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Energy Levels of ^{176}Lu†

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The γ-ray spectrum from thermal-neutron capture in enriched targets of ^{175}Lu has been studied in four energy intervals using Ge(Li) and Si(Li) detectors. Twenty transitions in the energy region between 5.3 and 6.0 MeV have been observed in ^{176}Lu with a Ge(Li) detector operated in conjunction with a large NaI detector as a two-quantum escape spectrometer. Low-energy γ radiation has been measured from 20–1000 keV in both singles and γ-γ coincidence experiments. Data from the reaction ^{176}Lu(d, d') have been analyzed. The combination of results of these experiments with those previously reported in the literature has resulted in the following spectroscopic interpretation of levels in ^{176}Lu (denoted by band-head energy in keV, K^π, and Nilsson configuration): ground state, $7^-[404\downarrow +514\downarrow]$; 126.5, $I=1$, $0^-[404\downarrow -514\downarrow]$; 198.0, $1^+[404\downarrow - 624\uparrow]$; 390.2, $1^-[404\downarrow -512\uparrow]$; 662.0, $3^-[404\downarrow -510\uparrow]$; and 791.5, $4^-[404\downarrow +510\uparrow]$. The neutron separation energy of ^{176}Lu is determined to be 6293 ± 4 keV.

I. INTRODUCTION

FOLLOWING the simple model description of the energy level structure of odd-odd deformed nuclei, the ground state of ^{176}Lu is expected to arise from the strong coupling of a proton with a neutron in the lowest Nilsson[1] orbitals. The 71st proton is expected to be in the $\frac{7}{2}^+[404]$ orbital, which is consistent with the measured ground-state spins of the odd-A lutetium isotopes ^{175}Lu and ^{177}Lu,[2] while the orbital for the 105th neutron is expected to be $\frac{7}{2}^-[514]$, consistent with the ground-state spins of the 105-neutron isotones, ^{175}Yb, ^{177}Hf, and ^{179}W.[2] These neutron and proton orbitals can couple parallel or antiparallel, giving rise to $K^\pi=7^-$ and $K^\pi=0^-$ rotational bands. The Gallagher-Moszkowski coupling rules[3] suggest that the $K^\pi=7^-$ configuration should be the ground state. Coulomb excitation studies,[4] (d,p) reaction studies,[5] and atomic beam measurements[6] have established the $I=7$ spin assignment for the ground state of ^{176}Lu. The work of Elbek *et al.*[4] established the $I^\pi=8^-$ and 9^- members of the ground-state rotational band at excitation energies 184 ± 2 and 388 ± 2 keV, respectively.

Early measurements on the decay of the 3.68-h ^{176}Lu isomer are reported in the *Nuclear Data Sheets*,[2] but because of a large uncertainty in the β^- end point energy of the $2.2\times10^{10}y$ ^{176}Lu ground-state decay, an accurate excitation energy for this isomer has not been determined. The spin of the 3.68-h isomeric level has been established as $I=1$ by atomic beam measurements.[7] The β^- branching ratio to the 0^+ and 2^+ ground-state rotational band of ^{176}Hf has been carefully measured by Gallagher *et al.*[8] and by Heinzelmann[9] to determine[10] the K-quantum number

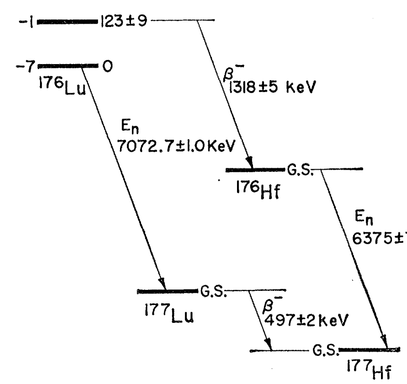

FIG. 1. Location of the 1^- isomer in ^{176}Lu from measured Q values. The ^{177}Hf and ^{177}Lu separation energies are from Refs. 7 and 8, respectively; the β end-point energies are from the *Nuclear Data Sheets* (Ref. 2).

of the isomer. These authors are in agreement that $K=0$ for this level and suggest the spin, parity, and configuration of $1^-0[404\downarrow -514\downarrow]$.

The only other ^{176}Lu states with previously assigned spins and parities are from the (d, p) work of Struble.[5] He has assigned the strongly populated states at

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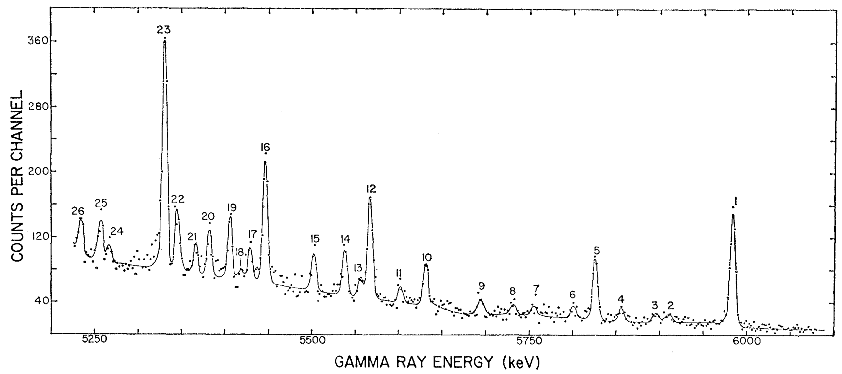

FIG. 2. The ^{175}Lu$(n,\gamma)^{176}$Lu primary γ-ray spectrum. The peak numbers correspond to those of Table I.

662 and 791 keV as $K^{\pi}=3^-$ and 4^- rotational band heads, respectively, arising from the configuration $[404\downarrow \pm 510\uparrow]$. Precise low-energy γ-ray measurements by Maier[11] and conversion electron measurements by Prokofjev *et al.*[12] following thermal-neutron capture in ^{175}Lu did not lead to the construction of an unambiguous decay scheme.

In Sec. II the energy relationship between the 1^- isomer and the 7^- ground state in ^{176}Lu is presented, after which (sec. III) the experimental results of the ^{175}Lu(n,γ) reaction are presented and interpreted as independently of model considerations as possible, and finally in Sec. IV the results are considered in terms of the current model for deformed odd-odd nuclei. These experimental studies were carried out using the facilities of the Omega West Reactor at Los Alamos and of the Florida State University Tandem Van de Graaff Laboratory.

TABLE I. Primary γ-ray transitions in ^{176}Lu following thermal-neutron capture in ^{175}Lu.

No.	E_γ (keV)	E_{ex} (keV)	ΔE_{ex} (keV)	$I_\gamma{}^a$ (rel)
1	5983.4	309.1	0.3	8.3
2	5909.5^b	383.0	2.0	0.7
3	5994.7^{b,c}	397.8	2.0	0.7
4	5855.5	437.0	0.5	0.8
5	5825.7	466.8	0.4	3.9
6	5802.0	491.0	2.0	0.8
7	5755.3^b	537.2	2.0	0.6
8	5731.4^c	561.1	0.9	0.6
9	5693.9	598.6	0.8	1.0
10	5630.5	662.0^d	···	2.3
11	5601.8^c	690.7	1.0	0.8
12	5566.7	725.8	0.4	5.4
13	5555.9	736.6	0.5	1.0
14	5537.6	754.9	0.4	2.3
15	5502.1	790.4	0.4	1.9
16	5446.1	846.4	0.4	6.0
17	5429.2	863.3	0.5	1.6
18	5421.0^b	872.0	2.0	0.4
19	5405.6	886.9	0.5	2.8
20	5382.0	910.5	0.6	2.0
21	5366.4	926.1	0.8	1.4
22	5345.0	947.5	1.0	1.6
23	5331.5	961.0	0.4	10.2
24	5268	1025	2.0	0.7
25	5258	1035	1.0	1.7
26	5234	1059	1.0	2.0

[a] Equivalent to photons per 1000 neutron captures in ^{175}Lu for transitions belonging to ^{176}Lu.
[b] Questionable lineshape, possibly complex.
[c] Probable ^{177}Lu transition.
[d] Excitation energy from Ref. 5.

II. ENERGY RELATIONSHIP OF THE 1^- ISOMER AND THE 7^- GROUND STATE IN ^{176}Lu

One of the important details in understanding the spectroscopy of ^{176}Lu involves the energy relationship between the known 1^- isomeric level and the 7^- ground state. The most reasonable interpretation[2] of earlier data suggests that the 1^- isomer lies approximately 290 keV above the ^{176}Lu 7^- ground state. Attempts to use this excitation energy in the interpretation of our data have been unsuccessful. In view of the uncertainties in the previous data, we have attempted to deduce this energy difference using a somewhat more complex but considerably more accurate energy cycle, shown in Fig. 1. In addition to the previously known β^- end points for the decay of the 1^- isomer of ^{176}Lu and of the ^{177}Lu ground state, we have used the recent measurements in our laboratories of the neutron separation energies for the reactions ^{176}Hf$(d,p)^{177}$Hf [13] and ^{176}Lu$(n,\gamma)^{177}$Lu.[14] We thus arrive at the value 123±9 keV as the energy difference between the 1^- ^{176}Lu isomer and the 7^- ground state. This value corresponds to a previously unassigned weakly populated state at 127±4 keV seen in the ^{175}Lu$(d,p)^{176}$Lu work of Struble.[5] The importance of this conclusion to the understanding of ^{176}Lu spectroscopy will become more obvious in the discussion of the level scheme.

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TABLE II. Energies and intensities of low-energy γ transitions from the $^{175}Lu(n,\gamma)^{176}Lu$ reaction.

	This work			Risø data[a]		
No.	E_γ (keV)	ΔE_γ (keV)	I_γ[b] [$\gamma/(100\ n)$]	E_γ (keV)	ΔE_γ (eV)	I_γ (rel.)
1	22.11	0.02	0.43			
2	25.15	0.03	0.14			
3	38.75	0.01	2.9	38.745	2	2.6
4	46.46	0.02	2.2	46.457	2	1.7
				51.906	3	0.4
5	58.6[c]	0.02	~0.1			
				64.459	13	0.5
6	66.19	0.04	1.5	66.159	3	2.2
7	71.52[d]	···	29.0	71.516	3	49.5
				71.835	5	1.4
8	73.05	0.05	1.3	73.124	5	1.5
9	81.6[c]	0.2	~0.3			
10	88.36[e]	0.02	9.8	88.366[e]	10	100.0
11	90.91	0.10	0.90	90.86	10	1.6
				93.193	9	0.5
12	93.54	0.08	0.94	93.441	8	1.0
				94.144	9	0.6
13	99.14	0.06	0.79	99.168	6	1.2
14	104.9	0.2	0.63	104.96	30	1.4
15	112.91	0.03	6.9			
				115.143	10	3.4
				118.73	20	0.4
16	119.5	0.2	0.87	119.705	9	1.3
				120.494	8	0.9
17	121.62[d,f]	···	2.0	121.620[g]	3	
18	124.0	0.2	0.51	124.03	20	1.2
19	129.8	0.1	0.89	129.786	7	2.0
20	133.7	0.2	0.51	133.695	7	1.2
21	138.9[f]	0.2	3.8	138.606[g]	5	
				139.39	10	4.6
22	140.8	0.3	0.34	140.48	30	4.6
				144.70[h]	40	···
				144.746[g]	6	
23	145.0[f]	0.4	1.4			
				145.870[g]	4	
				147.165[g]	5	
24	147.4[f,h]	0.2	3.3	147.537	8	3.7
25	150.39[f]	0.05	5.4	150.392[g]	3	
26	153.48	0.06	3.6	153.46	10	3.3
				158.48	20	0.4
				159.27	20	3.1
27	162.54[f]	0.07	2.0	162.492[g]	4	
28	169.0	0.2	0.70	169.65	30	1.4
29	171.7[f]	0.2	0.77	171.868[g]	8	
30	182.42	0.07	2.7	182.39	20	4.9
				184.17	30	1.6
31	185.0[f,h] }			185.20	60	9.1
32	186.7[f,h] }		6.6	185.96	60	3.9
33	188.3[f,h] }			187.00	40	2.0
				188.28	20	6.1
34	192.21[d]	···	9.6	192.210	12	17.0
35	197.0	0.2	1.3	197.28	30	3.1
36	201.52	0.06	4.1	201.58	30	11.9
37	203.9	0.7	0.20			
38	208.2	0.2	1.1			
39	214.1	0.2	1.1	214.08	30	3.0
40	217.0	0.1	2.0	216.97	40	5.9
41	219.2	0.2	1.4	219.31	30	2.9
42	222.1	0.3	0.90	222.01	50	2.1
43	225.35	0.05	9.6	225.37	30	25.0
44	227.95	0.09	3.2	227.94	30	6.4
45	233.85	0.11	2.1	233.67	30	5.6
46	236.2[c]	0.5	0.4			
47	239.0	0.2	1.1	238.3	100	2.7
48	251.3	0.2	0.8	251.12	660	2.8
49	254.3[c]	0.5	0.1			
				257.10[c]	50	0.8
50	259.5[f]	0.3	0.7	259.399[g]	17	
				262.77	50	6.6
51	263.59	0.07	6.7	263.68	40	14.3

TABLE II (*Continued*)

No.	This work E_γ (keV)	ΔE_γ (keV)	I_γ[b] [γ/(100 n)]	Risø data[a] E_γ (keV)	ΔE_γ (eV)	I_γ (rel.)
52	268.7[f]	0.2	1.4	268.801[g]	14	
53	271.8	0.2	1.8	271.88	50	3.6
54	274.4	0.5	0.52			
55	277.5	0.2	1.2	278.02	80	4.8
56	284.56	0.08	4.2	284.58	50	9.2
57	293.0[c]	0.5	0.6	292.08[c]	90	1.8
				295.40[c]	90	1.9
58	299.8[h]			300.08	90	2.7
59	300.9[h]		1.3	301.65	90	4.1
60	302.8[h]			303.75[c]	90	1.7
61	310.1	0.1	8.5	310.09	50	32.3
62	319.1[f]	0.2	1.1	319.04[g]	20	
63	330.2	0.3	0.9	330.59[h]	110	3.6
64	335.8	0.1	7.1	335.82	60	29.5
65	346.7	0.8	0.4			
66	349.9	0.5	0.7	350.49	150	3.6
67	355.7	0.6	0.5			
68	359.7	0.3	1.5	359.69	150	4.2
69	362.8	0.7	0.6			
70	367.3[f,h]	0.4	0.8	366.59	150	3.0
71	381.5	0.7	0.2			
72	384.0	0.9	0.1			
73	390.9[h]	0.9	0.3			
74	392.6[h]	0.6	0.7	392.8	200	5.6
75	402.8	0.9	0.4			
76	410.5	1.0	0.2			
77	413.5[f]	1.0	0.2	413.70[g]	40	
78	419.5	0.9	0.5			
79	422.6	0.8	0.6			
80	425.2	0.4	1.3	425.0	200	4.1
81	432.9	0.9	0.3			
82	439.5	1.0	0.2			
83	445.9[c]	1.0	0.2			
84	457.7[f]	0.2	3.0	457.90[g]	40	
85	470.4[c]	1.0	0.1			
86	476.4	0.7	0.2			
87	479.5	0.6	0.3			
88	486.2	0.7	0.2			
89	493.2	0.6	0.3			
90	508.9	0.7	0.8	509.29	250	7.8
91	511.0[d,i]	0.3	2.2			
				524.4	300	8.5
92	527.0	0.3	1.5			
93	549.7	0.4	0.9			
94	559.4	0.5	0.4			
95	564.3	0.3	3.4			
96	578.4	0.4	1.3			
97	587.4	0.8	0.2			
98	596.1	0.5	0.5			
99	625.6	0.5	0.6			
100	632.6	0.5	0.9			
101	636.8	0.6	0.4			
102	642.9	0.6	0.5			
103	660.4	0.6	0.4			
104	667.7	0.6	0.3			
105	672.8	0.5	0.8			
106	690.0	0.6	0.4			
107	693.0	0.6	0.3			
108	696.4	0.7	0.2			
109	710.1	0.5	0.7			
110	717.5[c]	0.8	0.1			
111	722.7	0.5	0.8			
112	728.3	0.6	0.4			
113	762.2[f]	0.6	0.6	761.52[g]	150	
114	765.8	0.6	0.5			
115	835.4	0.5	1.0			
116	839.4	0.5	2.7			
117	854.0	0.6	0.4			
118	865.0[c]	0.7	0.3			
119	870.6	0.6	0.6			
120	885.4	0.7	0.3			

TABLE II (*Continued*)

	This work			Risø data[a]		
No.	E_γ (keV)	ΔE_γ (keV)	I_γ[b] [γ/(100 n)]	E_γ (keV)	ΔE_γ (eV)	I_γ (rel.)
121	896.6	0.6	0.4			
122	972.6[c]	0.9	0.3			
123	977.0[c]	0.9	0.3			
124	1014.6[c]	0.9	0.3			
125	1041.0[c]	0.7	0.6			
126	1088.7	0.7	0.7			

[a] Reference 11.
[b] Equivalent to the number of photons per 100 neutron captures in ^{175}Lu for transitions belonging to ^{176}Lu using $\sigma_c = 23$ b.
[c] Questionable line.
[d] Used as internal calibration. Lu energies are from Ref. 11.
[e] ^{176}Hf $2^+ \rightarrow 0^+$.
[f] ^{177}Lu transition.
[g] 177 Lu transitions from Table II, Ref. 11.
[h] Complex structure.
[i] Annihilation.

III. EXPERIMENTAL METHODS AND RESULTS

A. High-Energy Neutron Capture γ Spectrum

^{175}Lu has a thermal-neutron capture cross section of 23b,[15] and it has a ground-state spin and parity $\frac{7}{2}^+$. The capture of thermal (s-wave) neutrons yields a compound state in ^{176}Lu with spin and parity 3^+ or 4^+ which can decay directly to low-lying states of ^{176}Lu. The most intense primary γ transitions are expected to be of dipole character. Thus, the low-lying states populated in this reaction can have spin and parity $2^\pm$, $3^\pm$, $4^\pm$, or $5^\pm$.

The high-energy transitions resulting from neutron capture in a 243-mg Lu_2O_3 sample enriched to 99.94%[16] in ^{175}Lu have been observed with a lithium-drifted germanium detector. Because of the 0.06±0.02%[16] 1980-b[15,17,18] ^{176}Lu impurity present in the enriched targets, about 2% of the γ radiation is expected to be due to thermal capture in ^{176}Lu. The Ge(Li) detector had an ~3-mm depletion depth and was operated inside a NaI annulus 30 cm long with a 20-cm o.d., and a 6.5-cm bore. This detector arrangement was located ~6m from the target, and by appropriate collimation only the Ge(Li) detector viewed the target. The system was operated as a two-quantum escape spectrometer to eliminate full-energy and single-escape peaks and to reduce the background from Compton events. In this arrangement pulses from the Ge(Li) detector were accepted in the analyzer only when they were in coincidence with a pulse of 1022 keV±10% in the NaI annulus detector.

The γ-ray transitions[19] from the ^{14}N$(n,\gamma)^{15}$N reaction, detected under the same conditions as the primary spectrum of interest, serve as a convenient source for calibrating the energy scale of the Ge(Li) data. Since the Lu target material was contained in a graphite holder, the 4945.46-keV[20] primary transition to the ground state of ^{13}C following neutron capture in ^{12}C is present in the high-energy spectrum and serves as an additional energy standard.

The intensities of the high-energy Lu transitions were calibrated against the nitrogen transition intensities[21] by comparing the line areas with those in the spectrum of ^{14}N$(n,\gamma)^{15}$N, obtained from a weighed target of melamine.

Figure 2 shows a portion of the primary γ-ray spectrum recorded with a 1600-channel pulse-height analyzer. The energy resolution was ~7-keV full width at half-maximum (FWHM) for ~6-MeV γ rays. Peak centroids and areas were obtained by least-squares fits of sums of Gaussian peaks to the (background subtracted) data. The corresponding energies and intensities for the primary transitions in ^{176}Lu are given in Table I. The neutron separation energy, $E_n = 6293 \pm 4$ keV, was obtained by identification of several of the more intense transitions to levels above 600 keV with the excitation energies of Struble[5] since there is no direct γ-ray connection to the ground state. This value is in good agreement with the measured (d, p) Q value of 4070±8 keV.[5] The excitation energies $(E_n - E_\gamma)$ of levels populated by primary transitions from the compound capture state are also listed in Table I.

B. Low-Energy (n, γ) Singles Spectrum

The low-energy γ-ray spectrum was measured in three sections with lithium-drifted germanium and silicon detectors. The Ge(Li) detector was operated inside the large NaI annulus detector; pulses from the Ge(Li) detector were accepted by the analyzer only when there was no coincident pulse in the annulus detector, thereby reducing background from Compton events. The relative detection efficiency of the Ge(Li)

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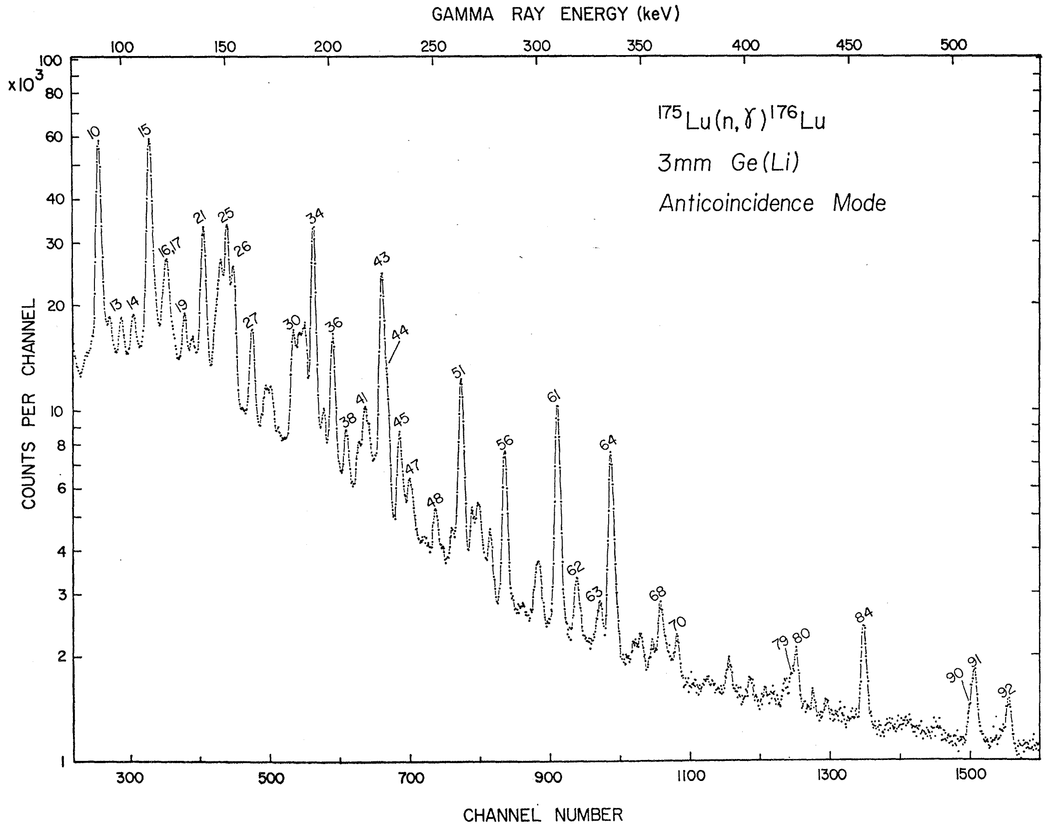

FIG. 3. Low-energy γ rays in ^{176}Lu from the reaction ^{175}Lu(n, γ). The Ge(Li) detector was run in an anti-Compton mode. Peak numbers correspond to those in Table II.

TABLE III. Multipolarities of ^{176}Lu transitions.

E_γ (keV)	Shell	I_e (rel)[a]	I_γ (rel)	I_e/I_γ	α (expt)	α (theoret)[b,c] $E1$	$E2$	$M1$	$M2$	Multipolarity
46.5	L_1	25	2.2	11.3	0.34	0.19	0.44	4.2	...	(Not $E2$)[d]
66.2	L_1	150	1.5	100	3.0	0.08	0.20	1.5	...	($M1$)
71.5	L_2	200	29	6.9	0.21	0.025	4.1	0.105	2.3	$E1$
71.5	L_1	<20	29	<0.69	<0.02	0.068	0.18	1.15	24.0	
71.5	L_3	<120	29	<4.1	<0.12	0.033	4.8	0.014	6.4	
71.5	L_1+L_2	220	29	7.6	0.23	0.093	4.3	1.26	26	
71.5	M_1	<20	29	<0.69	<0.02	0.015	0.05	0.25	5.2	
71.5	M_2+M_3	20	29	0.69	0.02	0.012	2.0	0.04	2.3	
112.9	K	150	6.9	22	0.63	0.21	0.72	2.1	15.0	$E2$
112.9	L_2	200	6.9	29	0.84	0.006	0.56	0.026	0.42	
112.9	L_3	200	6.9	29	0.84	0.006	0.42	0.003	0.60	
129.8	K	<20	0.89	22	<0.67	0.15	0.51	1.52	10	$E2(E1)$
139.4	K	25	<3.8	>6.6	>0.2	0.12	0.42	1.15	...	($E2$)
153.5	K	12	3.6	3.3	0.10	0.10	0.35	0.92	5.3	$E1$
182.4	K	50	2.7	18.5	0.55	0.064	0.22	0.56	3.0	$M1$
192.2	K	<20	9.6	<2.1	<0.062	0.056	0.19	0.50	2.5	$E1$
197.3	K	<20	1.3	15.4	<0.46	0.052	0.17	0.45	2.6	$M1$
201.6	K	20	4.1	4.9	0.15	0.048	0.16	0.42	2.2	$E2$
225.4	K	100	9.6	10.4	0.31	...	...	0.31	...	$M1$[e]
227.9	K	30	3.2	9.4	0.28	0.036	0.11	0.31	1.4	$M1$
251.1	K	5	0.8	6.2	0.19	0.029	0.086	0.23	1.0	$M1$
263.7	K	40	<6.7	>6.0	>0.18	0.025	0.08	0.23	0.90	$M1$
271.9	K	5	1.8	2.8	0.08	0.023	0.074	0.21	0.80	$E2$
284.6	K	20	4.2	4.8	0.14	0.022	0.066	0.17	0.67	$M1$
310.1	K	50	8.5	5.9	0.18	0.017	0.05	0.13	0.52	$M1$
335.8	K	30	7.1	4.2	0.13	0.014	0.041	0.105	0.40	$M1$
359.7	K	10	1.5	6.7	0.20	0.011	0.034	0.088	0.31	($M2$, $M1$)

[a] Reference 12.
[b] Reference 23.
[c] Reference 24.
[d] See text.
[e] Assignment consistent with K to L_1 ratio; theoretical conversion coefficient used for normalization.

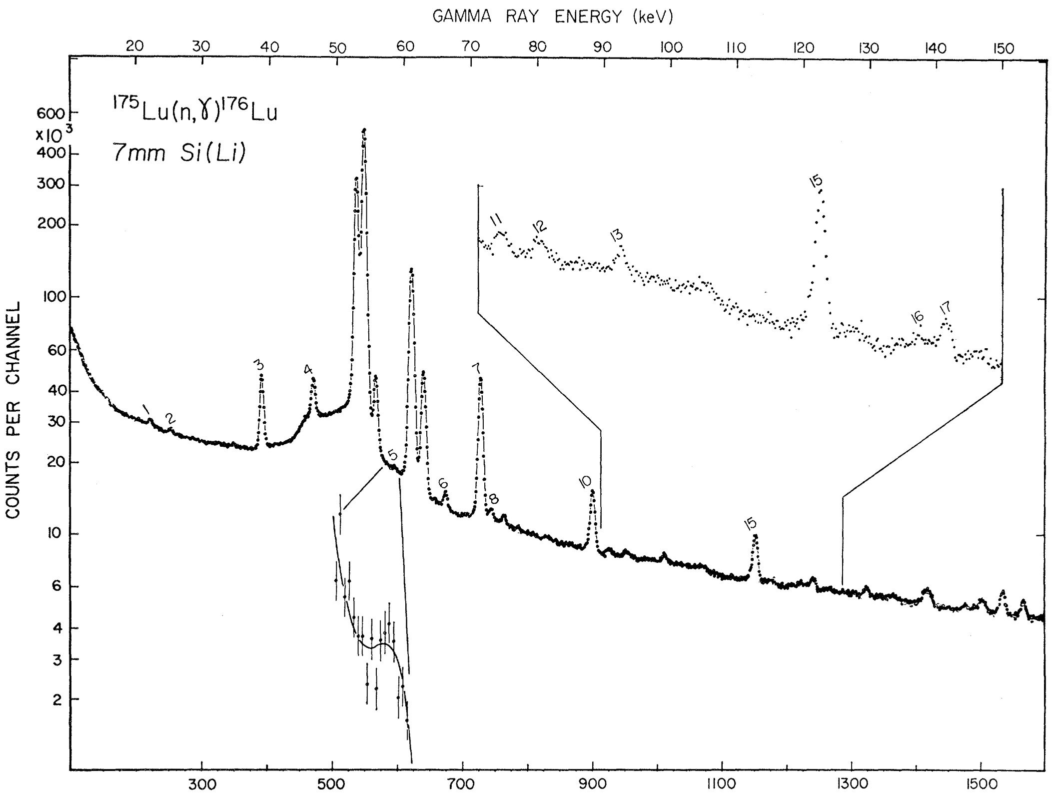

FIG. 4. Low-energy γ rays in ^{176}Lu observed with a lithium-drifted silicon detector. Peak numbers correspond to those in Table II.

spectrometer was previously determined using measurements on a series of radioactive sources of known relative intensity. The neutron flux and the detector efficiency were calibrated before each run by a measurement of the intensity of the 411.8-keV transition in ^{198}Hg following a timed irradiation of a weighed target of ^{197}Au. The partial cross sections of the γ-ray transitions were thus determined relative to the 98.8±0.3-b cross section of the ^{197}Au$(n,\gamma)^{198}$Au reaction. A portion of the γ-ray spectrum measured with the Ge(Li) detector is shown in Fig. 3.

A 7-mm-deep Si(Li) detector placed ~2.5 m from the target was used to detect γ rays having energies less than ~150 keV. A portion of the spectrum obtained with this detector is shown in Fig. 4. The energy resolution was ~0.6-keV FWHM at 70 keV. The relative intensities of the γ rays measured with the Si(Li) detector were normalized to several strong transition intensities measured with the Ge(Li) detector.

The γ-ray energies and intensities (corrected for absorption) for these measurements are listed in Table II. The uncertainties in the intensities listed in Table II are estimated to be less than ~15% for stronger (two significant digit entries) transitions above ~100 keV and ~20% for those below ~100 keV in energy. The 2.0-b intensity of the 88.36-keV $2^+\rightarrow 0^+$ transition in ^{176}Hf, following the decay of the 3.68-h isomer, was measured with the isomer in equilibrium at the beginning of the measurement. Using $(1+\alpha_T)=7.19\pm0.55$ total conversion[22] correction for the 88.36-keV transition and the measured[8,9] 60% β^- branching to the 2^+ level of ^{176}Hf, we obtain the value 24±6 b for the absorption cross section in ^{175}Lu which leads to the 3.68-h isomer in ^{176}Lu. This accounts for all of the 23±3-b total absorption cross section[15] within our experimental error. It has not been possible to estimate what fraction of the cross section leads to the ground state of ^{176}Lu. With the notable exception of the 112.91-keV transition and those few cases where it is not possible to resolve

TABLE IV. Energies and intensities of the ground-state rotational members observed in the ^{176}Lu(d,d') reaction.

I^π	Energy (keV)	Intensity (μb/sr) 95°	130°	Energy[a] (keV)
7^-	0	62 000	1200	
8^-	185.4±0.6	875	860	184±2
9^-	390.2±0.9	200	150	388±2
10^-	613.0±3.0	14	14	

[a] Reference 4.

[22] P. H. Stelson, in *Internal Conversion Processes*, edited by J. H. Hamilton (Academic Press Inc., New York, 1966), p. 213.

close or weak transitions with the solid-state detectors, the γ-ray energies observed in this work are in good agreement with the precision bent-crystal measurements of Maier,[11] which are given in Table II for comparison. Some 57 new transitions have been observed in this work at the extremes (<30 and >500 keV) of the low-energy spectrum. The observation of the 112.91-keV prompt γ ray has been possible in this work because of the relatively short time the Lu sample was exposed to the neutron flux, thus excluding all but a very small contamination ($\sim 8\%$) from the otherwise strong 112.95-keV[11] transition in ^{177}Hf that follows the decay of 6.7-day ^{177}Lu.

Experimental internal conversion coefficients obtained from the ratios of relative conversion electron intensities to γ-ray intensities for the more prominent transitions in the low-energy spectrum are listed in Table III. The conversion electron intensities are from the work of Prokofjev *et al.*[12] The experimental e^-_K/γ ratio obtained for the strong 225.4-keV transition was normalized to the theoretical $M1$ conversion coefficient. The $M1$ assignment for this transition is consistent with the ratio of K conversion to conversion in the L_1 shell.[12] The most probable multipolarities for 18 additional transitions are extracted by comparing the experimental conversion coefficients with the theoretical K- and L-shell conversion coefficients tabulated by Sliv and Band.[23] The M-shell conversion coefficients are from the tabulation of Hager and Seltzer.[24] In the case of the 71.5-keV transition, conversion in all the shells observed is consistent only with an $E1$ assignment. While the L_1 to L_2 ratio of conversion intensities is consistent with $E2$ radiation, the experimental (L_1+L_2) conversion coefficient extracted from their summed intensity is again consistent with the $E1$ assignment. This probably reflects the difficulty involved in the separation of these close lying conversion lines (the difference in the electronic binding energy between the L_1 and L_2 subshells is only ~ 0.5 keV). Similar difficulties are encountered in the assignment of a multipolarity to the 46.5-keV transition. The apparent $E2$ assignment can almost certainly be ruled out by observing that the conversion in the L_2 and L_3 shells ($\alpha_{L_2} \simeq \alpha_{L_3} \simeq 37$ for $E2$) would necessarily have to be extremely large. No such relatively strong conversion lines are observed.[12]

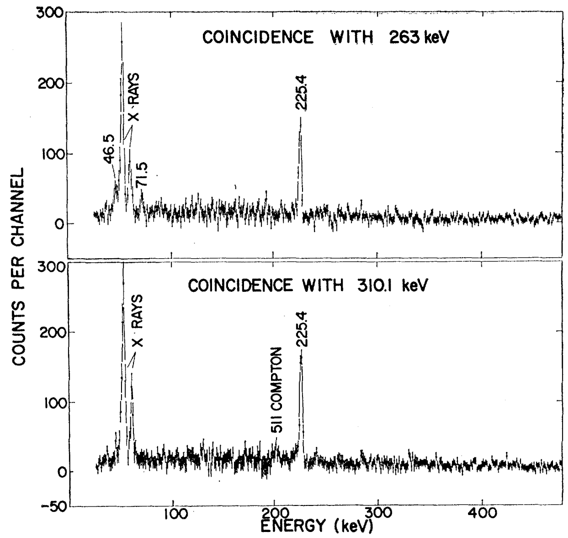

FIG. 6. ^{175}Lu$(n,\gamma\gamma')$. Spectra of γ rays in coincidence with the 263- and 310.1-keV transitions.

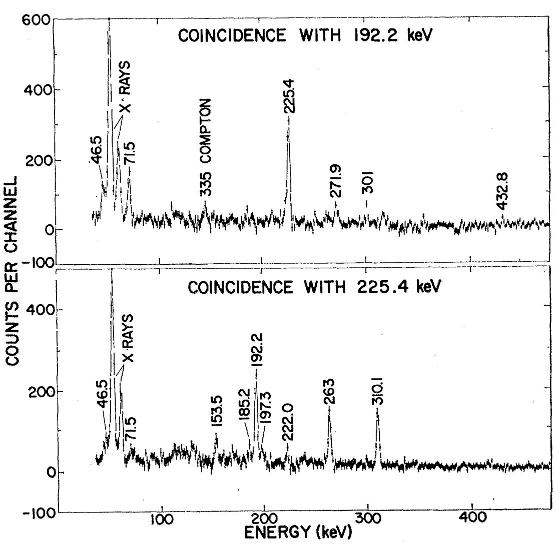

FIG. 5. ^{175}Lu$(n,\gamma\gamma')$. Spectra of γ rays in coincidence with the 192.2- and 225.4-keV transitions.

C. γ-γ Coincidence Measurements

An external thermal-neutron beam[25] from the Los Alamos Omega West Reactor was directed to a 500-mg sample of enriched ^{175}Lu$_2$O$_3$ situated between two large coaxial Ge(Li) detectors. These detectors, which have active volumes of 35 and 45 cm^3, were arranged in a 180° geometry with a sample-to-detector separation of approximately 2 cm. ^{6}LiF absorbers prevented irradiation of the detectors by scattered neutrons. Both detectors viewed the γ-ray energy spectrum below 1 MeV. Coincidences were detected using standard leading-edge timing techniques.

The digitized pulse amplitudes of each coincidence event were recorded on magnetic tape as the event occurred. In total, approximately 3×10^6 events were recorded. The magnetic tape was scanned by computer in order to extract the desired coincidence information.

[23] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), p. 1639.

[24] R. S. Hager and E. C. Seltzer, AEC Research and Development Report No. *CALT-63-60*, California Institute of Technology, 1967 (unpublished).

[25] E. B. Shera and D. W. Hafemeister, Phys. Rev. **150**, 894 (1966); also E. B. Shera and H. H. Bolotin, *ibid.* **169**, 940 (1968).

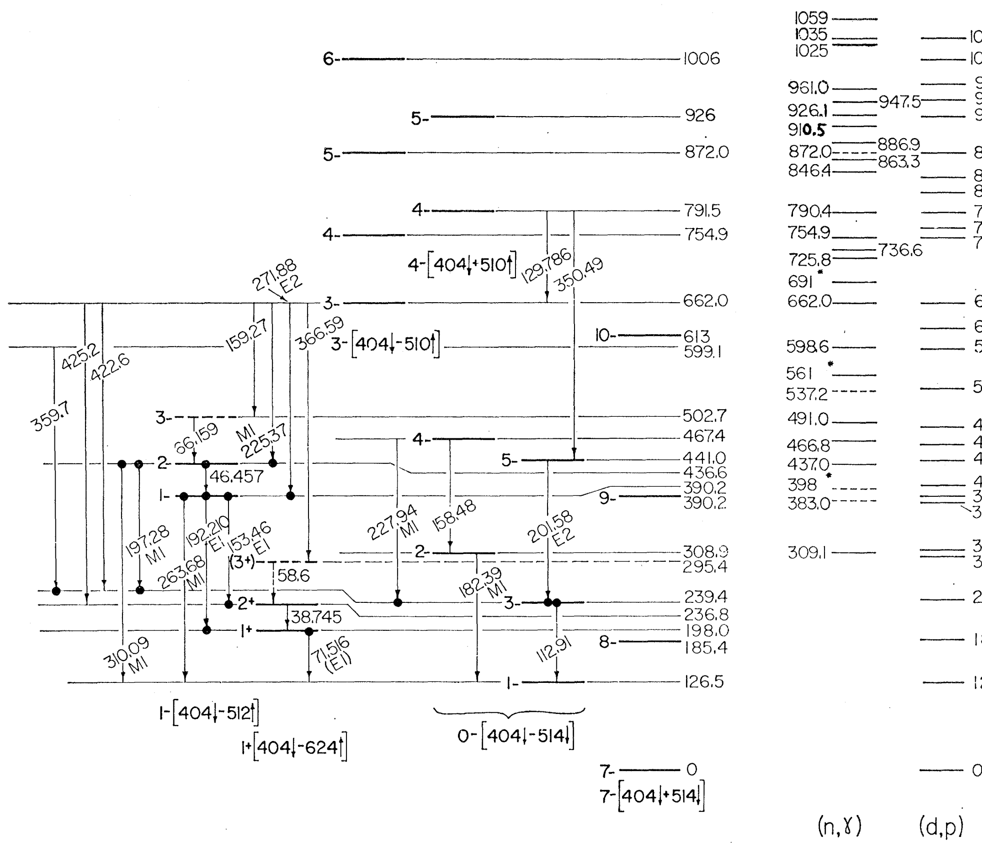

FIG. 7. The ^{176}Lu level scheme. The (d, p) energy levels are from Ref. 5. Energy levels populated by primary transitions are shown in the column labeled (n, γ). Those levels marked with an asterisk are questionable—the corresponding primary transitions may belong to ^{177}Lu. A large dot at the head or tail of a transition indicates that its placement is supported by the coincidence data.

In particular, a set of 45-cm^3 detector spectra was generated which corresponded to various digital "gates" selected in the 35-cm^3 detector channel. Digital gates were established at the energies of the prominent photopeaks and also at neighboring background regions. Algebraic manipulation of the resulting 45-cm^3 detector spectra then yielded the γ-ray spectrum in coincidence with a particular low-energy transition.

Several such coincidence spectra are shown in Figs. 5 and 6. These plots often include prominent backscattering peaks, as can be seen in the 192.2- and 310.1-keV coincidence spectra. Such peaks, which can have nearly the same width as photopeaks, are identified by the fact that $E_{\text{peak}}+E_{\text{gate}}=E_{\text{intense }\gamma}$. These peaks are particularly prominent if E_{gate} (or E_{peak}) is near the Compton edge of a strong transition, since the 180° detector geometry favors this scattering energy.

D. ^{176}Lu$(d,d')^{176}$Lu Spectroscopy

Metallic ^{176}Lu in the form of a thin target (35 μg/cm^2) on a thin carbon backing was bombarded with 12-MeV deuterons with the Florida State University Tandem Van de Graaff. The target was produced using the Florida State University Isotope Separator. It consisted of 7% ^{176}Yb, estimated from the intensity of the first 2^+ state in the reaction ^{176}Yb$(d, d')^{176}$Yb, and 93% ^{176}Lu. No detectable ^{175}Lu was present in the target.

The inelastic deuteron spectra were measured at laboratory angles of 75°, 95°, and 130°, with integrated deuteron beams of 15 000, 12 000, and 12 000 μC, respectively, using a Browne-Buechner magnetic spectrograph.[26,27] The deuteron groups were recorded photographically and later counted in $\frac{1}{2}$-mm strips with a microscope. The resulting track distributions were least-squares fitted with skewed Gaussians in order to obtain energies and intensities. Analysis of the groups corresponding to the lowest-lying states in ^{176}Lu is given in Table IV and compared with the work of Elbek.[4] The energies given in Table IV are averages of the values obtained at the three angles and can be given with such unusually high accuracy because of the presence of the 2^+ excited state group of ^{176}Yb in the spectra. The energy of this 2^+ state is known[2] with

[26] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

[27] R. A. Kenefick and W. N. Shelton, theses submitted to the Florida State University in partial fulfillment of the requirements of the Ph.D. degree, 1962 (unpublished).

TABLE V. ^{175}Lu$(n, \gamma\gamma')$. γ rays observed in coincidence with the gate energy are denoted: s for strong definite coincidences; y for moderately intense but definite coincidences; w for weak coincidences; and vw for very weak and questionable coincidences.

γ's in coincidence \ Gate	71.5	112.9	139.4 140.5	153.5	159.3	192.2	201.6	225.4	262.8 263.7	284.6	310.1	335.8
46.5	···	···	···	···	···	w	···	w	w	···	···	···
x rays	s	···	···	y	y	s	y	s	s	s	s	s
71.5	···	···	···	vw	···	s	···	w	y	y	···	y
99.2	···	···	···	···	···	···	···	···	···	···	···	w
112.9	···	···	···	···	···	···	s	···	···	vw	···	···
139.4+140.5	···	···	···	···	vw	···	···	···	···	w	···	···
153.5	vw	···	···	···	···	···	···	y	···	···	···	···
182.4	···	···	···	vw	···	···	···	···	···	···	···	···
185.2	···	···	···	···	vw	···	···	vw	···	···	···	···
192.2	s	···	···	···	···	···	···	s	···	···	···	···
197.3	···	y	···	···	···	···	···	y	···	···	···	···
201.6	···	s	···	···	···	···	···	···	···	···	···	vw
214.1	vw	···	···	···	···	···	···	···	···	y	···	···
222.0	···	···	···	···	···	···	···	w	···	···	···	···
225.4	y	···	···	y	···	s	···	···	s	vw	s	···
227.9	···	y	···	···	···	···	···	···	···	···	···	···
233.7	···	···	···	vw	···	···	···	···	···	···	···	···
251.1	···	···	···	···	···	···	···	···	···	···	···	y
262.8+263.7	···	···	···	···	···	···	···	s	···	vw	···	···
271.9	···	···	···	···	···	w	···	···	···	···	···	···
272.7	···	···	···	···	···	···	y	···	···	···	···	···
284.6	w	···	···	···	···	···	···	···	···	···	···	···
300.1+301.7	···	···	···	···	···	vw	···	···	···	···	···	···
310.1	···	···	···	···	···	···	···	s	···	w	···	···
335.8	y	···	···	···	vw	···	···	···	···	···	···	···
350.5	···	···	···	···	···	···	···	···	···	···	···	vw
359.7	···	w	vw	···	···	···	···	···	···	···	···	···
432.9	···	···	···	···	···	vw	···	···	···	···	···	···
511.0	y	w	···	···	···	w	···	···	···	···	···	···
564.3	···	···	···	···	···	···	···	···	···	···	···	w
596.1	···	···	···	···	···	vw	···	···	···	···	···	···

high precision. This impurity therefore serves as a convenient internal calibration and makes possible a more accurate testing of the rotational energy formula (Sec. IV A). The intensities in Table IV are given only at 95° and 130° because of a difficulty in the experimental procedure in the 75° run.

E. ^{176}Lu Level Scheme

The proposed decay scheme of ^{176}Lu is shown in Fig. 7. In the discussion that follows, the precision γ-ray data of Maier[11] are used where energy combinations are important. The decay scheme of Fig. 7 is based to a great extent on the two strong coincidence chains associated with the 225.37- and 112.91-keV γ rays.

The 192.210-, 263.68-, and 310.09-keV transitions are observed strongly in coincidence with the 225.37-keV γ transition. Additional weak coincidences with the 225.37-keV γ ray are seen at 46.457, 71.516, and 153.46 kev (see Fig. 5). The possibility of a triple cascade is ruled out by the fact that the 310.09-, 263.68-, and 192.210-keV transitions are not seen in coincidence with each other. The weak coincidence of the 46.457-keV line with 263.68- and 192.210-keV lines, along with the strong 192.210−71.516-keV coincidence and with the energy combinations 263.68+46.457=310.09, 192.210+71.516=263.68, and 225.37+46.457=271.88 keV, establish the cascade 225.37−310.09 keV, with the intermediate branching shown in Fig. 7. These energy spacings coincide with the spacings between the established levels at 662, 437, and 127 keV. Using the value 662.0 keV as an excitation energy reference, the value 126.5 keV is thus established for the energy of the 1^- isomer, with intermediate levels firmly established at 198.0, 390.2, and 436.6 keV. The weak 153.46-keV coincidence with 225.37 keV and the energy combination 153.46+38.746=192.210 keV further establish a level at 236.8 keV.

Coincidence with 112.91 keV (197.28, 201.58, and 227.94 keV), the 197.28-keV coincidence with the 225.37-keV transition, and the energy combination 112.91+197.28=310.08 keV firmly establish the decay of levels at 239.4, 441.0, and 467.4 keV, in agreement with known energy levels from the primary (n, γ) and (d, p) reactions.

Additional transitions placed in the decay scheme are based on the remaining coincidences (see Table V) and on energy differences. The coincidence data suggest that the 335.82- and 284.58-keV γ rays feed levels at 198.0 or 236.8 keV. However, our data do not allow the unambiguous placement of these transitions in the decay scheme.

Assuming the spin and parity assignment 3^- for

TABLE VI. Theoretical and experimental dipole branching ratios.

E_γ (keV)	I_i, K_i	I_f, K_f	$T_f/T_{f'}$ Theor	Expt
192.21	1, 1	1, 1	2.0	2.7
153.48	1, 1	2, 1		
310.1	2, 1	1, 0	5.8	6.5
197.0	2, 1	3, 0		

the 662.0-keV level,[5] which is based on the (d, p) reaction intensity to members of the $K^\pi=3^-$ rotational band, and using the measured spin and assigned parity 1^- for the 126.5-keV isomer, the spins and parities of the levels at 390.2 and 436.6 keV are required to be 1^- and 2^-, respectively, from the multipolarities of the 225.37-, 263.68-, 271.88-, and 310.09-keV transitions. The level at 308.9 keV can be unambiguously assigned a spin and parity of 2^- because this level is populated strongly by a primary transition following thermal-neutron capture (indicating $I^\pi=2^-$, 3^-, 4^-, or 5^-) and decays to the 1^- isomer via the 182.39-keV transition, which has $M1$ multipolarity. The same argument and result can be applied to the level at 436.6 keV, without recourse to the $I^\pi=3^-$ assignment for the 662.0-keV level.

The possible assignments for the levels at 198.0 and 236.8 keV are 0, 1, or 2, with positive parity. The possible spin assignments $I=1$, 2, or 3 for the level at 239.4 keV, $I=2$, 3, or 4 for the 467.4-keV level, and $I=0$–5 for the level at 441.0 keV, all of which must have negative parity, have been deduced from similar arguments involving the various population and depopulation modes of these states.

IV. DISCUSSION OF LEVEL SCHEME

Having established many of the basic features of the ^{176}Lu level scheme with as few assumptions as possible, we will now compare this scheme with the predictions of the collective model for deformed odd-odd nuclei, extending the scheme, where possible, with the aid of the theory.

A. $7^-[404\downarrow+514\downarrow]$ Ground-State Band

Because of the high spins of the $K^\pi=7^-$ ground-state band members, one does not expect these states to be strongly excited in the thermal (n, γ) reaction; thus, it is not surprising that γ-ray connections are not seen between these levels and other low-lying states. Inelastic scattering of deuterons from a target of ^{176}Lu (see Sec. II D), however, gives accurate energies for the first three excited members of the ground-state band (Table IV).

The one-parameter rotational energy formula does not fit the energy, within the experimental error, of the 9^- member of the band. Using the two-parameter rotational formula

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

and the energies of the $I^\pi=7^-$, 8^-, 9^- ($E=0$, 185.4 ± 0.6, and 390.2 ± 0.9 keV, respectively) rotational members, the rotational parameters

$$A=12.38\pm0.6 \text{ keV}$$

and

$$B=-6.2\pm0.4 \text{ eV}$$

are determined. Using these values of A and B, the $I^\pi=10^-$ rotational member is calculated to be at 612.9 ± 4.8 keV which is in good agreement with the weak state seen at 613 ± 3 keV.

B. $0^-[404\downarrow-514\downarrow]$ Band

The even-odd shift, in which the even- and odd-spin members of $K=0$ bands are displaced relative to each other, is well established by other experiments (see for example ^{170}Tm,[28] ^{166}Ho,[29,30] and ^{242}Am[31]). This effect, quantitatively treated by Newby[32] and others,[30] is especially significant because of its sensitivity to the choice of the nucleon-nucleon residual interaction. In the absence of Coriolis mixing with other intrinsic configurations, it would be expected that the even- and odd-member energies of the band could be fit separately with approximately the same rotational band parameters.

These model considerations suggest the interpretation of the states at 239.4 and 441.0 keV as the $I^\pi=3^-$ and 5^- rotational members of the *odd*-spin part of the $K=0^-$ band and the states at 308.9 and 467.4 keV as the 2^- and 4^- members of the *even* portion of the same band. Taking the 112.91-keV separation between the isomer and the 239.4-keV level as the 1^-, 3^- energy difference, we obtain

$$A_{\text{odd}}=11.29 \text{ keV}$$

from Eq. (1), with B set equal to zero. Using this value for A_{odd}, the separation energy between the 3^- and 5^- rotational states is calculated as 203.2 keV, in good agreement with the 201.58-keV $E2$ transition energy. The occurrence of the $I^\pi K=1^-0$ state as an isomer clearly indicates that the even members of the $K=0$ band are shifted upward in energy relative to the odd members, compared to a normal $I(I+1)$ sequence. Assuming the established

[28] R. K. Sheline, C. E. Watson, B. P. Maier, U. Gruber, R. H. Koch, O. W. B. Schult, H. T. Motz, E. T. Jurney, G. L. Struble, T. von Egidy, Th. Elze, and E. Bieber, Phys. Rev. **143**, 857 (1966).

[29] G. L. Struble, J. Kern, and R. K. Sheline, Phys. Rev. **137**, B772 (1965).

[30] H. T. Motz, E. T. Jurney. O. W. B. Schult, H. R. Koch, U. Gruber, B. P. Maier, H. Baader, G. L. Struble, J. Kern, R. K. Sheline, T. von Egidy, Th. Elze, E. Bieber, and A. Bäcklin, Phys. Rev. **155**, 1262 (1967).

[31] F. Asaro, I. Perlman, J. O. Rasmussen, and S. G. Thompson, Phys. Rev. **120**, 934 (1960).

[32] N. D. Newby, Jr., Phys. Rev. **125**, 2053 (1962).

$I^\pi=2^-$ state at 308.9 keV to have $K=0$, the 4^- rotational member could be expected to lie ~158 keV above this level, using the deduced value for A_{odd}. From the observed 158.48-keV transition between the 2^- level and the level at 467.4 keV we obtain

$$A_{\mathrm{even}}=11.32 \text{ keV},$$

and predict the 0^- level to be located at ~241 keV in excitation energy. That no such level is observed is not surprising in view of the fact that the only possible transition from within the band itself would be an ~68-keV $E2$ transition from the 2^- level at 308.9 keV. This transition would have to compete with the 182.39-keV $M1$ transition in the depopulation of the 2^- level and would thus be expected to be very weak. It is possible that the 0^- state might receive sufficient indirect population by the (n, γ) reaction that depopulation of this state via an $M1$ transition to the 1^- isomer would be observable. Maier[11] has reported a 115.143-keV transition, which is approximately the energy expected for such a transition. In the absence of further information, we can only speculate on the position of the 0^- state. The apparent even-odd shift

$$\Delta E=(E_0)_{\mathrm{even}}-(E_0)_{\mathrm{odd}}\approx 137 \text{ keV}$$

is unusually large compared to the known shifts[28,30] in other deformed nuclei.

C. $1^+[404\downarrow -624\uparrow]$ Band

In view of their possible spins (0, 1, or 2) and energy spacing, the two positive-parity states at 198.0 and 236.8 keV may be a $K^\pi=1^+$ rotational band. The Nilsson model predicts that the $\frac{9}{2}^+[624]$ neutron orbital should lie slightly above the $\frac{7}{2}^-[514]$ orbital, and indeed the $K^\pi=\frac{9}{2}^+$ bands attributed to this oribital are observed at 260 keV in ^{175}Yb [33] and at 321 keV in ^{177}Hf.[34,35] The coupling of this orbital with the lowest expected proton orbital ($\frac{7}{2}^+[404]$) would give rise to $K^\pi=1^+$ and $K^\pi=8^+$ bands with the $K^\pi=1^+$ band expected to be lower in energy.

The value of the rotational formula parameter

$$A=9.68 \text{ keV},$$

calculated from the above separation energy, assuming these states are the two lowest members of a $K^\pi=1^+$ band, is ~20% smaller than the value of the A parameter for the ground-state rotational band, in good agreement with the observed rotational parameter values for the $K=\frac{9}{2}^+[624]$ bands observed[35] in the odd-A Hf isotopes. A possible weak 58.6-keV transition (see inset, Fig. 4) suggests the existence of a 3^+ level at 295.4 keV, in good agreement with the 3^+ energy predicted from the rotational formula, using the above value of A. This level is possibly fed by a 366.59-keV transition from the 662.0-keV level.

The $E1$ branching ratio

$$T(E1, 1^-\to 1^+)/T(E1, 1^-\to 2^+)$$

from the 1^- level at 390.2 keV to the levels at 198.0 and 236.8 keV is in good agreement with that calculated for $\Delta K=0$ (see Sec. III D and Table VI), further supporting the $K^\pi=1^+$ band assignment.

D. $1^-[404\downarrow -512\uparrow]$ Band

The 1^- and 2^- states at 390.2 and 436.6 keV suggest the existence of a $K^\pi=1^-$ band. The 3^- rotational member would be predicted to lie ~69.6 keV above the 2^- state on the basis of the 1^-, 2^- separation energy ($A=11.6$ keV). A possible 3^- level is suggested at 502.7 keV, based on the energy combination 66.159+159.27=225.37 keV. This assignment, however, would require an unusually large B value in the rotational energy formula ($B\simeq -59$ eV) and must be regarded as very tentative.

A test of the above assignments is to compare the ratio of the intensities of the 310.09- and 197.28-keV $M1$ transitions depopulating the 2^- level at 436.6 keV, and of the 192.20- and 153.46-keV $E1$ transitions depopulating the 1^- level at 390.2 keV, with the predictions of the strong coupling theory. In taking the ratio of the transition strengths of two transitions of the same multipolarity depopulating a level with spin and K-quantum number I_iK_i to two levels of another band (I_f, $I_{f'}$; K_f), the specific nuclear dependence in the transition probabilities cancels, leaving only a geometrical factor. Thus, the dipole branching ratio may be written[10]

$$\frac{T(E1, M1; I_iK_i\to I_fK_f)}{T(E1, M1; I_iK_i\to I_{f'}K_f)}=\frac{T_f}{T_{f'}}=\left(\frac{\Delta E_{i\to f}}{\Delta E_{i\to f'}}\right)^3\left(\frac{\langle I_i1K_iK_f-K_i\mid I_fK_f\rangle}{\langle I_i1K_iK_f-K_i\mid I_{f'}K_f\rangle}\right)^2. \quad (2)$$

The observed and theoretical branching ratios for the 1^- and 2^- states are given in Table VI. The consistency between the two sets of values leads us to conclude that the states at 390.2, 436.6, and possibly 502.7 keV are members of a $K^\pi=1^-$ rotational band. The most reasonable Nilsson assignment for this band involves the coupling of the $\frac{5}{2}^-[512]$ Nilsson (hole state) orbital with the $\frac{7}{2}^+[404]$ proton orbital. We note that Eq. (2) predicts a weak transition (intensity about 0.7 $\gamma/100n$) between the band head of the $K^\pi=1^-$ band and the missing $I^\pi K=0^-0$ state discussed in Sec. IV B. The available γ-ray data provide no obvious candidate for such a transition (anticipated energy ≈148 keV). It is also interesting

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that, contrary to the behavior of the band head, the $I=2$ state of the $K^\pi=1^-$ band does not appear to decay to the $K^\pi=1^+$ band. A theoretical prediction, based on Eq. (2) and the observed transition intensity from the lowest two members of the $K^\pi=1^-$ band to the $I^\pi K=1^-0$ state, suggests a 436.6→198.0-keV transition of several times greater intensity than the upper limit established by the data of Table II. However, in view of the frequently anomalous behavior of $E1$ transitions in odd-A nuclei, we do not consider the present anomaly to be a compelling argument against the proposed assignments.

E. $3^-[404\downarrow \pm 510\uparrow]$ and $4^-[404\downarrow \pm 510\uparrow]$ Bands

The $K^\pi=3^-$ and $K^\pi=4^-$ bands, based respectively at 662.0 and 791.5 keV, have previously been assigned[5] to the coupling of the $\frac{1}{2}^-[510]$ neutron orbital with the proton orbital $\frac{7}{2}^+[404]$ on the basis of the observed (d, p) stripping cross sections. The results of the (n,γ) measurements are in agreement with these assignments, although the $I^\pi=5^-$ rotational members of these bands have been relocated.

The large difference in the moment of inertia parameters ($A_{K=3^-}\sim 11.8$ and $A_{K=4^-}\sim 13.7$ keV), and the anomalously large (d, p) cross sections to the spin 4 and 5 members of the $K=4$ band are suggestive of strong Coriolis ($\Delta K=1$) mixing. The work of Struble,[5] however, implies that the mixing between these two bands alone should not introduce large changes in cross section.

V. CONCLUSIONS

The investigation of the nuclear level scheme of ^{176}Lu presented in this work has revealed several rotational bands, all of which are describable in terms of the coupling of a neutron in low-lying Nilsson orbitals to the proton configuration $\frac{7}{2}^+[404]$. The $K=0$ band, in which the 3.7-h 1^- isomer appears as the lowest member, involves an anomalously large even-odd shift. We have not been able to find the 0^- member of this band, but have inferred its energy from the observed positions of other band members. Determination of the explicit location of this level through additional research would be valuable.

It is of interest to note that the odd-even shift of members of the $K=0$ band observed in ^{176}Lu in this study is in the opposite direction and much larger than shifts which have been observed in ^{170}Tm [28] and ^{166}Ho.[29,30] Perhaps because the configurations of these $K=0$ bands are all different, it is not surprising that the odd-even shifts are so different. On the other hand, the possible parity dependance of this shift which results from calculations using the formalism of Pyatov[36] is not borne out since the $K=0$ bands in ^{176}Lu, ^{170}Tm, and ^{166}Ho all have negative parity. It is apparent, therefore, that additional theoretical investigation is needed to explain the experimentally observed even-odd shifts. Using the selection rules suggested by Newby[32] and the fact that the shift in ^{176}Lu is so different from the others, the number of possible choices of a form for the residual neutron-proton interaction should be considerably reduced.

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