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THE DECAY OF 72Hf172

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ABSTRACT

The energy levels of $_{71}Lu^{173}$ have been studied from the electron-capture decay of 24.0-hour Hf^{173}, by means of high-resolution permanent-field electron spectrographs with and without "pre-acceleration", a double-focusing spectrometer, scintillation spectrometers, and gamma-gamma coincidence techniques. Properties of the levels are discussed in terms of the unified model of Bohr and Mottelson and the single-particle model of Nilsson appropriate for spheroidally-deformed nuclei. The following intrinsic states are identified in Lu^{173}: 7/2 + [404], ground; 1/2 - [541], 128.2 kev; 5/2 + [402], 356.8 kev; and 1/2 + [411], 425.0 kev. The ground state of Hf^{173} has the configuration 1/2 - [521]. The 1/2 - [541] orbital of Lu^{173} is interesting in that it originates from the $h_{9/2}$ proton state beyond the 82-proton shell and also in the fact of its high decoupling parameter ($a = 4.2$) which causes the $I = 5/2$ rotational state to be found below the $I = 1/2$ fundamental state. M1 and E2 relative transition probabilities within the 1/2 - [541] band are discussed, and the theoretical parameter b_{M1}, upon which the M1 transition probability in a $K = 1/2$ band depends, is estimated both from the experimental results and from the Nilsson wave-functions. Log ft values of the Hf^{173} decay are also discussed.

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I. INTRODUCTION

The intrinsic energy levels available to protons and neutrons in odd-mass isotopes of highly deformed nuclei have been studied by many investigators, and a detailed summary and interpretation of known levels has been given by Mottelson and Nilsson.[1] In the region of 71 and 73 protons (isotopes of lutetium and tantalum), the situation has not been entirely clear. According to the strict level order of the Nilsson diagram,[2] the ground state of the 71st proton (lutetium) is expected to be 7/2 + [404] and that of the 73rd proton (tantalum) 9/2 - [514]. Experimentally 7/2 + [404] is found in both cases as the ground state, while the relative position of the 9/2 - [514] state appears to vary markedly. In Lu^{175} the 9/2 - state lies at 396 kev[3] and in Lu^{177} it is at 147 kev.[4] This large difference is not expected from the Nilsson model, and indeed even the direction is unexpected, because the deformation of Lu^{175} is probably greater than that of Lu^{177} and hence, according to the Nilsson diagram, the 9/2 - ⟷ 7/2 + spacing should be smaller in Lu^{175} than in Lu^{177} rather than larger. In the tantalum isotopes the two states are very close-lying (30 kev separation in Ta^{179} [5] and 6 kev separation in Ta^{181} [6]). In addition to these two states, the 5/2 + [402] and 1/2 + [411] levels are expected as excited states of the 71st proton. In an attempt to clarify the relative positions of intrinsic states of the 71st proton, we have examined the lutetium energy levels that arise

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

from the decays of the parent isotopes Hf^{171} and Hf^{173}. In this paper we discuss the decay of Hf^{173}.

II. PREPARATION OF SOURCES

Hf^{173} was prepared via the $(\alpha,3n)$ reaction, by irradiations of the "separated isotope" $Yb_2{}^{172}O_3$† with 38 Mev helium ions from the Crocker 60-inch cyclotron. Carrier-free hafnium was separated from the active rare-earth oxide by a procedure which essentially consisted of adsorption of hafnium from concentrated HCl solution onto an anion-exchange resin column, followed by thorough washing of the column to ensure removal of all rare-earths and finally elution of the hafnium with 6M HCl. The activity was transferred by means of a special "dipping" device to one side of a 0.25 mm platinum wire which was then carefully aligned in the spectrograph source-holder. A wire source was prepared on one occasion also by vacuum evaporation. For the conversion coefficient measurements, the activity was liquid-deposited onto a 3 x 8 mm aluminum strip. Sources for gamma-ray and coincidence spectroscopy were liquid-deposited onto microscope-slide glasses.

III. INSTRUMENTATION

The internal conversion spectrum of Hf^{173} was measured with 180° permanent-magnet, photographic-recording spectrographs having field strengths 50, 100, 150, and 340 gauss.[7] The resolution ($\Delta p/p$) obtained with standards in these instruments was ~ 0.1%. Relative intensities of the lines were measured by a visual comparison method that has been described by Albridge et al.[8] A 25-cm, double focusing spectrometer was used to measure the intensities and conversion coefficients of some of the stronger transitions.

Photon spectra were examined under a variety of conditions with 5cm x 5cm and 7.6 cm x 7.6 cm NaI(Tl) crystals connected to either a Penco 100-channel

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† Obtained from separated Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

analyzer or a T.M.C. 256 - channel analyzer. Gamma-gamma coincidence measurements were made both with a conventional fast-slow system coupled to the Penco analyzer and with a two-dimensional coincidence analyzer which utilizes paper-tape data output.

IV. HALF-LIFE OF Hf^{173}

In the course of these experiments, a sample of Hf^{173} was followed for 11 days in a flowing methane proportional counter. The value of the Hf^{173} half-life which resulted from this measurement is 24.4±1.0 hours. This is to be compared with previously reported values 23.6[9], 28[10], 44[11], and 23.5 hours.[12]

V. CONVERSION ELECTRON SPECTRUM

The Hf^{173} conversion-electron spectrum is summarized in Table I, and a portion of the spectrum is reproduced in Fig. 1. The absolute error of the energy values of the individual electron lines is estimated to be $\leq$ 0.2% for lines of lower energy than 500 kev and ~ 0.4% for higher energy lines. An internal standard in the hafnium was provided by the presence of Hf^{175}, which has transitions of 113.81±0.05 and 343.40±0.08 kev, measured by Hatch, Boehm, Marmier, and Du Mond.[3] The relative precision of lines measured in our work is better than 0.1% (except for the very weakest lines) so for lines in the vicinity of the Hf^{175} transitions the absolute accuracy should approach 0.1%. The lines were recorded on several different spectrographs, and the energy values quoted in Table I are either weighted averages of the results of several experiments or are taken from the readings of a particularly good plate.

The relative intensities of close-lying electron lines, determined from photographic plates, are estimated to be good to within 20%, but because

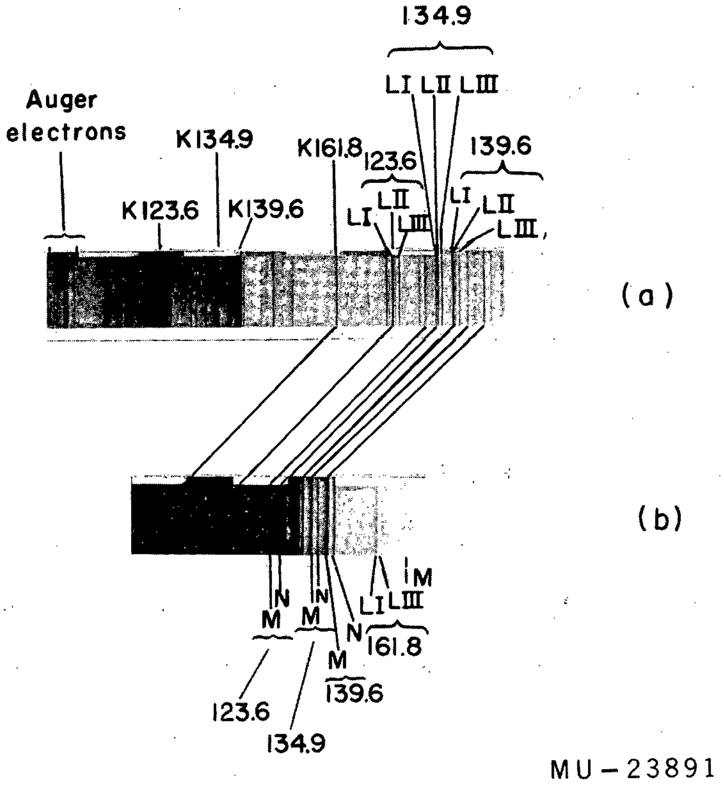

Fig. 1. (a) Portion of mixed Hf^{171} - Hf^{173} electron spectrum.
(b) Portion of Hf^{173} electron spectrum.

Table I. Hf^{173} Conversion-Electron Data

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Electron Intensity		
				180° Spect.	Harmatz et al.[13]	Double foc. Spect.
2.40[a]	M_{II}	4.66				
2.63[a]	M_{III}	4.65		L_{II}/L_{III} ~0.6		
4.13[a]	N_{II}	4.63				
4.19[a]	N_{III}	4.65				
4.61[a]	O	4.65				
			4.65			
14.56	K	77.86		~7.0	~5	
66.98	L_I	77.85		~1.0	~1	
67.47	L_{II}	77.82		W		
			77.8			
60.25	K	123.55		1,300	780	1800
112.68	L_I	123.55		190	100	340
113.23	L_{II}	123.58		53	28	
114.31	L_{III}	123.55		64	32	
121.06	M_I	123.56		60	32	
121.52	M_{III}	123.55				
123.09	N	123.59		13	7.5	
			123.6			
71.65	K	134.95		460	260	460
124.06	L_I	134.94		58	32	225
124.59	L_{II}	134.94		100	51	
125.69	L_{III}	134.94		90	46	
132.69	M_{II}	134.95		69	33	
132.90	M_{III}	134.93				
134.56	N	134.96		30	12	
			134.9			
76.28	K	139.58		1,700	1,000	1950
128.72	L_I	139.58		248	140	375
129.22	L_{II}	139.57		69	36	
129.35	L_{III}	139.59		53	22	
137.07	M_I	139.57		94	54	
137.36	M_{II}	139.59				
139.03	N	139.54		34	15	
			139.6			

Table I. Hf^{173} Conversion-Electron Data (continued)

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Electron Intensity		
				180° Spect.	Harmatz et al.[13]	Double foc. Spect.
98.48	K	161.78		64	37	63
150.95	L_I	161.82		9	5.3	
151.46	L_{II}	161.81		1.4		
151.57	L_{III}	161.81		2.0	1.1	
159.30	M_I	161.80		2.4	1.7	
161.25	N	161.76		W	0.5	
			161.8			
107.95	K	171.25		0.9		
			171.3			
233.44	K	296.74		72	57	72
285.89	L_I	296.77		12	8	
287.50	L_{III}	296.75		5	1.2	
294.23	M	296.72		6	2	
			296.7			
243.05	K	306.35		11.3	10.5	11.2
295.50	L_I	306.37		2.0	1.7	
.....	L_{III}	......		.....	~ 0.4	
303.78	M	306.30		0.6	0.45	
			306.4			
247.84	K	311.15		18.0	17.0	18.5
300.30	L_I	311.19		2.9	2.5	
.....	L_{III}	......		......	0.55	
308.75	M	311.24		0.7	0.7	
			311.1			
293.50	K	356.80		5.5	5	6.8
345.85	L_I	356.73		1.0	0.95	1.2
354.27	M	356.76		0.3	0.25	
			356.8			
359.08	K	422.38		0.75	0.7	0.8
411.40	L_I	422.29		W	W	
			422.3			

Table I. Hf^{173} Conversion-Electron Data (continued)

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Electron Intensity 180° Spect.	Harmatz et al.[13]	Double-foc. Spect.
476.03	K	539.33		1.8	2.15	1.65
528.41	L_I	539.28		0.36	0.27	
			539.3			
485.79	K	549.09		1.9	2.5	2.0
538.21	L_I	549.08		0.4	0.36	
			549.1			
492.10	K	555.40		0.4	0.56	0.46
544.61	L_I	555.47		0.09	~0.1	
			555.4			
503.91	K	567.21		0.40	0.46	
			567.2			
513.52	K	576.82		0.10	0.14	
			576.8			
553.70	K	617.00	617.0	0.04	not resolved	
561.03	K	624.33	624.3	0.05	0.06	
654.09	K	717.39	717.4	0.10	0.10	
696.11	K	759.41	759.4	0.18	0.18	
701.04	K	764.34	764.3	0.05	0.06	
789.30	K	852.60	852.6	0.14	0.12	
794.05	K	857.35	857.35	0.05	not resolved	
810.36	K	873.66	873.7	0.05	0.07	
815.16	K	878,46	878.4	0.10	0.13	
834.40	K	897.70		1.00	1.4	1.0
886.81	L_I	897.67	897.7	0.18	0.19	
968.80	K	1032.10	1032.1	0.32	0.42	
973.70	K	1037.00	1037.0	0.26	0.32	
1005.86	K	1069.16	1069.2	0.052	0.065	

Table I. Hf^{173} Conversion-Electron Data (continued)

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Electron Intensity		
				180° Spect.	Harmatz el al.[13]	Double foc. Spect.
1141.0	K	1204.3	1204.3	0.17	0.21	
1145.7	K	1209.0	1209.0	0.07	0.08	
Probable Assignments						
105.93	K		169.3	~0.6		
109.31	K		172.6	1.1		
218.32	K		281.6	1.8		

[a] These lines were observed with the 50-gauss pre-accelerator spectrograph.

of the large corrections which must be made for geometric and photographic-efficiency effects it is difficult to assign error limits to widely spaced lines. For this reason we have made independent measurements with the double-focusing spectrometer of the relative intensities of principal lines in the spectrum. Both sets of data are given in Table I, with normalization to the K-line of the 296.7 kev transition. In most cases, the deviations between the two sets of measurements are smaller than 10%, though in the case of the 123.6 kev transition the photographic value is ~30% low. We estimate the relative precision of the double-focusing intensity values to be ±20%.

Our energy measurements are in good agreement with earlier results of Harmatz, Handley, and Mihelich.[13] The photographic intensity values of these authors, also given in Table I, deviate considerably from our values, the deviations being almost a factor of two in some cases. It is important to know these intensities accurately for the determination of the transition multipolarities.

VI. PHOTON DATA

Photon spectra were taken with a 7.6-cm x 7.6-cm NaI crystal. Fig. 2 shows a typical singles spectrum obtained with 0.76-cm cadmium and 0.013-cm copper absorbers placed between the source and crystal, at a source-to-crystal distance 5.1 cm. Other spectra were taken with no absorber. The spectra were analyzed in the usual manner of successive subtractions of "standard" line shapes, and the relative intensities were computed by using Heath's[14] values of the total efficiencies and peak-to-total ratios. The results of the analyses are given in Table II.

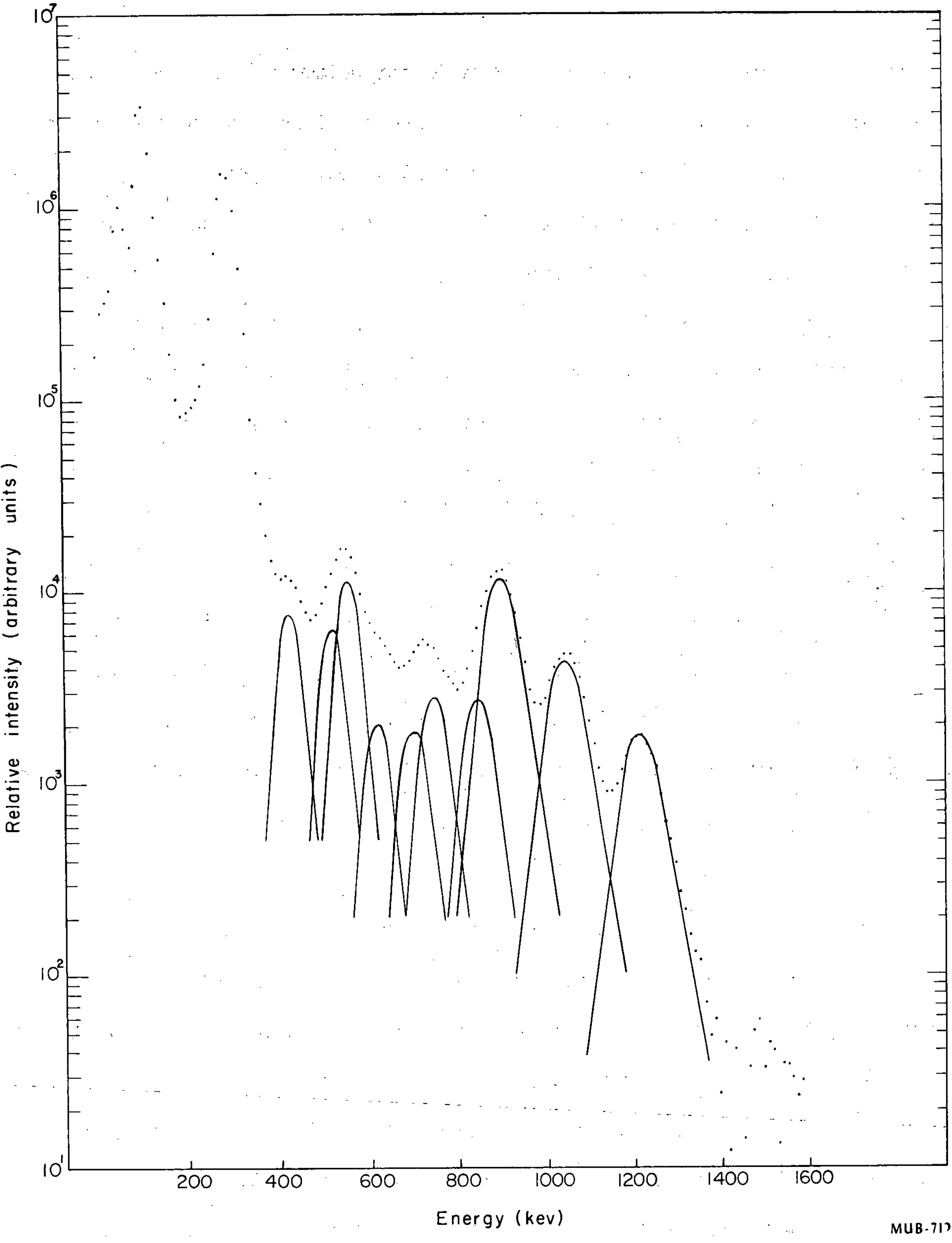

Fig. 2. Singles gamma-ray spectrum of Hf^{173} taken with 7.6cm x 7.6cm NaI crystal.

Table II. Hf^{173} Relative Photon Intensities

E_{γ}[a] (kev)	Relative Intensity[b]	E_{γ} (kev)	Relative Intensity
K X-ray	13,500±2000	1032.1	124 ±13
123.6	11,800±1200	1037.0	
134.9		1069.2	
139.6		1204.6	56 ± 6
161.8	653±130	1209.7	
296.7	6360±640	1350±10	32 ± 12
306.4		1480±10	14 ± 7
311.2		1570±15	~8
356.8	64±25	1700±15	~5.4
422.3	563±18	1800±20	~4.6
539.3	140±21	1910±40	~3
549.1		2000±40	~2
555.4		2120±50	~1.2
567.2		~2260	<0.5
576.8			
617.0	20±10		
624.3			
717.4	27±9		
759.4	42±9		
764.3			
852.6	46±16		
857.4			
873.3			
878.4			
897.7	230±35		

[a] When applicable, the photon energies are those determined in electron spectrographic measurements.

[b] These intensities are normalized in the manner adapted in Table III.

VII. CONVERSION COEFFICIENTS AND MULTIPOLARITIES: THE 123.6- AND 296.7-kev TRANSITIONS

The strongest transition in both the electron and photon spectra is that of 123.6 kev. Harmatz et al.[13] have measured the half-life of this transition as 70 μsec, and we have confirmed this result, with a measured value $t_{1/2}$=70±15 μsec. From the L-subshell ratio (Table I), $L_I/L_{II}/L_{III}$ = 1.00/0.28/0.34, it appears that this transition is an electric dipole, although a mixed M1-E2 transition is not excluded. (For a pure E1 the theoretical subshell ratios, from Rose's tables,[15] are $L_I/L_{II}/L_{III}$ = 1.00/0.22/0.27, and for a 75% M1-25% E2 mixture $L_I/L_{II}/L_{III}$ = 1.00/0.47/0.34). In order to distinguish between these two possibilities, we have measured the absolute conversion coefficient of the 123.6 kev transition by use of the double focusing spectrometer and a 7.6 cm x 7.6 cm NaI crystal coupled to the 100-channel analyzer. Normalization between the two instruments was made with a source of Cs^{137}, which has a known conversion coefficient (β_K = 0.093).[16] The "uncorrected" measured value of the conversion coefficient was (0.11±0.03). In the scintillation spectrum the photopeaks of the 134.9- and 139.6-kev transitions are not resolved from the 123.6-kev peak, so a correction must be made for their contributions to the composite photopeak. It seems certain from the L-subshell ratios of the 134.9- and 139.6-kev transitions that these are M1-E2 mixtures, with approximately 74% and 15% E2 radiation, respectively; thus their K-conversion coefficients, interpolated from Rose's tables, are 0.71 and 1.2, respectively. With this information we compute the contribution of the 134.9- and 139.6-kev transitions to the measured composite value and so obtain the corrected coefficient 0.13±0.05. From a comparison with the theoretical value[15] of an

E1 transition, 0.17, and that of a 75% M1-25% E2 admixture, ~ 1.0, there is little doubt that the 123.9-kev transition is an electric dipole.

From the measured half-life of the 123.9 kev transition and from its assignment as an E1, one notes that the retardation factor of the photon transition is $\sim 10^9$. It is not unusual for E1 transitions to be "slow"; in fact, in the region of deformed nuclei, they are usually retarded by factors of 10^3 -10^6. However, only when E1 transitions are forbidden by the K-selection rule have so great retardations been observed. (e.g., from the decay of the 392-kev level (K = 7/2) in Pu^{239} to members of the ground (K = 1/2) rotational band,[17] where $\Delta K = 3$, the E1 transitions are retarded by $\sim 10^7$). Furthermore, it is known from studies of a number of E1 transitions in deformed nuclei [18] that the internal conversion coefficients of those E1 transitions not forbidden by the K-selection rule become anomalously large when the photon hindrance is greater than $\sim 10^4$, and in one case (84 kev transition in Pa^{231}) where the photon hindrance is $\sim 10^6$ the L_I and L_{II} coefficients are higher than the theoretical values by factors 21 and 15, respectively. In the case of Hf^{173} decay, the L-subshell ratios of the 123.6-kev transition are in good agreement with the theoretical ratios, and the deviation of our experimental K-conversion coefficient from the theoretical value is within experimental error; hence it is natural to conclude from its very large retardation that this transition is highly K-forbidden. This interpretation is important in the understanding of the level scheme.

Next to the group of transitions at 120 - 140 kev, the 296.7-kev transition is the strongest in the spectrum. We have determined its multipolarity by two independent techniques. First, as described above, the intensities of conversion electrons and photons of this transition were compared with those from the standard, Cs^{137}. Here the 296.7-kev photon is unresolved in the scintillation spectrum from the 306.3- and 311.1-kev photons, so one actually measures the quantity

$$(e/\gamma)_{297} \times \frac{\gamma_{297}}{\gamma_{297}+\gamma_{306}+\gamma_{311}} .$$

Our measured value of this quantity was 0.0095± 0.003. To correct for the contributions of the 306- and 311-kev photons we assume that the transitions are all of the same multipolarity and substitute the known quantity $\frac{e_{297}}{e_{297}+e_{306}+e_{311}}$ for $\frac{\gamma_{297}}{\gamma_{297}+\gamma_{306}+\gamma_{311}}$ in the above expression. With this correction we find $(e/\gamma)_{297} = 0.013 \pm 0.005$. This figure is within experimental error of the theoretical E1 conversion coefficient (0.016).

The conversion coefficient was also measured by the "internal-external conversion" technique, inherently a more accurate method. The conversion coefficient is given by the following expression [19]

$$\epsilon = \frac{A_e}{A_\gamma} \tau_k \, f \, d \, b$$

where $\frac{A_e}{A_\gamma}$ = relative intensities of internal and photoelectron K-lines.

τ_k = absolute photoelectric cross section for the K-shell of the converter (uranium).

f = photoelectric angular distribution correction factor.*

d = thickness of converter (here, 2.19 mg/cm^2).

b = dimension factor.

This measurement, made with the 25-cm double focusing spectrometer, yielded the value $(e/\gamma)_{297} = 0.013 \pm 0.004$, also in good agreement with the theoretical E1 value.

As a further check on the multipolarity assignments, the conversion

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* The value of the f-factor applicable for the geometry of this experiment was kindly supplied by the "BESK-Service", Nobel Institute of Physics, Stockholm, Sweden.

coefficients of the weaker 306.4- and 311.1-kev were also determined by the internal-external method and were found to be essentially equal to that of the 296.7-kev transition; thus it is verified that all three of these transitions are electric dipoles. The relevant portions of the internal and external spectra are shown in Fig. 3.

In Table III we have normalized all the relative electron and photon intensity data to the theoretical E1 value (which differs only slightly from the measured values) of the 296.7-kev conversion coefficient, in order to obtain conversion coefficients and multipolarities of the other transitions. In this Table the total absolute transition intensities are also given.

VIII. LEVEL SCHEME; ENERGY SUMS AND BASIC COINCIDENCE RESULTS

The most obvious result of examination of energy sums and differences of the Hf^{173} transitions is the absence of differences of 123.6 kev. That the 123.6-kev transition stands alone in the scheme is consistent with its long (70 μsec) half life; that it stands at the bottom of the scheme is established both by its strong intensity and from the apparent lack of prompt coincidences with other photons.

Another feature of the scheme is that there is evidently a prominent low-energy transition. The difference 4.7 ± 0.2 kev is noted seven times:

139.6 - 134.9 = 4.7
311.1 - 306.4 = 4.7
764.3 - 759.4 = 4.9
857.3 - 852.6 = 4.7
878.4 - 873.7 = 4.7
1037.0 -1032.1 = 4.9
1209.0 -1204.3 = 4.7

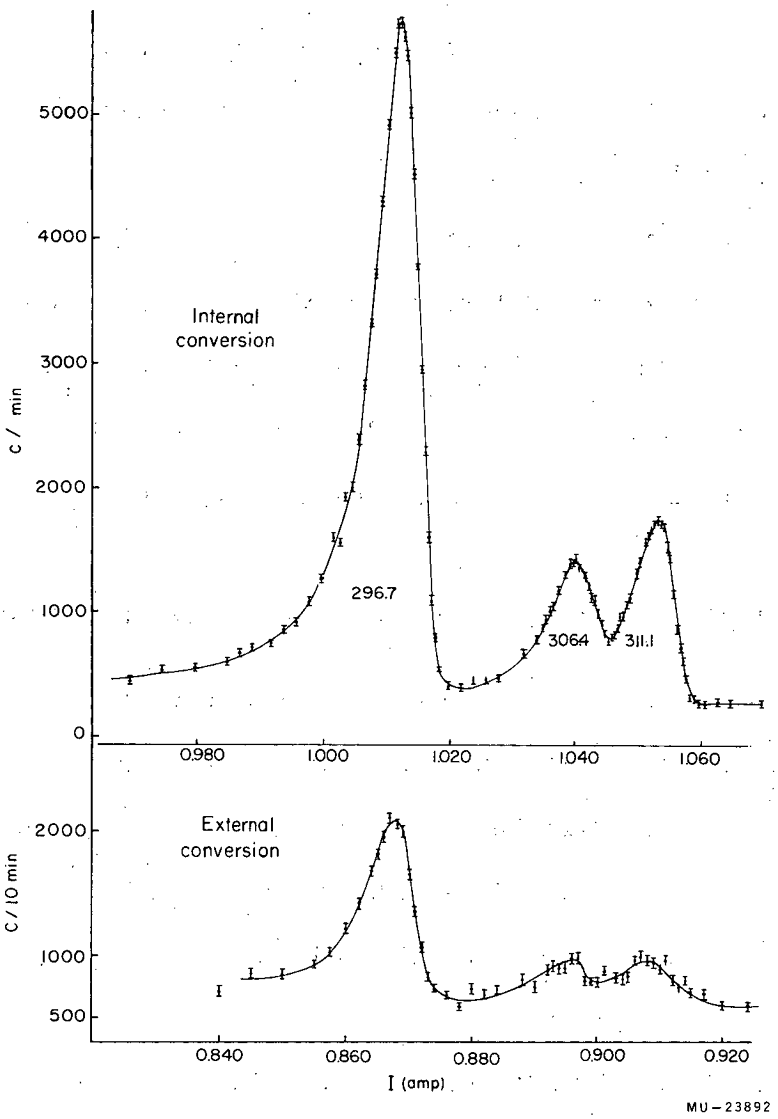

Fig. 3. Internal-external conversion spectrum of 297, 306, and 311-kev transitions.

TABLE III. Experimental K-Conversion Coefficients and Total Transition Intensities

Transition Energy (kev)	Relative Electron Intensity (arbitrary units)		Relative Photon Intensity		$(e/\gamma)_k$	Multipole-order	Total Transition Intensity (% EC decays)
	K	ΣL,M...					
K - X				13,500±2000			
4.64	L_{II}/L_{III}	~ 0.6				E2	
77.8	.....	10				M1	0.08
123.6	1800	410	9970 [a]		0.18	E1	98.5
134.9	460	320	610	11800±1200	0.75	M1-E2 (74±4%E2)	11.2
139.6	1950	500	1200		1.6	M1-E2 (15±3%E2)	29.7
161.8	63	15		653±130	0.096	E1	5.9
296.7	72	25	4500		[0.016] [b]	E1	37.2
306.4	11.2	3	700 [c]	6360±640	0.016 [c]	E1	5.8
311.1	18.5	4	1160 [c]		0.016 [c]	E1	9.55
356.8	6.8	1.5		64±25	0.11	M1-E2	0.5
422.3	0.8	......		56±18	0.014	E1 or E2	0.46
539.3	1.7	0.5					
549.1	2.0	0.5					
555.4	0.46	0.1		140±21			1.2
567.2	0.40	......					
576.8	0.10	......					
617.0	0.04	......		20±10	0.005±0.004	E1 or E2	0.16
624.3	0.05	......					
717.4	0.10	......		27±9	0.004±0.003	E1 or E2	0.22
759.4	0.18	......		42±9	0.006±0.004	E2	0.34
764.3	0.05						

Table III. Experimental K-Conversion Coeffiecints and Total Transition Intensities (continued)

Transition Energy (kev)	Relative Electron Intensity (arbitrary units)		Relative Photon Intensity	$(e/\gamma)_k$	Multipole-order	Total Transition Intensity (% EC decays)
	K	ΣL,M...				
852.6	0.14	......	46±16			0.38
857.4	0.05	......				
873.7	0.05	......				
878.4	0.10	......				
897.7	1.0	0.2	230±35	0.0043±0.001	E2	1.9
1032.1	0.32	......	124±13			1.0
1037.0	0.26	......				
1069.2	0.052	......				
1204.6	0.17	......	56±6	0.004±0.001	E2	0.46
1209.0	0.07	......				

[a] Experimental composite photon intensity divided according to the known, independently determined, conversion coefficients of these transitions. See text.

[b] Photon relative intensity scale normalized to the theoretical E1 conversion coefficient of the 296.7-kev transition, 0.016.

[c] These conversion coefficients were determined, relative to that of the 296.7-kev transition, by internal - external conversion measurements. See Fig. 3.

In the initial experiments with the permanent magnet spectrograph this transition was unobserved, because of the poor efficiency of the photographic plates for electrons of 2 - 4 kev. However, with use of a 50-gauss permanent field spectrograph employing 9.70 kev pre-acceleration,[20] it was subsequently possible to observe this transition, and its energy was measured as 4.65±0.05 kev. This energy agrees well with the accurately measured energy difference between the 134.9- and 139.6-kev transitions, 4.64±0.02 kev.

Table IV shows those energy sums involving crossover transitions, all but one of which differ from the measured crossover energies by less than 0.05%. Making use of these energy sums, one arrives at the energies of the levels shown in Fig. 4. The placement of those transitions which could be resolved in the scintillation spectrum was confirmed with gamma-gamma coincidence measurements. The level scheme of Fig. 4 incorporates essentially all the information obtained in this study. Discussion of the properties of the individual levels of Lu^{173} follows.

Table IV. Energy sums with crossovers in the decay of Hf^{173}.

Sum	Crossover
134.9 + 161.8 = 296.7	296.7
134.9 + 624.3 = 759.2	759.4
134.9 + 717.4 = 852.3	852.6
134.9 + 897.7 =1032.6	1032.1
134.9 +1069.2 =1204.1	1204.3
139.6 + 624.3 = 763.9	764.3
139.6 + 717.4 = 857.0	857.4
139.6 + 897.7 =1037.3	1037.0
139.6 +1069.2 =1208.8	1209.0

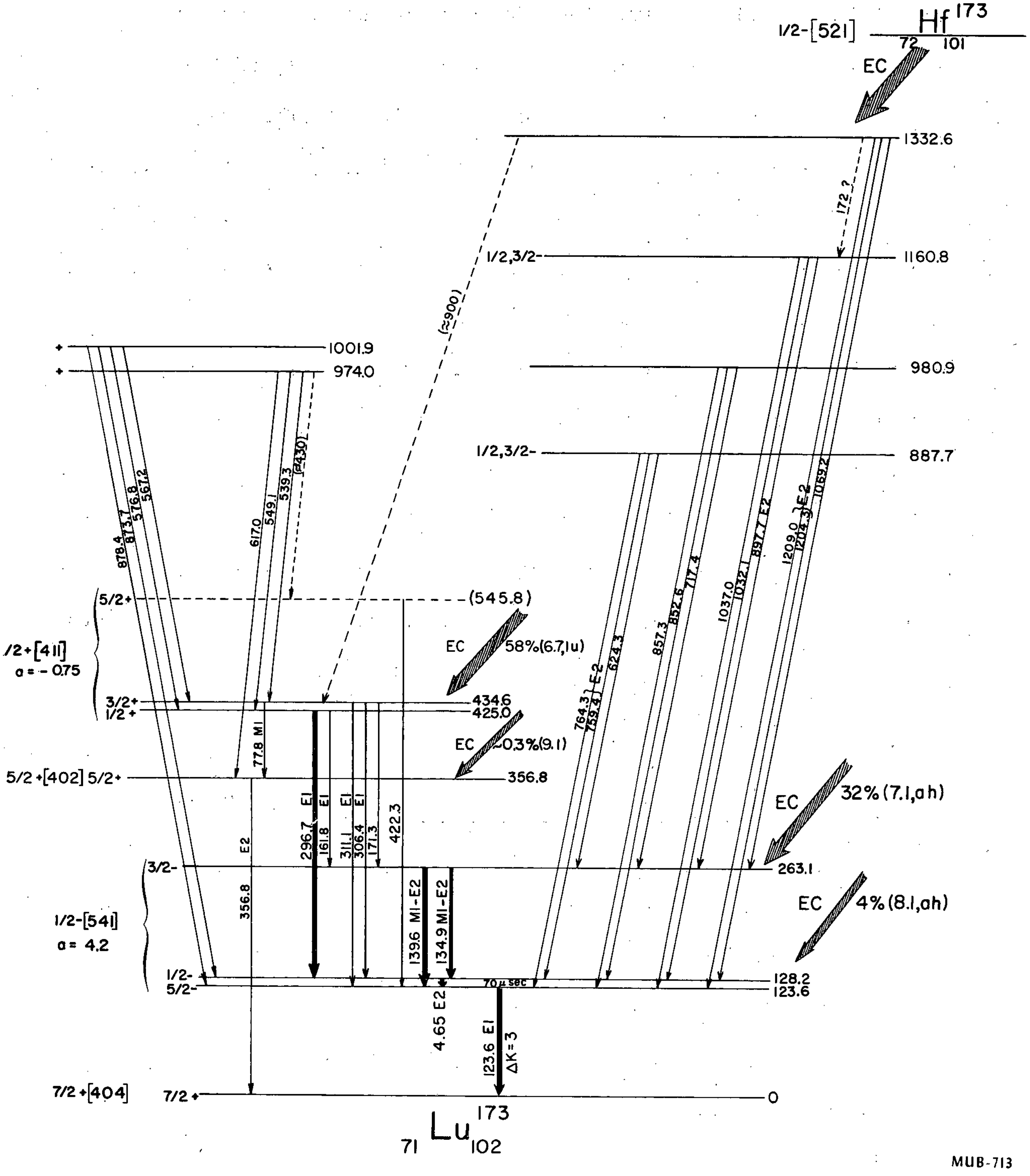

Fig. 4. Decay scheme of Hf^{173}.

IX. GROUND STATE AND K = 1/2 - BAND

The ground state of Lu^{173} has been assigned by Dzhelepov et al.[21] as the Nilsson state 7/2 + [404]. Although we do not confirm the excess of X-rays from Lu^{173} decay upon which Dzhelepov et al. base this assignment, i.e., evidence of a direct ground-to-ground electron capture transition, we feel nevertheless that the assignment is correct. From its conversion coefficient the 123.6-kev transition is shown to be an electric dipole, and the level at 123.6 kev must therefore have spin and parity 5/2-, 7/2-, or 9/2-. The particle state 9/2- [514] is indeed expected to lie near the 7/2+ [404] state, but intrinsic states of K = 7/2- or 5/2- are not expected near ground. The choice of K = 9/2 for the 123.6-kev state is not consistent, however, with the apparent K-forbidden character of this E1 transition, inferred from the combined fact of the 10^9 -fold photon retardation and the normal L-subshell ratios and conversion coefficient. Our interpretation of the data is that the 123.6-kev state has K = 1/2-, I = 5/2.

The 134.9- and 139.6-kev transitions, mixed M1-E2 multipoles, are in all likelihood intra-band rotational transitions. Thus, the states at 123.6-, 128.3- and 263.2-kev are interpreted as rotational states of a single K = 1/2 band. In a K = 1/2 band, the I = 5/2 state lies lower than the I = 1/2 state only if the decoupling parameter, a, exceeds the value +4; in particular, when $4 < a < 5$ the levels are ordered; I = 5/2, 1/2, 9/2, 3/2, 13/2 etc. With the interpretation of this band as shown in Fig. 4 we calculate from the transition energies that a = + 4.2. (The I = 9/2 and I = 13/2 members are not seen). Consistent with this interpretation is the fact that the 4.6 kev transition, which takes place between the 5/2 and 1/2 states, is electric quadrupole.

In the Nilsson diagram, a portion of which is shown in Fig. 5 (see

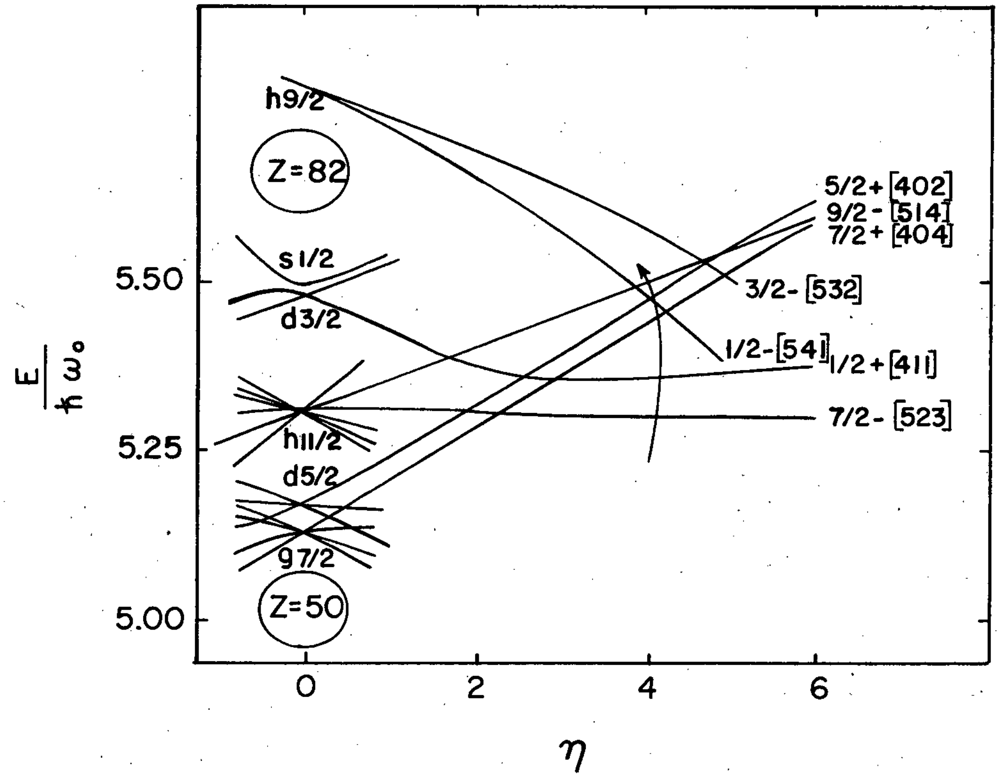

Fig. 5. Portion of Nilsson diagram for protons.

there is no intrinsic state with K = 1/2- in the latter part of the 50-82 proton shell. In this shell the only K = 1/2- state is 1/2- [550], which fills at the beginning of the shell. However, the first asymptotic state beyond the 82 proton shell is 1/2- [541] (originating from the $h_{9/2}$ state of the spherical potential), and it may not be unreasonable to find, at the large deformations characteristic of the lutetium nuclei ($4 < \eta < 6$), that the energy of this state has become sufficiently low to be competitive with the 7/2+ [404] and 9/2- [514] states.

As a check of this hypothesis, we have calculated the value of a, the decoupling parameter, with use of the Nilsson wave functions [1] for the 1/2- [541] proton state ($\mu = 0.7$) by means of the relation [2]

$$a = (-)^{\ell} \sum_{\ell} \left(a_{\ell_0}^{2} + 2\sqrt{\ell(\ell+1)}\; a_{\ell_0} a_{\ell_1} \right).$$

We obtain the values a = +4.3 and +3.5 for deformation parameters $\eta = 4$ and 6, respectively. These theoretical values are in good agreement with the experimental number (+4.2) and lend confidence to the suggested quantum assignments of these levels.

The K = 1/2 assignment to the 123.6-kev level allows a natural explanation (by the K - selection rule) for the high retardation of the E1 transition to ground (K = 7/2) since in this case $\Delta K = 3$, and dipole radiation is allowed only for $\Delta K \leq 1$.

Another check on the K - quantum assignment of this rotational band, a type of check frequently made, is the comparison of the relative reduced transition probabilities B(L) of two radiations of a given multipole, within the band. In most cases, according to Alaga et al.[22] the ratio $\frac{B(L,\, I_i \rightarrow I_f)}{B(L,\, I_i \rightarrow I_{f''})}$ is given simply by the geometric factors involved (ratios of squares of vector addition coefficients). However, where $L \geq K_i + K_f$, as it is in this case since $K_i = K_f = 1/2$, the transition matrix elements are a sum of two products of geometrical and intrinsic factors, and a parameter b depending on the intrinsic wave function is introduced. The following expression then applies:

$$\frac{B(L, I_i \rightarrow I_f)}{B(L, I_i \rightarrow I_{f'})} = \left[\frac{\langle I_i L K_i K_f - K_i \mid I_i L I_f K_f\rangle + b(-)^{I_f+K_f} \langle I_i L K_i, - K_f - K_i \mid I_i L I_f - K_f\rangle}{\langle I_i L K_i K_f - K_i \mid I_i L I_{f'} K_f\rangle + b(-)^{I_{f'}+K_f} \langle I_i L K_i, -K_f - K_i \mid I_i L I_{f'} - K_f\rangle}\right]^2$$

For the comparison of M1 reduced transition probabilities within a K=1/2 band, the parameter b must be evaluated from theory. For collective E2 transitions within the band, however, the quantity b vanishes,[22] so the ratios of the E2 components of the mixed M1-E2 radiations 134.9 and 139.6 kev should still be independent of the nuclear wave functions. Our experimental result,

$$\frac{B(E2,\ 3/2 \rightarrow 1/2)}{B(E2,\ 3/2 \rightarrow 5/2)} = 2.1 \pm 0.4$$

agrees within experimental error with the theoretical value, 2.34.

According to Nilsson,[2] the parameter b_{M1} is given by:

$$b_{M1} = \frac{g_\Omega - 2a\,(g_\ell - g_R) + g_s - 2g_\ell}{2\,(g_\Omega - g_R)}$$

where a = decoupling parameter

g_s = gyromagnetic ratio of intrinsic spin of odd proton

g_ℓ = gyromagnetic ratio of orbital motion of odd proton = 1

g_Ω = total g factor of odd proton

g_R = collective gyromagnetic ratio of the even-even core.

Some comments are necessary about the values of these g factors selected for the calculation:

g_R. For uniformly charged nuclear matter, $g_R \simeq \frac{Z}{A} \simeq 0.4$.

The analysis of collective gyromagnetic ratios by Nilsson and Prior[23] has shown however that for Yb^{172} g_R is ~ 0.3, a value substantially lower than Z/A. We shall use this value, $g_R = 0.3$.

g_s. For a free proton, $g_s = 5.585$. Chiao and Rasmussen,[24] in an analysis of empirical magnetic moment data, point out that in odd-Z nuclei the effective g_s value for protons in nuclear matter is roughly ~ 4 instead of the free value. For the calculation we shall use $g_s = 3.5$, 4.0, and 4.5.

g_Ω. The g factor for the projection of the spin and orbital angular momentum of the odd proton on the symmetry axis was calculated from the definition $g_\Omega = \frac{1}{\Omega}\left[g_s \left\langle s_{Z'} \right\rangle + g_\ell \left\langle \ell_{Z'} \right\rangle\right]$ where the projections were obtained from the Nilsson wave functions appropriate to the state 1/2 - [541] at a deformation parameter $\eta = 4$.

With the three assumed values of g_s we find $b_{M1} = -4.4$, -4.8 and -5.2.

In Fig. 6 a comparison is made of the experimentally and theoretically determined values of b. The solid curve represents the double-valued function $\frac{B(M1, 3/2 \rightarrow 1/2)}{B(M1, 3/2 \rightarrow 5/2)}$ plotted against b. From the experimental branching ratio 0.13±0.025 one finds $b = -4.2 \pm 0.6$ or -0.5 ± 0.1. In view of the assumptions involved in the calculation, the agreement between the theoretical value of b (-4.8 ± 0.4) and the experimental value $b = -4.2$ appears very satisfactory and further strengthens the quantum assignment of this band.

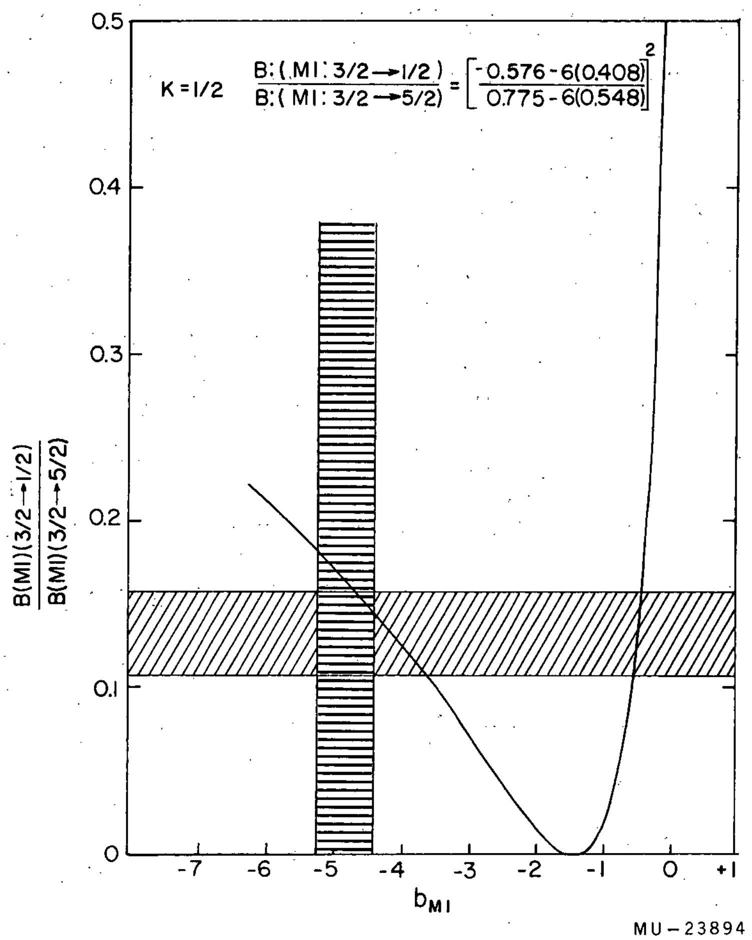

Fig. 6. Reduced M1 transition probabilities as function of b_{M1} for 1/2- [541] band.

X. K = 1/2 + [411] BAND

The intrinsic K = 1/2 proton state labelled [411] is found as the ground state of the thulium isotopes ${}_{69}\mathrm{Tm}^{169}_{100}$ and ${}_{69}\mathrm{Tm}^{171}_{102}$ and may be expected as a low-lying excited state of ${}_{71}\mathrm{Lu}^{173}_{101}$. This state is characterized in ${}_{69}\mathrm{Tm}^{169}$ by the decoupling parameter -0.76 and an inertial parameter $\frac{3\hbar^2}{\mathfrak{J}}$ = 74 kev.[1]

We observe in Lu^{173} two levels which have the properties of the 1/2 and 3/2 members of this band, at 425.0 and 434.8 kev, respectively. The de-excitation spectrum from the 425.0- and 434.8-kev levels is as expected from the assigned spins: a pair of E1 transitions from the ground (I = 1/2) member of the [411] band to the 1/2 and 3/2 members of the [541] band, and another pair of E1 transitions from the I = 3/2 state of [411] to the close-lying 5/2 and 1/2 members of the [541] band. The multipolarities were established to be E1 by the absolute conversion coefficient determinations discussed in Section VII. A weak transition was also seen which fits the energy difference between the I = 3/2 states of the [411] and [541] bands but its multipolarity has not been established.

The decoupling parameter appears from the 1/2 - 3/2 spacing, 9.6 kev, to be similar to that of the thulium bands (if the moment of inertia is also similar). On this basis the 5/2 state is expected to lie in the neighborhood of 540 kev. Though this state is probably populated only very weakly by the decay of Hf^{173} we have tenuous evidence from the γ-γ coincidence data that it lies at 546 kev. If this is correct, the decoupling parameter is calculated to be $\underline{a}$ = -0.75 and the inertial parameter $\frac{3\hbar^2}{\mathfrak{J}}$ = 76.5 kev.

XI. SPIN OF $_{72}Hf^{173}_{101}$

According to the strict level order of the Nilsson diagram[2], the 99th and 101st neutrons would be expected to occupy respectively the 1/2 - [521] and 7/2 + [633] orbitals. $_{68}Er^{167}_{99}$ and $_{70}Yb^{169}_{99}$ are known from experiment to have spin and parity 7/2+ while $_{68}Er^{169}_{101}$ and $_{70}Yb^{171}_{101}$ have spin and parity 1/2 -, so the level order is in these cases apparently reversed. The evidence from this work that the electron-capture decay of Hf^{173} populates the low-spin members of K = 1/2 bands, leads to the unambiguous conclusion that in the Hf^{173} ground state the 101st neutron also occupies the 1/2 - [521] orbital. Consistent with this interpretation is the recent observation by Harmatz, Handley, and Mihelich [25] that this K = 1/2 state is heavily populated in the decay of $_{73}Ta^{173}$.

XII. THE 356.8-KEV LEVEL

A level at 356.8 kev in Lu^{173} was established, from sum relationships and from observations in the coincidence experiments that the 357-kev photon is in coincidence with 540-kev radiation but not with 297-kev radiation. The experimental K-conversion coefficient of the 356.8-kev transition, 0.11±0.04, lies nearest the theoretical M1 coefficient (0.09), though some E2 admixture cannot be excluded (α_k(E2) = 0.032). The weak 77.8-kev transition which excites this state (from decay of the 434.6-kev 3/2+ level) appears from its L_I conversion to be an M1 transition also, so the assignment 5/2+ is indicated for the 356.8-kev level. This state is probably the 5/2 +[402] orbital, which is expected to lie close to the 1/2 + [411] orbital in Lu^{173}.

XIII. HIGHER LEVELS IN Lu^{173}

At the right side of Fig. 3. are grouped those higher levels which decay predominantly to the odd-parity band 1/2-[541] while on the left are two states which decay to the even-parity band 1/2 + [411].

It was not possible to determine the conversion coefficients of all the high energy transitions, because many of them are unresolved in the scintillation spectrum. Those which could be resolved (the 760 - group, the 897.7, and the 1200-kev group) appear to be E2 transitions.

Because of the spin 1/2 of the parent Hf^{173} it is clear that all the high-lying states observed here, populated by electron capture decay, also have low spins, probably 1/2 or 3/2. That some of the transitions to the lower bands may be collective is indicated by their E2 character, and the possibility is strong that they arise from vibrational states.

XIV. INTENSITY BALANCE AND LOG FT VALUES

Within the experimental errors the total transition intensities given in Table III are consistent with the decay scheme shown in Fig. 4. Since the intensity of the 123.6 kev transition is sufficient within 5% to account for the feeding of the higher levels, we conclude that essentially all of the electron capture decays give rise to the 123.6 kev level (except for the weak 357-kev crossover). With the following assumptions: 100% abundance for the 123.6-kev transition, an L/K capture ratio 0.137 (from Rose and Jackson)[26] a fluorescence yield 0.939 (from Wapstra et al.)[27], we calculate that the number of K X-rays expected on the basis of the decay scheme of Fig. 4 is equal within experimental error, to the measured value given in Table III. The absence of excess X-rays indicates that there is no direct electron-capture decay to the ground state of Lu^{173}, a conclusion consistent with assigned spin values 1/2- and 7/2+ for the ground states of Hf^{173} and Lu^{173}, respectively.

In order to calculate log ft values, knowledge of the total decay energy is necessary. The most energetic transition observed by Harmatz et al.[13] from the electron spectrum is 1780 kev, while the highest energy photon we observe in the scintillation spectrum is ~ 2 Mev. In calculating the log ft values, we have assumed a total decay energy of 2.5 Mev, though a value of 2 Mev would not change the results significantly. The log ft values are shown in parentheses in Fig. 3, along with the classification according to the asymptotic quantum number selection rules[22] for those beta branches leading to characterized levels. That the ft value for the beta branch leading to the 128.2-kev level $(I = 1/2-, K = 1/2-)$ is about ten times that to the 263.2-kev level $(I = 3/2-, K = 1/2-)$ is somewhat disturbing. However, this result might be caused by a mixed Fermi and Gamow-Teller transition to the 128.3-kev level, whereas the transition to the 263.2-kev level is pure Gamow-Teller.

The direct electron-capture population of the 356.8-kev state is $\leq 0.3\%$, which corresponds to a log ft value ≥ 9.1. According to the quantum assignment 5/2 + [402] this transition is expected to be of the first-forbidden "unique" type, also hindered in the asymptotic quantum numbers. The log ft values tabulated by Mottelson and Nilsson[1] for transitions of this type in deformed nuclei are all > 8.4, as is the case here.

The combined log ft value for electron capture to the 1/2 and 3/2 members of the 1/2 + [411] band is 6.8. These transitions are classified, in the Mottelson-Nilsson[1] notation, as first-forbidden unhindered (1u).

XV. ACKNOWLEDGEMENTS

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REFERENCES

1. B. R. Mottelson and S. G. Nilsson, Mat. Fys. Skr. Dan. Vid. Selsk. 1, No. 8 (1959).

2. S. G. Nilsson, Dan. Mat. Fys. Medd 29, No. 16 (1955).

3. E. N. Hatch, F. Boehm, P. Marmier, J.W.M. DuMond, Phys. Rev. 104, 745 (1956).

4. J. P. Mize, M. E. Bunker, and J. W. Starner, Phys. Rev. 103, 182 (1956).

5. T. J. Rock, Proc. Roy. Soc. Canada 50, 28A (1956).

6. A. H. Muir and F. Boehm, Phys. Rev. 122, 1564 (1961); U. Hauser, Nuclear Phys. 24, 488 (1961).

7. W. G. Smith and J. M. Hollander, Phys. Rev. 101, 746 (1956).

8. R. G. Albridge, J. M. Hollander, C. J. Gallagher, and J. H. Hamilton, Nuclear Phys. (in press).

9. G. Wilkinson and H. G. Hicks, Phys. Rev. 81, 540 (1951).

10. A. H. Wapstra and C. Jongejans, Physica 20, 36 (1954).

11. W. E. Nervik and G. T. Seaborg, Phys. Rev. 97, 1092 (1955).

12. V. I. Baranovskii and A. V. Kalyamin, Izvestiya Akademii Nauk SSSR (Seriya fizicheskaya) 23, 831 (1959); Columbia Technical Translations p. 825.

13. B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 114, 1082 (1959).

14. R. L. Heath, "Scintillation Spectrometry Gamma-Ray Spectrum Catalogue", Phillips Petroleum Co. Report IDO-16408 (TID-4500) July, 1957.

15. M. E. Rose, "Internal Conversion Coefficients" (North-Holland Publishing Co., Amsterdam; Interscience Publishers, Inc., N.Y.), (1958).

16. S. Hultberg, D. J. Horen, and J. M. Hollander, Nuclear Phys. (to be published); C. de Vries, Nuclear Phys. 18, 454 (1960); A. H. Wapstra, Arkiv för fysik 7, 275 (1954).

17. J. M. Hollander, W. G. Smith, and J. W. Mihelich, Phys. Rev. 102, 740 (1956).

18. F. Asaro, F. S. Stephens, J. M. Hollander, and I. Perlman, Phys. Rev. 117, 492 (1960).

19. S. Hultberg and R. Stockendal, Arkiv för fysik 14, 565 (1959).

20. R. G. Albridge and J. M. Hollander (to be published); R. G. Albridge, UCRL-8642 (Thesis), 1960.

REFERENCES (con't)

21. B. S. Dzhelepov, B. K. Preobrazhenskii, and V. A. Sergienko, Izvestiya Akademii Nauk SSSR (Seriya fizicheskaya) 22, 795 (1958); Columbia Technical Translations, p. 789.

22. G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Dan. Mat. Fys. Medd. 29, No. 9 (1955).

23. S. G. Nilsson and O. Prior, Mat. Fys. Medd. Dan. Vid. Selsk. 32, No. 16 (1961).

24. L. W. Chaio and J. O. Rasmussen, unpublished data (June, 1961).

25. B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 119, 1345 (1960).

26. M. E. Rose and J. L. Jackson, Phys. Rev. 76, 1540 (1949).

27. A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, "Nuclear Spectroscopy Tables", North-Holland Publishing Co., Amsterdam; Interscience Publishers, Inc., N.Y. (1959).