2⁻		0.03±0.03	0.31±0.06
9/2⁺	9/2	6.7 ±0.3[a]	6.72±0.25

[a] Normalized to 6.7.
[b] See Ref. 7.

[7] M. S. El-Nesr and E. Bashandy, Nucl. Phys. **31**, 128 (1962).

Three rotational bands have been identified, one in Lu^{177} and two in Hf^{177}. The rotational structures shown in Fig. 1 have been substantiated by the cascade and crossover energy relationship and by the balance of transition intensities in and out of each level. The Lu^{177} band is built on the $K=7/2^+$ ground state. The $9/2^+ \rightarrow 7/2^+$ transition was known previously from the Yb^{177} decay.[6] This band includes 5 rotational states up to spin $17/2^+$. It is presumably excited via an isomeric transition of 115.83 keV. The 112.97- and the 249.69-keV transitions in the $K=7/2^-$ band in Hf^{177} were also observed in the 155-day period. A system of cascade and crossover transitions built on the known $9/2^-$ and $11/2^-$ states in this band could be established up to spin $21/2^-$. Transitions to and from the $19/2^-$ state could not be seen. In addition to the $K=7/2^-$ band, a rotational band built on the 321.3-keV level with $K=9/2^+$ was also established with a complete set of cascade and crossover transitions up to spin $21/2^+$.

Table III. Energies and relative intensities of gamma rays observed in the decay of Lu^{177*}.

Gamma energy (keV)	Relative intensity (% error)	Assignment in Fig. 1.
(36.52)	<2	
55.15±0.02	10 (15%)	Hf interband
71.64±0.02	9 (20%)	Hf interband
(90.19)	<1	
105.36±0.02	100[a]	Hf $K=9/2$
(106.16)	~1	
112.97±0.02	251 (5%)	Hf $K=7/2$
115.83±0.04	9 (20%)	Lu interband
117.01±0.04	12 (20%)	Hf interband
121.56±0.03	62 (5%)	Lu $K=7/2$
128.48±0.02	125 (5%)	Hf $K=9/2$
136.68±0.02	17 (20%)	Hf $K=7/2$
145.59±0.06	11 (20%)	Hf interband
147.10±0.06	27 (10%)	Lu $K=7/2$
153.25±0.04	134 (5%)	Hf $K=9/2$
159.92±0.08	5 (20%)	Hf $K=7/2$
171.84±0.08	41 (10%)	Lu $K=7/2$
174.37±0.06	110 (5%)	Hf $K=9/2$
177.05±0.08	34 (10%)	Hf interband
195.40±0.1	9 (20%)	Lu $K=7/2$
204.00±0.08	130 (10%)	Hf $K=9/2$
208.36±0.06	610 (5%)	Hf interband
214.32±0.1	79 (10%)	Hf $K=9/2$
217.98±0.1	37 (15%)	Lu $K=7/2$
228.48±0.08	340 (5%)	Hf interband
233.75±0.1	43 (10%)	Hf $K=9/2$
249.69±0.1	62 (10%)	Hf $K=7/2$
268.38±0.1	32 (15%)	Lu $K=7/2$
281.77±0.1	121 (5%)	Hf $K=9/2$
291.73±0.3	20 (20%)	Hf interband
296.13±0.2	65 (10%)	Hf $K=7/2$
299.07±0.3	10 (20%)	Hf interband
306.02±0.3	13 (20%)	Hf interband
313.54±0.3	12 (20%)	Hf interband
318.80±0.2	86 (5%)	Lu $K=7/2$
321.36±0.2	≤12	Hf interband
327.66±0.3	149 (10%)	Hf $K=9/2$
341.78±0.4	14 (30%)	Hf $K=7/2$
367.35±0.4	25 (20%)	Lu $K=7/2$
378.36±0.3	223 (10%)	Hf $K=9/2$
384.96±0.4	37 (20%)	Hf $K=7/2$
413.7 ±0.5	163 (10%)	Lu $K=7/2$
418.6 ±0.5	185 (10%)	Hf $K=9/2$
466.2 ±1	23 (30%)	Hf $K=7/2$

[a] Normalized to 100.

Table IV. Maximum possible relative intensities for unobserved gamma transitions in Hf^{177}.

Gamma energy (keV)	$K_i \rightarrow K_f$	$I_i \rightarrow I_f$	Energy region searched (keV)	Minimum visible relative intensity[b]
243[a]	7/2 7/2	21/2 19/2	239 –246	50
223[a]		19/2 17/2	220 –225	3
425[a]		19/2 15/2	418 –431	1
202.6		17/2 15/2	201 –204	17
182.4		15/2 13/2	181 –184	3
40.8	9/2 7/2	21/2 21/2	39.3– 42.3	3
284[a]		21/2 19/2	280 –287	70
70[a]		19/2 19/2	68.8– 70.2	0.4
88.7		17/2 17/2	85.0– 90.7	0.7
291.3[c]		17/2 15/2	290 –293	8
173.6	7/2 9/2	21/2 19/2	170 –176	21
85.6		17/2 15/2	85.0– 88.0	0.7
36.3		15/2 13/2	34.8– 37.8	4
87.8		13/2 9/2	85.0– 90.7	0.7

[a] Assuming that the $19/2^-(K=7/2)$ level is located at about 1017 keV.
[b] Using the same intensity normalization as in Table III.
[c] This gamma ray may have been observed as the 291.73-keV transition which is assigned to the $19/2^+(K=9/2) \rightarrow 17/2^-(K=7/2)$ transition.

A number of interband transitions were seen in Hf^{177} as shown in the decay scheme of Fig. 1. Only transitions from the $K=9/2^+$ band into $K=7/2^-$ band could be found, although a careful search for some $K=7/2^- \rightarrow K=9/2^+$ transitions was made. The maximum possible intensities for these lines and for a number of other unobserved transitions in Hf^{177} are given in Table IV.

The Hf^{177} $K=7/2^-$ band is excited from a state at 1315.2 keV by a transition of 55.15 keV. This, again, was reaffirmed from feeding and bleeding considerations. The 1315.2-keV state also feeds the $19/2^+$ level of the $K=9/2$ band by a 228.48-keV transition. This follows from the energy combination. Internal conversion electron intensities revealed that the 55.15- and the 228.48-keV transitions are $E1$ and $E2$, respectively, fixing the spin and parity of the 1315.2-keV state to be $23/2^+$. This state is presumably a three-particle state and is reached by β decay from Lu^{177*} through a first forbidden transition.

It is unlikely that the $21/2^+(K=9/2)$ state is excited directly via β decay from Lu^{177*}. The large change in the intrinsic configuration would presumably make this β decay very unfavorable. The weakly suggested line at 36.52 keV (Table III) might possibly be due to an intrinsic state with large K value as tentatively indicated in the decay scheme of Fig. 1. Owing to the low intensity of this gamma line and to the circumstance that conversion electrons below 30 keV were not detectable in the β spectrometer such a tentative assignment cannot be substantiated. A number of regions specified by energy combinations with 36.52 keV were examined but no other gamma rays were observed which might tie down the location of a level from which this transition might originate. If the suggested 1337.6-keV state were a $K=21/2^+$ three-particle state one would expect an interaction with the close lying $21/2^+(K=9/2)$ state whose undisturbed energy is predicted to be 1330 keV. This interaction may be responsible for the observed 29-keV downward shift of the $21/2^+(K=9/2)$ level.

No assignments of the weak lines at 90.19 keV and at 106.16 keV were made. Therefore, they are not shown in Fig. 1.

For the balance of the total intensity populating and depopulating each state, conversion coefficients were used from the tables of Rose.[8] The mixing ratios of all the rotational cascade transitions were derived from the crossover-to-cascade ratio (see Table VI) as explained below. To get the mixing ratio of the ground-state transitions, an average value of $[(g_K-g_R)/Q_0]^2$ was taken for each band.

DISCUSSION

The Rotational Energy Spectra

The energy levels of the $K=7/2^+$ Lu^{177} band can be analyzed with the formula

$$E(I)=AI(I+1)+BI^2(I+1)^2.$$

In Fig. 3, $[E(I)-E(I-1)]/2I$ is plotted as a function of $2I^2$ resulting in a rather remarkable fit to a straight line with $A=13.77$ keV and $B=-0.00658$ keV. The $Lu^{177}K=7/2^+$ band, therefore, can be described with high accuracy with only 2 parameters from spin 7/2 up to spin 17/2.

Similar analysis for the Hf^{177} $K=7/2^-$ and $K=9/2^+$ bands are illustrated in Figs. 4 and 5. In the Hf^{177} $K=7/2^-$ case, the points due to spin $19/2^-$ and $21/2^-$ are in parenthesis due to the fact that the $19/2^-$ level has not been observed. This level is estimated to lie

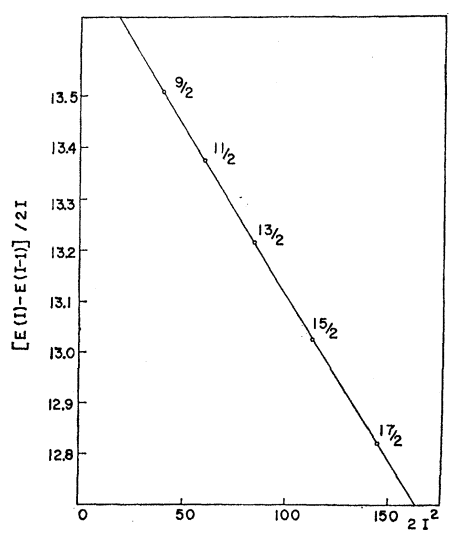

FIG. 3. Rotational energy spacings in the $K=7/2^+$ band in Lu^{177}.

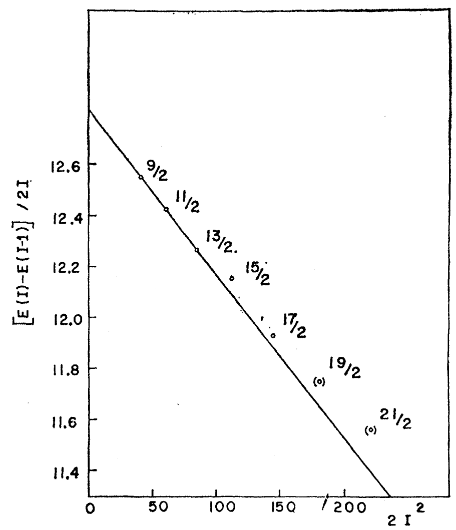

FIG. 4. Rotational energy spacings in the $K=7/2^-$ band in Hf^{177}.

about 223 keV above the $17/2^-$ level. The experimental point 21/2 in Fig. 4 is obtained based on this estimate for the 19/2 state. The rotational parameters A and B have been derived from energy values of the first three excited states of the $K=7/2^-$ and $K=9/2^+$ bands. They are contained in Table V. Both Hf^{177} bands show considerable deviations from the predictions of the 2-parameter description. The energies of the $17/2^+$ and $19/2^+$ states in the $K=9/2$ band are both too low by about 6.8 keV. The $21/2^+$ state deviates by as much as 29 keV from the 2-parameter prediction. A possible explanation for this large downward shift as being due to an interaction with a close lying $21/2^+$ intrinsic state has been mentioned above.

The 115.83-keV Isomeric Transition

The transition populating the Lu^{177} $K=7/2^+$ band has been classified as $E3$ from internal conversion data. We have measured the intensities of the gamma rays leading in and out of the 853.8-keV level in Lu^{177} and conclude that the total internal conversion coefficient of the 115.8-keV transition is 24 ± 3. The theoretical value[8] for an $E3$ transition is $\alpha_{tot}\simeq 40$.

An independent determination of this conversion coefficient has been made from the relative conversion electron intensities. Using the β spectrometer we have compared the LII and $LIII$ conversion peaks of the

TABLE V. Rotational parameters A and B for the bands in Lu and Hf. Only the three lowest excited states were employed in the analysis.

K	A (keV)	B (keV)
Lu^{177} $7/2^+$	13.77	-0.00658
Hf^{177} $7/2^-$	12.81	-0.0060
Hf^{177} $9/2^+$	8.82	$+0.0127$

[8] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, Holland, 1958).

115.8-keV line with the K peak of the 204.0 line. Assuming $\alpha_K(204)=0.46$ from the known $M1/E2$ branching ratio, we find $\alpha_{LII}\simeq\alpha_{LIII}=5.9\pm1.5$, leading to $\alpha_{LIII\ \mathrm{exp}}/\alpha_{LIII\ \mathrm{th}}=0.62$. From the established branchings the $E3$-decay rate is found $T(E3)/T(E3)_W=2\times10^{-9}$, where $T(E3)_W$ is the Weisskopf estimate.

Branching Ratios within Bands and g Factors

A comparison of the crossover-to-cascade branching ratios in a rotational band, $\lambda=T_\gamma(E2)/[T_{\gamma'}(E2)+T_{\gamma'}(M1)]$ where γ and γ' denote the crossover $I\rightarrow I-2$ and cascade $I\rightarrow I-1$ transitions, respectively, provides information on the g factors in a rotational band. According to the rotational model the quantity g_K-g_R is a constant for all the rotational states in an unperturbed band. The magnetic dipole transition rate, $T(M1)$, therefore, should have a well determined value for all transitions depending only on the energy of γ', the spin-coupling coefficients and the constant g_K-g_R. For the analysis we have used

$$\lambda=\left(\frac{E_\gamma}{E_{\gamma'}}\right)^5\frac{[(2I+2)(2I-2+2K)(2I-2-2K)]/(2K)^2(2I-1)4}{1+[(g_K-g_R)/Q_0]^2 2.87\times10^5(2I+2)(2I-2)E_{\gamma'}^{-2}},$$

where Q_0 is the intrinsic quadrupole moment. $E_{\gamma'}$ is given in keV. The quantity $[(g_K-g_R)/Q_0]^2$ and the branching ratio

$$T_{\gamma'}(M1)/T_{\gamma'}(E2)=1/\delta^2=[(g_K-g_R)/Q_0]^2\times2.87\times10^5(2I+2)(2I-2)E_{\gamma'}^{-2}$$

have been calculated and are listed in Table VI for the transitions within the $K=7/2^+$ band of Lu^{177} and the $K=7/2^-$ and $9/2^+$ bands of Hf^{177}. The value of $[(g_K-g_R)/Q_0]^2$ is also given in Fig. 6 for the transitions between different states within each band. It can be seen that for each band this quantity is constant within the limit of error.

Taking an average value of $[(g_K-g_R)/Q_0]^2$ for the Lu^{177} $K=7/2$ band and using $Q_0=7.45$ from Coulomb excitation[9] of the analogous state in the Lu^{175} nucleus, we find $|g_K-g_R|=0.375\pm0.025$. This can be compared to the value of the corresponding state in Lu^{175}, $g_K-g_R=0.344\pm0.010$ quoted by deBoer and Rogers[10] and derived from Coulomb excitation and lifetime measurements. The Hf^{177} $K=7/2^-$ band has an exceptionally small magnetic transition rate.[10] Using $Q_0=6.74$[11] we find $|g_K-g_R|\leq0.03$. Finally, for the $K=9/2^+$ band in Hf^{177} we find an average value from our experiment of $|g_K-g_R|=0.370\pm0.012$. In deriving this result we have employed the Coulomb excitation value[11] for Q_0 of the analogous state in Hf^{179} $(K=9/2)$. A comparison of g_K-g_R for $K=9/2$ can be made between Hf^{177} and Hf^{179}. For the latter nucleus, Bernstein and deBoer[12] find $g_K-g_R=0.376\pm0.025$, while Blaugrund *et al.*[13] find $|g_K-g_R|=0.47\pm0.02$. The present value for Hf^{177} seems to agree well with Ref. 12. A change in the value of g_R of a few percent due to the addition of 2 neutrons might be expected when Hf^{177} and Hf^{179} as well as Lu^{175} and Lu^{177} are compared.

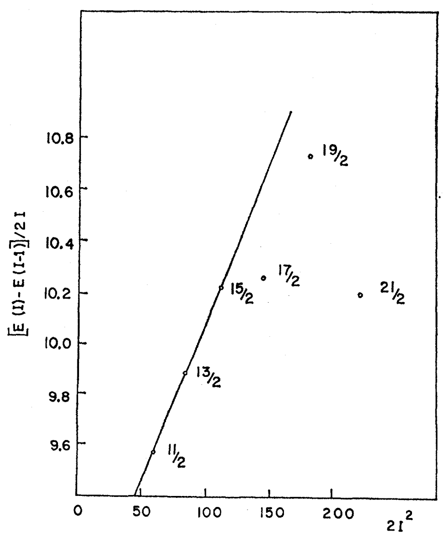

FIG. 5. Rotational energy spacings in the $K=9/2^+$ band in Hf^{177}.

TABLE VI. The g factors and branching ratios for the rotational states in Lu^{177} and Hf^{177}. λ is the experimental ratio between crossover $I\rightarrow I-2$ and cascade $I\rightarrow I-1$ transitions. $1/\delta^2$ is the magnetic dipole-electric quadrupole branching ratio, $M1/E2$, in the transition $I\rightarrow I-1$. g_K-g_R is associated with the transition $I\rightarrow I-1$ and Q_0 is the intrinsic quadrupole moment of the nucleus in the state with spin I.

	I	λ	$(g_K-g_R/Q_0)^2$	$1/\delta^2$
Lu^{177} $K=7/2^+$	11/2	1.19±0.21	1.7±0.5 ×10⁻³	2.6
	13/2	2.10±0.25	2.4±0.35×10⁻³	3.8
	15/2	2.8 ±0.8	3.2±1.0 ×10⁻³	5.6
	17/2	4.7 ±0.8	2.8±0.6 ×10⁻³	4.8
Hf^{177} $K=7/2^-$	11/2	4.5 ±0.3	<0.02 ×10⁻³	<0.035
	13/2	13 ±3	<0.01 ×10⁻³	<0.02
	15/2	>7	<0.07 ×10⁻³	<1.3
Hf^{177} $K=9/2^+$	13/2	0.34±0.04	2.8±0.4 ×10⁻³	8.0
	15/2	0.90±0.07	2.5±0.2 ×10⁻³	6.8
	17/2	1.35±0.16	3.0±0.4 ×10⁻³	8.1
	19/2	1.72±0.23	3.5±0.5 ×10⁻³	8.6
	21/2	2.33±0.35	4.1±0.6 ×10⁻³	11.0

[9] B. Elbek, M. C. Olesen, and O. Skilbreid, Nucl. Phys. **10**, 294 (1959).

[10] J. deBoer and J. D. Rogers, Phys. Letters **3**, 304 (1963).

[11] O. Hansen, M. C. Olesen, O. Skilbreid, and B. Elbek, Nucl. Phys. **25**, 634 (1961).

[12] E. M. Bernstein and J. deBoer, Nucl. Phys. **18**, 40 (1960).

[13] A. E. Blaugrund, Y. Dar, and G. Goldring, Phys. Rev. **120**, 1328 (1960).

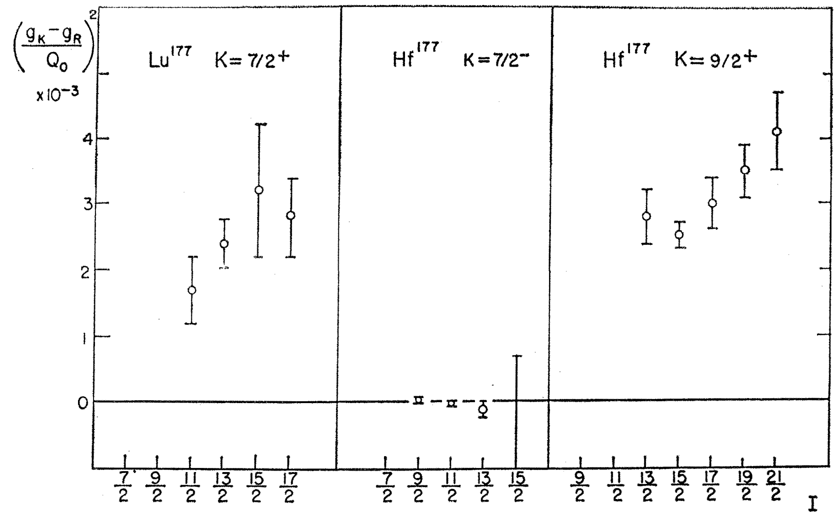

FIG. 6. Magnetic properties of three rotational bands in Lu^{177} and Hf^{177}. The quantities $[(g_K - g_R)/Q_0]^2$ were derived from crossover-to-cascade branching ratios. The 9/2 value in Hf^{177} was obtained from the known δ^2 and is included for comparison.

Electric Dipole Transitions

A number of $E1$ transitions have been observed leading from the $K=9/2^+$ band into the $K=7/2^-$ band in Hf^{177}.

The relative reduced transition strengths from a state I_i in the $K=9/2$ band into states I_f and $I_{f'}$ of the $K=7/2$ band are listed in Table VII. The $E1$ transition rates normalized on computed rotational $E2$ and $M1$ rates are given in Table VIII in units of single-particle $E1$ transition rates. The hindrance can be seen from this table to be between 10^4 and 10^5 except for the 321-keV transition, where it is even larger. These $E1$ transitions are classified according to the Nilsson model to be K forbidden. Their branching ratios as summarized in Table VII are thus not expected to follow the predictions from the spin coupling coefficients.

TABLE VII. Relative El reduced transition strengths from $K=9/2$ to $K=7/2$ states in Hf^{177} deduced from the experiment.

I_i	I_f	$I_{f'}$	$\frac{B(El)K_i=9/2, I_i \rightarrow K_f=7/2, I_f}{B(El)K_i=9/2, I_i \rightarrow K_f=7/2, I_f'}$
9/2	9/2	7/2	175
9/2	11/2	9/2	0.37
11/2	11/2	9/2	15.8
13/2	13/2	11/2	7.7
15/2	15/2	13/2	20

TABLE VIII. $E1$ rates for $K=9/2$ to $K=7/2$ transitions in Hf^{177}.

$K=9/2$ I_i	$K=7/2$ I_f	E_γ(keV)	$T(E1)/T(E1)_W$ [a]
9/2	7/2	321.4	0.013×10^{-5} [b]
9/2	9/2	208.4	3×10^{-5} [b]
9/2	11/2	71.6	1.2×10^{-5} [b]
11/2	9/2	313.5	0.5×10^{-5} [c]
11/2	11/2	177.0	7×10^{-5} [c]
13/2	11/2	306.0	0.9×10^{-5} [d]
13/2	13/2	145.6	7×10^{-5} [d]
15/2	13/2	299.1	0.6×10^{-5} [e]
15/2	15/2	117.0	12×10^{-5} [e]
19/2	17/2	291.7	3×10^{-5} [f,g]

[a] $T(E1)_W$ is the "Weisskopf estimate" $T(E1)=1.5\times10^5 A^{2/3} E_\gamma^3$, in keV and sec.
[b] Based on measured half-life $\tau_{1/2}=6.3\times10^{-10}$ sec of the 321-keV state and branching ratios of Table VI.
[c] Based on the rotational transition rate for the 105.4-keV transition taking $[(g_K-g_R)/Q_0]^2=0.003$ from Fig. 6 and $Q_0(K=9/2)=6.85$ barns (see Ref. 9).
[d] Based on the rotational electric quadrupole transition rate $T(E2)$ of the 233.75-keV transition from the 13/2 state assuming $Q_0=6.85$ barns as above.
[e] Based on $T(E2)$ of the 281.77-keV transition as in footnote d.
[f] Based on $T(E2)$ of the 378.4-keV transition as in footnote d.
[g] Assuming 291.7-keV transition leads from $17/2 \rightarrow 15/2$ (see remark in Table IV), this value would be 4.

ACKNOWLEDGMENTS

The authors are indebted to O. B. Nielsen for communicating to them some of his results prior to publication, and to J. deBoer, J. D. Rogers, B. Stech, and S. Wahlborn for illuminating discussions. The help of R. Hager and L. Varnell with the gamma spectrometer is greatly appreciated.