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Decay of the Five-Quasiparticle Isomeric States in ^{177}Hf†

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The decay of 51.4-min ^{177m_2}Hf has been studied in detail by means of Ge(Li) detectors and a Si(Li) detector. The L-subshell conversion-electron ratios for the 214.0-keV isomeric transition were measured with a double-focusing β-ray spectrometer. An $E3$ multipolarity was deduced for the isomeric transition, and thus a spin-parity of $I^\pi=\frac{37}{2}^-$ was established for the isomeric state. Coincidence measurements identify the $K^\pi=\frac{23}{2}^+$ rotational band up to the $I=\frac{31}{2}$ member. The rotational-model quantity $(g_K-g_R)^2/Q_0^2$, derived from the γ-ray intensities of the cascade and crossover transitions, was used to deduce the gyromagnetic ratios for this band.

I. INTRODUCTION

In a recent article,[1] a new high-spin isomer ^{177m_2}Hf ($t_{1/2}=51.6$ min) was reported. The main features of its decay were deduced from γ-ray intensity measurements. This new high-spin isomer was interpreted as being a $K^\pi=\frac{37}{2}^-$ five-quasiparticle state with a possible Nilsson configuration of $\frac{7}{2}^+[404]_p$, $\frac{9}{2}^-[514]_p$, $\frac{7}{2}^-[514]_n$, $\frac{9}{2}^+[624]_n$, $\frac{5}{2}^-[512]_n$.

In this paper we report a more detailed study employing high-resolution γ-ray spectroscopy, Ge(Li)-Ge(Li) γ-γ coincidences, and conversion-electron measurements. These results confirm the previously deduced decay scheme of Ref. 1 establishing the $K^\pi=\frac{23}{2}^+$ rotational band up to the $I=\frac{31}{2}$ member and the spin-parity of the isomeric state. Evidence is also presented which suggests that the $K^\pi=\frac{37}{2}^-$ isomeric state may be populating a second three-quasiparticle band in ^{177}Hf.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

Sources of ^{177m_2}Hf were produced by irradiation of isotopically enriched $^{176}Yb_2O_3$ (96%) with 46-MeV α particles. The cross section of the ^{176}Yb-$(\alpha,3n)^{177m_2}$Hf reaction at this energy was estimated to be ≈1.5 mb. Typically, sources of 10–20 μCi of ^{177m_2}Hf were produced for each experiment. After radiochemical separation the only observed contaminant was 23.6-h ^{173}Hf, produced from other ytterbium isotopes.

The hafnium was separated carrier free from the irradiated targets in the following manner. The target was dissolved in hot 3 N HNO_3. Hafnium was extracted for 5 min into a few milliliters of 0.5 M TTA in xylene. The organic phase was scrubbed 3 times with 3 N HNO_3 and was then gently evaporated to dryness in a platinum crucible.

The organic portion was removed by heating it several times with 13 N HF. The hafnium activity was then taken up in a few drops of the HF solution, evaporated onto either a nickel or platinum backing, and flamed to red heat. The measured cross section and the observed activity of these sources indicated that the bulk (≈60%) of the radiohafnium was reclaimed by this method. The time required for the chemical separation was about 30 min.

Sources of hafnium used for mass separation were first radiochemically separated. 5 mg of hafnium carrier was added for the TTA-xylene extraction. The hafnium fraction was then back extracted from the organic phase with 0.5 N HNO_3–0.5 N HF solution, the fluoride ions complexed with boric acid, and the hydroxide of hafnium precipitated with concentrated NH_4OH. The hydroxide precipitate was dissolved in 3 N HNO_3 and hafnium tetramandelate precipitated with mandelic acid. Hafnium was then converted to oxide by heating at 800°C in a muffle furnace. The hafnium oxide was introduced into the ion source of the Brookhaven electromagnetic isotope separator and converted to the volatile chlorides by passing a controlled stream of carbon tetrachloride over the heated sample. The hafnium chlorides were subsequently ionized, accelerated, and mass analyzed. The collected ^{177}Hf sample was used for γ-ray measurements.

γ-ray spectra were obtained with a 39-cm^3 Ge(Li) detector which has a resolution of 0.95 keV at 122 keV and 1.86 keV at 1332 keV. Figure 1 shows a γ-ray spectrum of a typical hafnium source. Analysis of the γ-ray spectra were performed by means of a modified version of the BRUTAL[2] computer code. The CLSQ[3] program was used for γ-ray decay curve resolutions. The energy and efficiency calibrations were determined with International Atomic Energy Agency standard sources. Internal energy calibrations were performed by using several of the γ-ray lines of ^{177m_1}Hf which are known[4–8] to within ±0.1 keV. All of the γ-rays in Fig. 1 have been assigned to ^{177m_2}Hf with 1.1-sec ^{177m_1}Hf in equilibrium, except for those labeled ^{173}Hf. Identical lines observed in the decay of the mass separated source confirmed the assignments of these γ-rays to ^{177}Hf. Table I lists the γ-ray energies and relative intensities of ^{177m_2}Hf with ^{177m_1}Hf in equilibrium. The measured half-lives of the more intense γ-rays ($I_\gamma > 40$) averaged 51.4 ± 0.5 min.

In Table II are listed the γ-ray energies and relative intensities assigned to the decay of ^{177m_2}Hf. The 214.0-, 295.1-, and 326.7-keV γ rays of ^{177m_2}Hf were observed as unresolved doublets with the 214.4-, 296.5-, and 327.7-keV γ-rays of 1.1-sec ^{177m_1}Hf in equilibrium. The γ decay of 1.1-sec ^{177m_1}Hf has been studied previously[4–6] from the β^- decay of 161-day ^{177m}Lu. However, Bernthal and Rasmussen[7] observed a 10% increase in the relative intensities over the values previously reported[4,5] though they have not reported all the values. We therefore found it necessary to produce sources of ^{177m}Lu for measurement of the relative γ-ray intensities of ^{177m_1}Hf following the β^- decay of ^{177m}Lu. A table of the γ-ray energies and relative intensities of ^{177m}Lu measured in this work is given in the Appendix. These values are in good agreement with those of Bernthal and Rasmussen.[7,8] Contributions from 1.1-sec ^{177m_1}Hf in the γ-ray multiplets of the ^{177m_2}Hf sources were resolved by use of the values included in the Appendix.

Ge(Li)-Ge(Li) γ-γ coincidences were measured for the 214.0-, 254.8-, 277.3-, 295.1-, 311.5-, 326.7-, 572.4-, 606.5-, and 638.2-keV γ-rays. Table III lists the results of these measurements. Accidental coincidences were typically 3–5% of the true coincidence counting rate. Figure 2 shows the coincidence spectrum for the 214.0-217.0-keV gated region. (The gate was set on the high-energy side of the 214.0-214.4-keV doublet in order to minimize contributions from the strong 208.4-keV γ ray.) The enhancements of the 277.3-, 295.1-, 311.5-, 326.7-, 572.4-, 606.5-, and 638.2-keV γ rays clearly indicate they are in coincidence with the 214.0-keV isomeric transition. This, together with the additional coincidence information in Table III, supports the decay scheme shown in Fig. 3.

The 120.5- and 254.8-keV γ rays were not observed in coincidence with the 214.0-keV isomeric transition, although there is weak evidence that they are in coincidence with the 277 ± 4- and 327 ± 5-keV gated regions. In the gated region (255 ± 4 keV), the 120.5-keV γ ray was strongly enhanced and is therefore definitely in coincidence with the 254.8-keV transition. As to the other γ rays in this gated spectrum (including the 277.3- and 325.7-keV transitions), they are presumably due to the presence of the Compton distributions of higher-energy γ rays in the gate, and cannot be definitely attributed to coincidences with the 254.8-keV transition. The assignments, therefore, of the 120.5- and 254.8-keV γ rays in coincidence with the 277 ± 4- and 327 ± 5-keV gated regions are listed as questionable in Table III.

Conversion-electron measurements were performed with the Brookhaven double-focusing β-ray spectrometer and a Si(Li) detector of 2-mm depth. The β-ray spectrometer was only employed to measure the L-conversion-electron lines of the 214.0-keV isomeric transition. The spectrome-

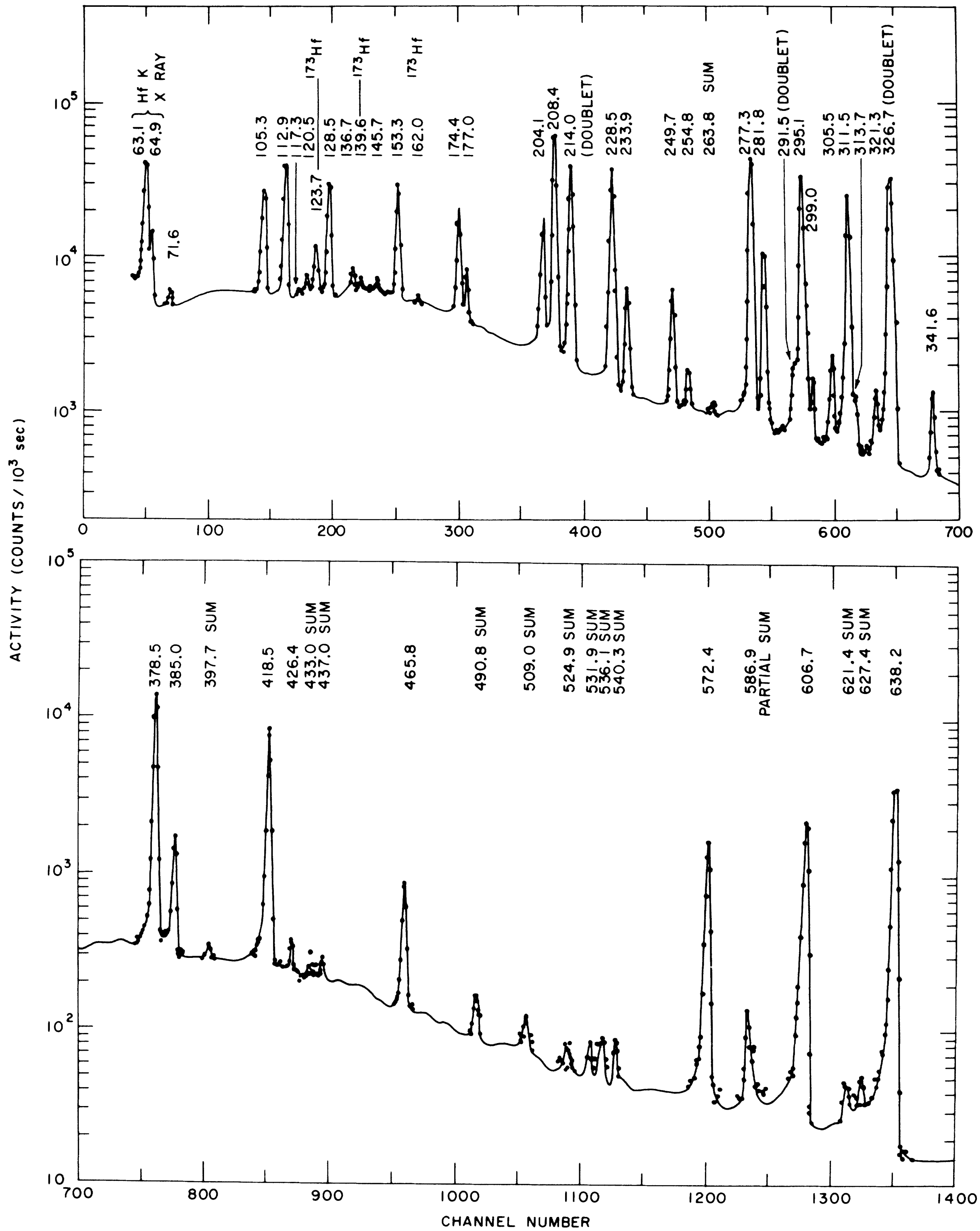

FIG. 1. Typical singles Ge(Li) γ-ray spectrum of radiochemically separated ^{177m2}Hf. All of the γ rays were assigned to ^{177m2}Hf except those labeled ^{173}Hf.

TABLE I. γ-ray energies and intensities of ^{177m2}Hf and ^{177m1}Hf in equilibrium.

E_γ (keV) [a]	I_γ (Relative) [b]	E_γ (keV) [a]	I_γ (Relative) [b]
71.7	6.7 ± 0.7	291.4 } 292.5 }	16.2 ± 1.9 [c]
105.3	≡100.0		
113.0	176.8 ± 12.7	295.1 } 296.5 }	499.1 ± 38.4 [c]
117.2	1.4 ± 0.2		
120.5	6.3 ± 1.0	299.0	14.9 ± 1.3
128.5	130.4 ± 10.0	305.5	15.1 ± 1.8
136.7	12.4 ± 3.4	311.5	386.8 ± 26.7
145.8	8.6 ± 0.8	313.7	9.6 ± 0.9
153.3	145.4 ± 11.2	321.3	16.0 ± 1.5
174.4	109.3 ± 8.3	326.7 } 327.7 }	576.5 ± 43.8 [c]
177.0	30.2 ± 2.4		
204.1	129.1 ± 9.9	341.6	17.8 ± 1.8
208.4	525.8 ± 40.5	378.5	239.8 ± 18.5
214.0 } 214.4 }	323.6 ± 24.9 [c]	385.1	26.3 ± 2.6
		418.5	167.8 ± 13.1
228.5	318.1 ± 23.9	426.5	3.9 ± 0.5
233.9	47.1 ± 3.7	465.8	18.3 ± 1.6
249.7	53.2 ± 4.2	572.4	47.0 ± 3.8
254.8	8.8 ± 0.8	586.9	≤3.6 ± 0.5 [d]
277.3	499.0 ± 39.0	606.5	75.9 ± 5.9
281.8 } 283.4 }	124.8 ± 9.9 [c]	638.2	133.2 ± 10.3

[a] Error in the γ-ray energy is ±0.1 keV.
[b] Normalized to I_γ(105.3 keV) ≡ 100.0 units.
[c] Doublet γ-ray intensities.
[d] Some contribution of summing in intensity.

ter was operated at a momentum resolution of 0.2% and 1- or 2-min counts were taken starting at the lowest momentum setting. Figure 4 shows the results of the measurement. Each point has been corrected for decay and background. In addition to ≈7-counts/min background of the spectrometer a source background of ≈200 counts/min was also observed. This source background was attributed to the tails of the 277.3-keV K and 214.0-keV M lines. The uncertainties of $L_{\rm I}$, $L_{\rm II}$, and $L_{\rm III}$ intensities were ±10, ±5, and ±5%, respectively. The L-subshell ratios of $L_{\rm I}/L_{\rm II}/L_{\rm III}$ =0.139/1/0.52 measured in the present work were within experimental error of the theoretical values[9] $L_{\rm I}/L_{\rm II}/L_{\rm III}$ =0.127/1/0.56 for a pure $E3$ transition. (A limit of <0.2% $M4$ admixture in the 214.0-keV transition was deduced.)

Figure 5 shows the conversion-electron spectrum of ^{177m2}Hf measured with a Si(Li) detector. The detector had an energy resolution of 5 keV full width at half maximum. Table IV summarizes the results of the measurement. The conversion-electron intensities have been normalized to the intensity of the 214.0-keV L conversion-electron line. The γ-ray intensities (column 2) were taken from Table II, and the theoretical conversion coefficients (column 5) were obtained from the tables of Hager and Seltzer.[9] The 212-keV electron line was observed as an unresolved multiplet of the 214.0-keV M and N lines and the 277.3-keV K line. The intensity of the 277.3-keV K line was determined by subtracting from the total line intensity the contributions of the 214.0-keV M and N lines. These contributions had been estimated from the 214.0-keV L-lines intensity and the theoretical $L/(M+N)$ ratio. $E2$ admixtures of 6–8% in the $M1$ cascade ($I \to I-1$) transitions (277.3, 295.1, 311.5, and 326.7 keV) were derived from the crossover/cascade γ-ray intensity ratios. However, owing to the large uncertainty of the K and L conversion-electron intensities, a precise measurement of the admixtures could not be made. The K/L ratios for the crossover ($I \to I-2$) transitions (572.4, 606.6, and 638.2 keV) are consistent with $E2$ multipolarity assignments.

TABLE II. γ-ray energies and intensities of ^{177m2}Hf.

E_γ (keV)	Relative γ-ray intensity [a]	Multipolarity	Total conversion coefficient (α) [b]	Relative transition intensity [c]
120.5	1.3 ± 0.3			
214.0	54.0 ± 3.5	$E3$	1.546	104.1 ± 10.0
254.8	1.8 ± 0.2			
277.3	≡100.0	$M1$ + ~8% $E2$	0.226	92.8
295.1	91.6 ± 7.5	$M1$ + 7.4% $E2$	0.191	82.6 ± 7.9
311.5	77.5 ± 6.5	$M1$ + 6.7% $E2$	0.166	68.4 ± 6.5
326.7	90.6 ± 7.8	$M1$ + 6.4% $E2$	0.146	78.6 ± 7.9
572.4	9.4 ± 0.7	$E2$	0.013	7.2
606.5	15.2 ± 1.2	$E2$	0.011	11.6 ± 1.1
638.2	26.7 ± 2.0	$E2$	0.010	20.4 ± 2.0

[a] Normalized to I_γ (277.3 keV) ≡ 100.0 units.
[b] Taken from Ref. 9.
[c] Normalized to T_γ (277.3 keV) + T_γ (572.4 keV) = 100.0 units.

TABLE III. γ-γ coincidence results of ^{177m_2}Hf. × indicates observed coincidence, ? indicates doubtful coincidence.

Coin. \ Gate	214	255	277	295	311	326	572	606	638
120.5		×	× ?			× ?			
214.0			×	×	×	×	×	×	×
254.8			× ?			× ?			
277.3	×			×	×	×		×	×
295.1	×		×		×	×			×
311.5	×		×	×		×	×		
326.7	×		×	×	×		×	×	
572.4	×				×	×			
606.5	×		×			×			
638.2	×		×	×			×		

III. DISCUSSION

$K^\pi = \frac{23}{2}^+$ Rotational Band

The energy and spin-parity of the 1.1-sec $K^\pi = \frac{23}{2}^+$ isomeric state of ^{177}Hf have been well established[4-8] from the β decay of 161-day ^{177m}Lu ($K^\pi = \frac{23}{2}^-$). This isomeric state has been assigned[6] a Nilsson configuration of $\frac{7}{2}^+[404]_p$, $\frac{9}{2}^-[514]_p$, $\frac{7}{2}^-[514]_n$. From the decay of the 51.4-min isomeric state of ^{177}Hf, the rotational members up to $I = \frac{31}{2}$ were established[1] within the $K^\pi = \frac{23}{2}^+$ band (see Fig. 3). Substitution of the three lowest energy levels (E_I) of the $K^\pi = \frac{23}{2}^+$ band into the formula

$$E_I = E_0 + AI(I+1) + BI^2(I+1)^2 \qquad (1)$$

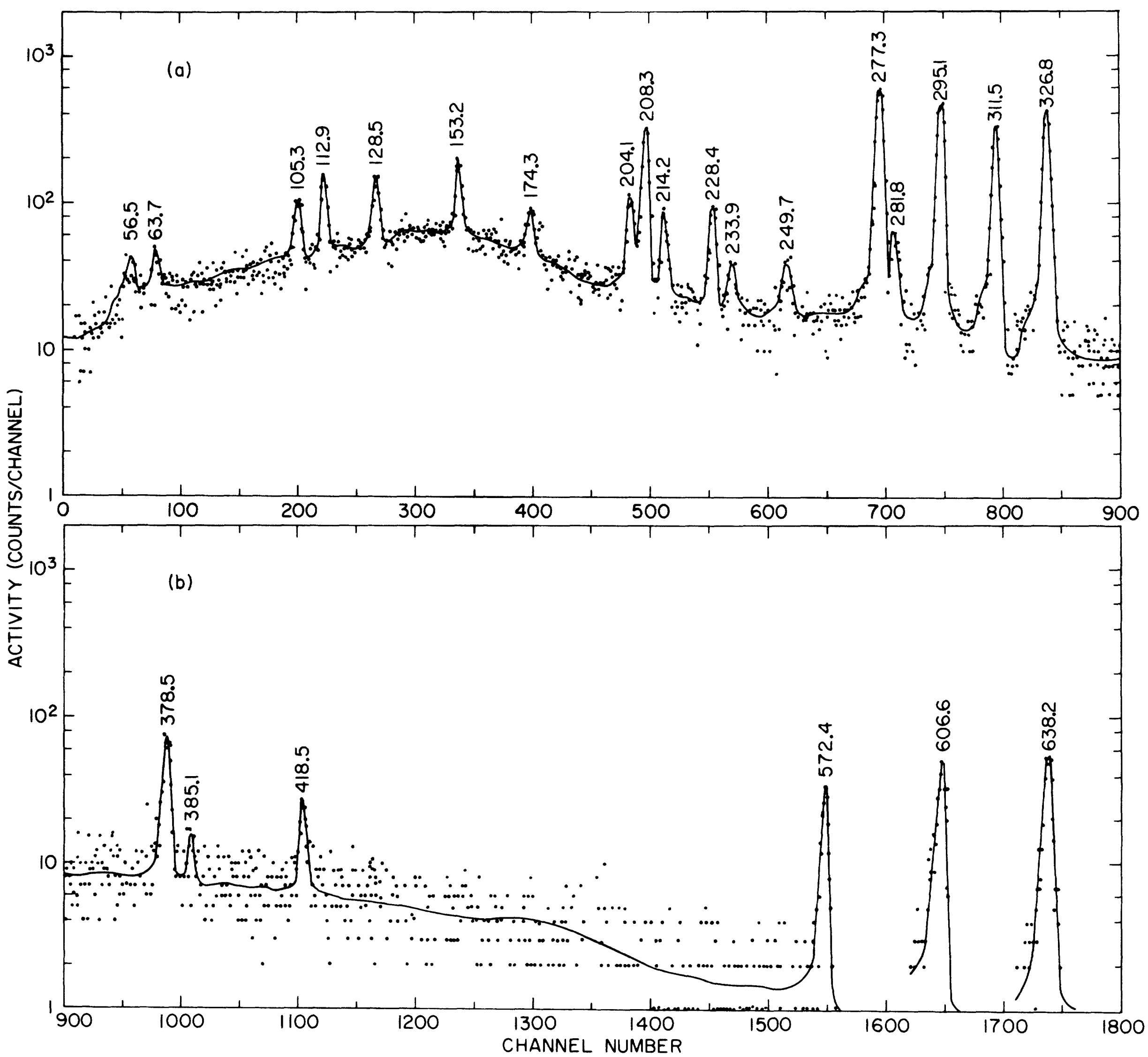

FIG. 2. Ge(Li)-Ge(Li) γ-γ coincidence spectrum gated on the 214.0-217.0-keV γ-ray region.

gave values of $A = 12.07$ keV and $B = -3.12$ eV. Energies of the remaining two band members calculated from these parameters agreed to within ±1.6 keV with the experimental values. The parameters determined for the $\frac{7}{2}^-[514]_n$ ground-state band were $A = 12.83$ keV and $B = -6.87$ eV. It is remarkable that the parameters for these two bands are so similar.

Assuming the Alaga[10] rules are valid for the $E2$ components of the cascade and crossover transitions within the $K^\pi = \frac{23}{2}^+$ band, one can calculate the $E2/M1$ mixing ratios (δ^2) of the cascade transitions and the gyromagnetic factors, g_K and g_R, within the framework of the rotational model. The $E2/M1$ mixing ratio (δ^2) can be derived from the following formula

$$1/\delta^2 = \left(\frac{E_\gamma}{E_{\gamma'}}\right)^5 \frac{[(2I+1)(I-2+K)(I-1-K)]}{(2K)^2(2I-1)\lambda} - 1\,, \qquad (2)$$

where λ is the experimental crossover/cascade ratio with γ and γ' denoting the crossover ($I \to I-2$) and cascade ($I \to I-1$) transitions, respectively. The rotational-model quantity $(g_K - g_R)^2/Q_0^2$ can then be obtained from the following formula:

$$\frac{1}{\delta^2} = \frac{2.87\times 10^5 (2I+2)(2I-2)}{E_{\gamma'}^2}\,\frac{(g_K - g_R)^2}{Q_0^2}\,, \qquad (3)$$

where $E_{\gamma'}$ is in keV. In Table V are listed the experimental crossover/cascade ratios (λ), the $E2/M1$ mixing ratios (δ^2), and the quantity $(g_K - g_R)^2/Q_0^2$ for the three cascade transitions within the $K^\pi = \frac{23}{2}^+$ band. The values of $(g_K - g_R)^2/Q_0^2$ are constant within the experimental error with an averaged value of $(5.52 \pm 0.61)\times 10^{-3}$. Inserting the value[11] $Q_0 = 6.74$ b determined for the ground state, one obtains $g_K - g_R = 0.50 \pm 0.03$.

Assuming the contributions of the three particles of the $K^\pi = \frac{23}{2}^+$ state are additive, one obtains

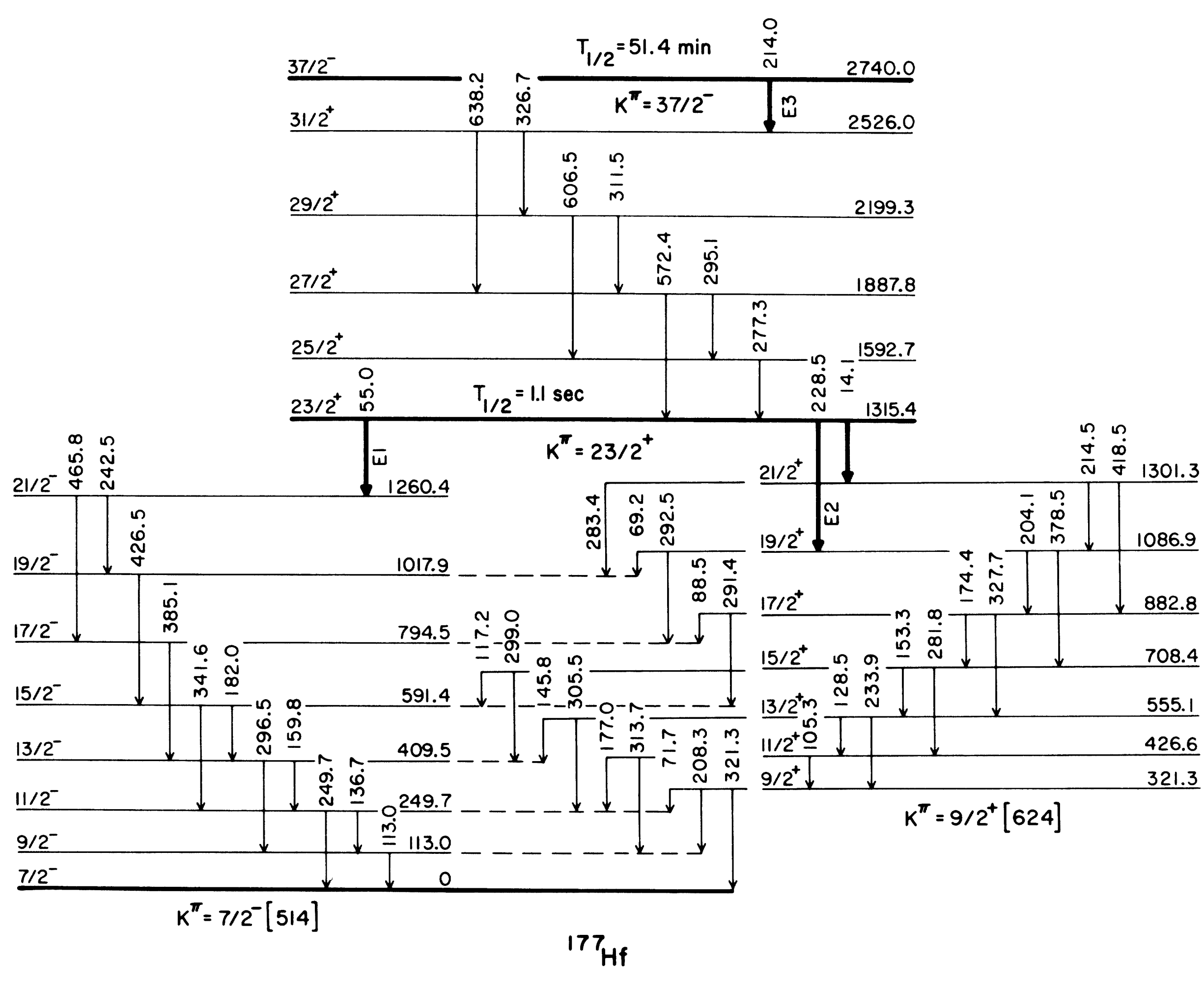

FIG. 3. Proposed decay scheme of 51.4-min ^{177m_2}Hf ($K^\pi = \frac{37}{2}^-$). The decay of 1.1-sec ^{177m_1}Hf ($K^\pi = \frac{23}{2}^+$) was previously (Refs. 4–8) well established.

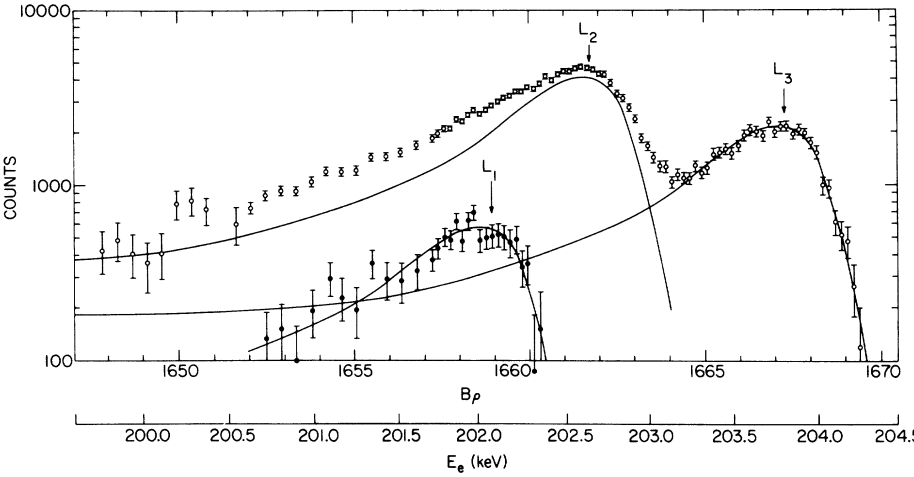

FIG. 4. L-conversion-electron spectrum of the 214.0-keV isomeric transition of ^{177m_2}Hf. The spectrum was obtained with a double-focusing β-ray spectrometer.

for the intrinsic g factor the expression

$$g_K = \frac{1}{K}(\Omega_1 g_{\Omega 1} + \Omega_2 g_{\Omega 2} + \Omega_3 g_{\Omega 3}) , \qquad (4)$$

where Ωg_Ω for the individual particles are given[12, 13] by

$$\Omega g_\Omega = \Omega g_l + (g_s - g_l)\langle S_z\rangle . \qquad (5)$$

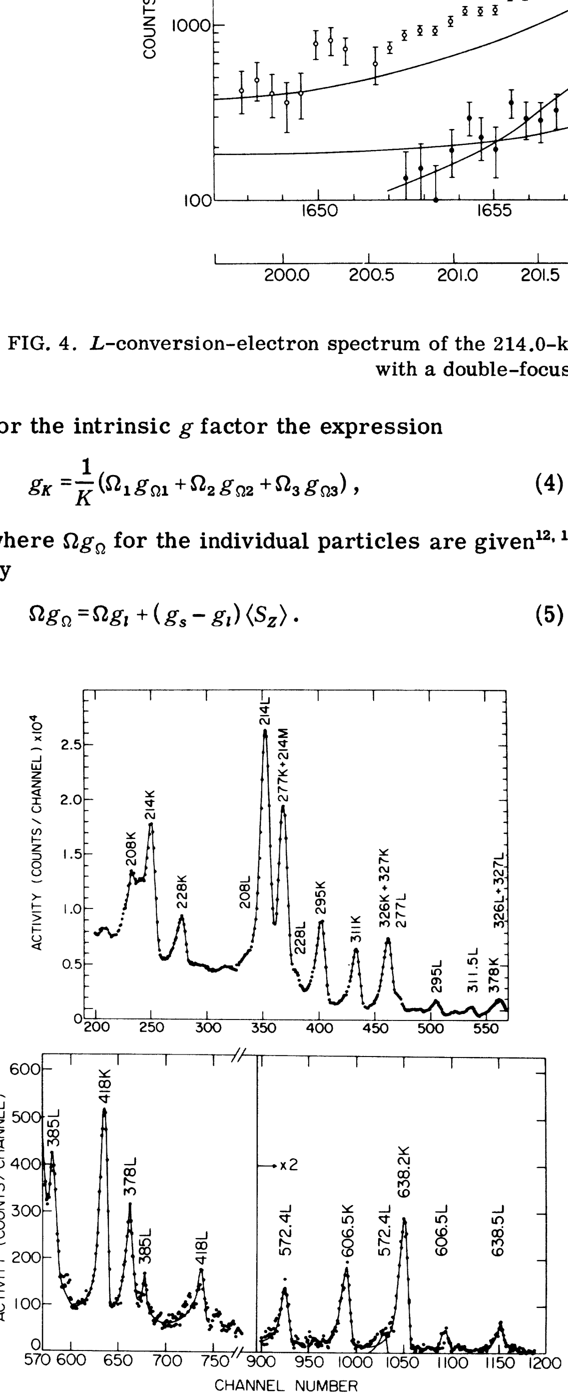

FIG. 5. Conversion-electron spectrum of ^{177m_2}Hf taken with a 2-mm-depth Si(Li) detector which had a resolution of 5 keV full width at half maximum.

The calculated g_K value is relatively insensitive to the assumed g_s factor and the deformation. We have used a value of $g_s^{\rm eff} = (0.512 \pm 0.032) g_s^{\rm free}$ (where $g_s^{\rm free}$ is 5.585 for protons and −3.826 for neutrons) which was experimentally derived[14] for the $\frac{7}{2}^-[514]_n$ ^{177}Hf ground state. The expectation values of the z component of the spin ($\langle S_z\rangle$) were calculated using Nilsson[12] wave functions with a deformation[15] of $\eta = 4.88$. The calculated values of $\langle S_z\rangle$ were −0.374, −0.455, and 0.451 for the $\frac{7}{2}^-[514]_n$, $\frac{9}{2}^-[514]_p$, and $\frac{7}{2}^+[404]_p$ orbitals, respectively. Using the above values in Eqs. (4) and (5) we calculate $g_K = 0.76$ for the $K^\pi = \frac{23}{2}^+$ state. The collective gyromagnetic factor (g_R) can now be determined using our experimental value of $g_K - g_R = 0.50 \pm 0.03$, yielding $g_R = 0.26 \pm 0.03$. This value of g_R is in agreement with the predicted[15] values, $g_R = 0.24$ and 0.28, and the experimental value[14] for the ^{177}Hf ground state, $g_R = 0.253 \pm 0.013$.

$K^\pi = \frac{37}{2}^-$ Isomeric State

A spin-parity of $\frac{37}{2}^-$ was assigned to the isomeric state based on the data presented above, with the $K^\pi = \frac{23}{2}^+$ rotational band established up to the $I^\pi = \frac{31}{2}^+$ rotational level by an $E3$ transition. A state with $K^\pi = \frac{37}{2}^-$ can only be explained if one assumes it to be a five-quasiparticle state. No combinations of three-quasiparticle Nilsson orbitals are available at this excitation energy that could produce this high spin. The lowest-energy five-quasiparticle state expected in ^{177}Hf is the $K^\pi = \frac{37}{2}^-$ state with a Nilsson configuration of $\frac{7}{2}^+[404]_p$, $\frac{9}{2}^-[514]_p$, $\frac{7}{2}^-[514]_n$, $\frac{9}{2}^+[624]_n$, $\frac{5}{2}^-[512]_n$.

Formation of the high-spin state can be viewed as a coupling of the $\frac{7}{2}^-[514]_n$ ground state of ^{177}Hf with protons from a broken pair in the $\frac{7}{2}^+[404]_p$ and $\frac{9}{2}^-[514]_p$ orbitals and neutrons from a broken pair in the $\frac{5}{2}^-[512]_n$ and $\frac{9}{2}^+[624]_n$ orbitals. The expected energy above the ground state is

$$E(\tfrac{37}{2}^-) \approx 2\Delta_p + 2\Delta_n , \qquad (6)$$

where Δ_p and Δ_n are the proton and neutron pairing energies respectively, obtained from cranking-model calculations.[15] The pairing energies (Δ_p and Δ_n) can be identified with the odd-even mass differences (P_p and P_n). Using the values $\Delta_p = P_p = 780$ keV and $\Delta_n = P_n = 720$ keV given by Prior, Bohem, and Nilsson,[15] one estimates the five-quasiparticle energy at ≈3.0 MeV. A closer approximation can be obtained by using the three-quasiparticle energy of the $K^\pi = \frac{23}{2}^+$ state and the odd-even mass difference for the broken neutron pair,

$$E(\tfrac{37}{2}^-) \approx E(\tfrac{23}{2}^+) + 2\Delta_n , \qquad (7)$$

which yields 2755 keV above the ground state. This is to be compared with the value of $E(\frac{37}{2}^-) = 2740.0$ keV in Fig. 3.

The hindrance factor[16] (H) calculated for the K-forbidden $E3$ isomeric transition is 2.41×10^5, or a factor of 22 for each degree of forbiddenness, $\nu = \Delta K - L = 4$. Such a hindrance factor would be expected for a transition between states with relatively pure K quantum numbers. However, it should be noted that the K-forbiddenness factor ($f \approx 22$) for the 214.0-keV transition is about 3 to 5 times smaller than for other $E3$ K-forbidden transitions in this mass region. For example, $f(E3) \approx 62$ and ≈ 96, respectively, for ^{177m}Lu ($K^\pi = \frac{23}{2}^-$) and ^{179m_2}Hf ($K^\pi = \frac{25}{2}^-$).[17] The decrease in the K-forbidden factor for ^{177m_2}Hf may be an indication that either: (a) The initial state or the final state may be admixed with other five- or three-quasiparticle states, respectively, or (b) due to the similarity of the initial and final state configurations the decay of the two additional neutrons is somewhat more favored over the configurations involved in the decay of ^{177m}Lu and ^{179m_2}Hf.

The 120.5- and 254.8-keV γ-rays were observed to decay with the same half-life of 51.4-min ^{177m_2}Hf but were not observed in coincidence with the 214.0-keV isomeric transition. However, they were found to be in coincidence with each other. One can exclude the possibility that they belong to a weak branch in the decay of the $K^\pi = \frac{23}{2}^+$ isomeric state, since its decay has been well studied[4-7] (see Appendix). One can also exclude the possibility of contamination, since these γ rays were observed in the γ-ray spectrum of mass-separated ^{177m_2}Hf. We believe that these weak transitions indicate that the $K^\pi = \frac{37}{2}^-$ five-quasiparticle state may be populating a second three-quasiparticle band in ^{177}Hf. The 120.5- and 254.8-keV γ-rays have been observed[18] with in-beam spectroscopy through the ^{176}Yb(α, $3n$)^{177}Hf reaction and were found to have lifetimes of 10–20 nsec. Owing to the low intensity of these γ rays we could not establish other members in this decay branch. There are only two other Nilsson orbital configurations available for construction of other three-quasipar-

TABLE IV. Relative conversion-electron intensities of ^{177m_2}Hf.

E_γ (keV)	I_γ [a]	Multipole order	Conversion line	α_{Theory} [b]	$I_\gamma \alpha_{\text{th}}$ [c]	I_{ce}(Exp.) [c]
214.0	54.0 ± 3.5	$E3$	K	4.298×10^{-1}	51.7	52.6 ± 1.7
			L	8.320×10^{-1}	≡ 100.0	≡ 100.0
277.3	≡ 100.0	$M1/E2$	K	1.971×10^{-1}	43.9	45.3 ± 2.1 [d]
			L	3.022×10^{-2}	6.7	7.2 ± 0.3
295.1	91.6 ± 7.5	$M1/E2$	K	1.666×10^{-1}	34.0	34.7 ± 1.5
			L	2.550×10^{-2}	5.2	5.3 ± 0.3
311.5	77.5 ± 6.5	$M1/E2$	K	1.440×10^{-1}	24.8	28.1 ± 1.3
			L	2.201×10^{-2}	3.8	4.5 ± 0.3
326.7	90.6 ± 7.8	$M1/E2$	K	1.267×10^{-1}	25.5	29.4 ± 1.3
			L	1.933×10^{-2}	3.9	4.7 ± 0.4
572.4	9.4 ± 0.7	$E2$	K	1.099×10^{-2}	0.230	0.220 ± 0.015
			L	2.266×10^{-3}	0.047	0.045 ± 0.005
606.6	15.2 ± 1.2	$E2$	K	9.651×10^{-3}	0.327	0.345 ± 0.021
			L	1.928×10^{-3}	0.065	0.070 ± 0.007
638.2	26.7 ± 2.0	$E2$	K	8.622×10^{-3}	0.512	0.562 ± 0.042
			L	1.679×10^{-3}	0.100	0.114 ± 0.010

[a] See Table II.

[b] Theoretical conversion coefficient (α) taken from the tables of Hager and Seltzer (Ref. 9). The conversion coefficients listed for the $M1/E2$ admixed transitions are the values for pure $M1$ transitions.

[c] The relative conversion-electron intensities are normalized to I_{ce} (214-keV L line) ≡ 100.0 units.

[d] See text for explanation of intensity.

TABLE V. The g factors and branching ratios for the $K^\pi = \frac{23}{2}^+$ rotational band in ^{177}Hf. λ is the experimental ratio between crossover $(I \to I-2)$ and cascade $(I \to I-1)$ transitions, δ^2 the $E2/M1$ mixing ratios of the $(I \to I-1)$ transitions, and $(g_K - g_R)^2/Q_0{}^2$ a rotational model parameter.

I	λ	δ^2	$10^3(g_K - g_R)^2/Q_0{}^2$
$\frac{27}{2}$	0.103 ± 0.007	0.080 ± 0.008	5.23 ± 0.63
$\frac{29}{2}$	0.196 ± 0.017	0.072 ± 0.007	5.63 ± 0.51
$\frac{31}{2}$	0.294 ± 0.027	0.068 ± 0.007	5.70 ± 0.68

ticle states within ≈0.5-MeV excitation energy of the $K^\pi = \frac{23}{2}^+$ state, namely,

$$(\tfrac{7}{2}^+[404]_p,\ \tfrac{9}{2}^-[514]_p,\ \tfrac{9}{2}^+[624]_n)K^\pi = \tfrac{25}{2}^-$$

and

$$(\tfrac{7}{2}^-[514]_n,\ \tfrac{9}{2}^+[624]_n,\ \tfrac{5}{2}^-[512]_n)K^\pi = \tfrac{21}{2}^+.$$

The estimated band-head energies for the $K^\pi = \frac{25}{2}^-$ and $\frac{21}{2}^+$ three-quasiparticle states were calculated as ≈1640 and ≈1440 keV, above the ground state, respectively, by use of an equation similar to Eq. (7).

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TABLE VI. γ-ray energies and relative intensities of ^{177m}Lu.

E_γ (keV) [a]	I_γ (Relative) [b]	E_γ (keV) [a]	I_γ (Relative) [b]
71.7	7.4 ± 0.7	249.7	51.3 ± 2.5
105.3	$\equiv 100.0$	268.8	28.3 ± 1.5
113.0	179.1 ± 8.4	281.8	116.7 ± 5.3
115.9	5.0 ± 0.5	283.4	4.3 ± 0.6
121.6	48.7 ± 2.9	291.4 }	14.9 ± 1.3 [c]
128.5	126.9 ± 5.7	292.5 }	
136.7	11.4 ± 1.1	296.5	44.5 ± 2.7
145.8	7.5 ± 0.8	299.1	14.3 ± 1.0
147.1	30.2 ± 2.3	305.5	14.5 ± 1.2
153.3	150.0 ± 7.1	313.7	11.5 ± 0.8
159.8	5.0 ± 0.6	319.0	85.7 ± 4.7
171.8	41.0 ± 2.2	321.3	11.6 ± 0.9
174.4	105.3 ± 5.3	327.7	145.9 ± 6.4
177.0	28.9 ± 1.8	341.6	14.9 ± 1.3
181.9	0.8 ± 0.2	367.4	24.8 ± 1.6
195.6	7.2 ± 0.7	378.5	232.2 ± 10.7
204.1	119.0 ± 5.6	385.1	24.5 ± 1.6
208.4	510.0 ± 22.4	413.7	137.5 ± 7.0
214.4	54.6 ± 3.1	418.5	167.0 ± 8.4
218.1	25.1 ± 3.0	426.5	3.4 ± 0.4
228.5	310.0 ± 12.6	465.9	19.4 ± 1.3
233.9	47.1 ± 2.3		

[a] Error in the γ-ray energies is ±0.1 keV.
[b] Normalized to I_γ(105.3 keV) ≡ 100.0 units.
[c] Doublet γ-ray intensity.

APPENDIX

Sources of 161-day ^{177m}Lu were produced by 5-h irradiation of 3 mg of 75% enriched $^{176}Yb_2O_3$ in the Brookhaven High Flux Beam Reactor ($\phi_n \approx 2 \times 10^{14}$ neutrons $sec^{-1}\,cm^{-2}$). The 6.7-day ^{177}Lu decayed during the 120-day prior to mass separation. The source strength after mass separation was 9×10^5 dis/min. The γ-ray energies and relative intensities of ^{177m}Lu are listed in Table VI. These measurements were used to determine contributions of ^{177m_1}Hf to the unresolved multiplets in ^{177m_2}Hf.

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Nuclear Orientation Study of the Decays of ^{126,127,128}Sb†

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Angular distributions have been measured for a number of γ rays emitted by ^{126,127,128}Sb polarized at low temperatures in iron. From the 0–90° anisotropies of the angular distributions, taking the proposed spin values $J=8$ (^{126,128}Sb) and $J=\frac{7}{2}$ (^{127}Sb), the ground-state magnetic moments have been deduced to be: $|\mu(^{126}\mathrm{Sb})| = 1.28 \pm 0.07\ \mu_N$; $|\mu(^{127}\mathrm{Sb})| = 2.59 \pm 0.12\ \mu_N$; $|\mu(^{128}\mathrm{Sb})| = 1.31 \pm 0.19\ \mu_N$. Based on the anisotropies of the ^{127}Te γ rays the following ^{127}Te spin assignments are favored (level energies in keV): $\frac{3}{2}^+$ (0), $\frac{1}{2}^+$ (61), $\frac{11}{2}^-$ (88), $\frac{9}{2}^-$ (341), $\frac{5}{2}^+$ (473), $\frac{7}{2}^-$ (632), $\frac{7}{2}^+$ (686), $\frac{5}{2}^+$ (784), $\frac{9}{2}^-$ (786), $\frac{7}{2}^+$ (924), $\frac{5}{2}^+$ or $\frac{9}{2}^+$ (1077), $\frac{5}{2}^+$ (1142), $\frac{5}{2}^+$ (1290). Based on these spin assignments, $E2/M1$ mixing ratios have been deduced for a number of ^{127}Te γ rays.

I. INTRODUCTION

In a number of recent publications,[1-3] we have reported investigations of the angular distribution of γ rays emitted by ^{122,124,125}Sb nuclei polarized in Fe at low temperatures. Among the parameters which were deduced from these measurements were the angular momentum multipolarities of the β- and γ-radiation fields and the Sb ground-state magnetic moments. We report here similar investigations of the decays of ^{126,127,128}Sb.

II. DECAY SCHEMES

The decays of ^{126,127,128}Sb to levels of ^{126,127,128}Te are illustrated in Figs. 1, 2, and 3, respectively. β and γ radiations and conversion electrons emitted in the decay of the 12.4-day ^{126}Sb have been investigated by Orth, Dropesky, and Freeman,[4] and spin assignments for the higher-lying ^{126}Te states have been proposed by Kiselev *et al.*[5]; the decay scheme of Fig. 1 is based primarily on the latter work. β and γ radiations from the decay of 3.9-day ^{127}Sb were studied by Ragaini, Gordon, and Walters (RGW)[6] and by Takemoto, Iwashita, and Kageyama.[7] The measurement of RGW[6] proposed several spin assignments; the level scheme of Fig. 2 is taken primarily from that work, with additional spin and parity assignments based on the present work included. β and γ spectra from the 8.6-h ^{128}Sb decay were investigated by Kiselev *et al.*,[5,8] and γ-ray coincidence and conversion-electron studies were done by Kerek.[9]

Additional investigations of the ^{126}Te levels have been done through the (d,p) reaction by Graue *et al.*[10] and through the $(\alpha, 2n)$ reaction by Kerek.[11] The ^{127}Te levels have also been studied by Graue *et al.*[12] through the (d,p) reaction. The reaction data are consistent with the level identifications proposed in the above decay studies.

III. EXPERIMENTAL DETAILS

A. Sample Preparation

The Sb isotopes were produced by α-induced fission of U. Following chemical separation of the Sb, a small amount of ^{125}Sb was added; the well-understood decay of ^{125}Sb[3] permits its use as thermometer and also as a verification of the success of the Sb diffusion into the Fe. A quantity of this solution was placed on the surface of a 0.1-mm 99.99%-pure Fe foil, and the Sb was allowed to diffuse into the Fe by annealing at 1100°C for 2 h in a H_2-Ar atmosphere. During annealing, ^{54}Mn and ^{57}Co activities, which had previously been adsorbed onto the walls of the annealing crucible, diffused into the foil. The low-energy γ