Nuclear Spectroscopy of Neutron-Deficient Lu, Ta, and Re Isotopes

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The systematic behavior of nuclear energy levels has been studied with Lu ($Z=71$), Ta ($Z=73$), and Re ($Z=75$) activities produced in the ORNL proton cyclotron. Conversion-electron data are presented for electron-capture decay of $Lu^{170,174m}$, $Ta^{173-178}$, and $Re^{179,181}$. Level schemes are proposed based on these and on previously published transition data for $Lu^{169,171}$. The properties of odd-A nuclei in the strongly deformed region of odd-N numbers 95–107 are discussed in connection with predictions of Mottelson and Nilsson. Two activities, Lu^{174m} and Re^{179} ($\sim$20 min), are previously unreported.

I. INTRODUCTION

ONE observes in strongly-deformed, odd-mass nuclei both particle excited states and associated rotational excitations.[1] The number of excited levels and transitions between them is such that high resolution spectroscopy is necessary to classify the radiations.

Spectra of neutron-deficient activities of Lu, Ta, and Re have been studied with internal-conversion, photographic-recording, permanent-magnet spectrographs. The radioactivities, produced by proton irradiation (at 22 Mev) in the ORNL 86-inch Cyclotron, were separated chemically[2] from enriched targets.[3] By use of high-intensity, mass-free activities electroplated onto fine wires, it has been possible to record radiations up to 3 Mev which are 10^{-6} times as intense as the strongest line. We have measured precisely the relative transition energies (internally consistent to within 0.1 kev in many cases). The isotopic assignment is based on relative activation with enriched isotopes.

We have indicated multipole assignments (other than $M1$) for the more intense transitions in the range of 20 to 350 kev based on K/L ratios and L and M subshell ratios. The errors which should be assigned to our energy and intensity measurements were discussed previously.[4] The intensity of the Auger-electron spectrum has been utilized, in some cases, to estimate the fraction of electron-capture decay directly to the ground state. These intensities must be used with some discretion since only peak heights (corrected for radius of orbit and film response) are measured, and the primary KLL Auger effect is relatively small (4%). Although little photon or coincidence data are available in most cases, the conversion data, correlated with theoretical predictions, serve in many instances to establish a partial level scheme which is consistent and reasonable.

Mottelson and Nilsson[5] have performed analyses of the intrinsic states of odd-A nuclei having an ellipsoidal equilibrium shape. They have described the relevant levels in terms of the asymptotic quantum number notation and have classified experimentally observed levels. We have reported[6] on the striking regularities in level structure of neutron-deficient, odd-A isotopes of Tb ($Z=65$), Ho ($Z=67$), and Tm ($Z=69$), which agree with their predictions. We shall present, in this paper, evidence for the level ordering of odd-A nuclei having odd-neutron numbers in the range 95 to 107.

A set of asymptotic quantum numbers $[Nn_z\Lambda]$ and K are used by Mottelson and Nilsson to characterize the different single-particle states in the limit where the nuclear potential becomes an anisotropic harmonic oscillator. In this limit, the quantum numbers are N, the total number of nodes in the wave function; n_z, the number of nodal planes perpendicular to the symmetry axis; Λ, the projection of orbital angular momentum on the symmetry axis; and K, the projection of intrinsic spin on the symmetry axis.

We shall discuss special properties which depend on the odd-nucleon orbital such as (1) inertial constant, $3\hbar^2/\mathscr{I}$, and the decoupling parameter, "a", (2) reduced transition probabilities, both interband and intraband, and (3) electron-capture branching and $\log(ft)$ estimates. Data on the strength of transitions between different intrinsic states may allow a test of the utility of selection rules based on the asymptotic quantum numbers.

As a corollary to the odd-A analysis, we will discuss electron-capture decay to some even-even nuclides in

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[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[2] F. F. Felber, Jr., thesis, University of California Radiation Laboratory Report UCRL-3618, January, 1957 (unpublished).

[3] Enriched isotopes were made available by the Isotopes Division of the Oak Ridge National Laboratory.

[4] J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **108**, 989 (1957).

[5] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **1**, No. 8 (1959).

[6] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **114**, 1082 (1959).

TABLE I. Conversion electron data for Ta^{173}(2.5 hr) → Hf^{173}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a, b]
37.4		>150	20		75		
58.0[c]		42	*w*	28	23		
69.75		365	875	1000	500	110	$M1/E2=1.3(3/2- \rightarrow 1/2-)$
81.5	>125	<100[d]	350	320	d	d	$E2(5/2- \rightarrow 1/2-)$
90.2	110	d					
115.0	60						
160.4	290	60					$(7/2- \rightarrow 5/2-)$
172.1	370	e	175[e]	110	d		$E2(7/2- \rightarrow 3/2-)$
180.6	90		d	20	*w*		$E2(9/2- \rightarrow 5/2-)$

[a] Multipole assignments are made on the basis of K/L and L ratios.
[b] Intensity data are arbitrarily normalized to 1000 units for the most prominent line. "*w*" indicates a weak line.
[c] Not assigned in decay scheme.
[d] Composite of two or more lines.
[e] L_I and L_{II} lines partially resolved.

this region. We report very complex internal conversion electron data following electron-capture decay of Lu^{170} and Ta^{176}. The data were examined for evidence of quadrupole vibrational states ($K=2+$) as recently observed in Er^{166} and Er^{168} at approximately 800 kev.[7] A study of the low-energy spectrum of Lu^{174} activity showed a 76-kev ($E2$) transition converting in the Yb daughter and several transitions of lower energy converting in Lu. A similar case was observed for Ho^{162} (67 min) which will be discussed in a subsequent publication. In this instance, transitions of 38.3 and 57.8-kev energy were found to convert in Ho instead of Dy, as was previously reported.[4]

II. RESULTS

A. Ta^{173}(2.5 hr)→Hf^{173}

Proton irradiation of targets enriched in Hf^{174} (8%) gave rise to an activity attributed to Ta^{173} which initiates a decay chain ending with stable Yb^{173}. Transitions observed in Ta^{173} are compiled in Table I. Two transitions of 90 and 170 kev have been reported by Faler.[8] Our half-life of 2.5 hr for this nuclide was obtained by comparison of relative decay rates of the prominent lines in Ta^{173} with lines belonging to Ta^{178} (2.1 hr).

The most intense transitions in the spectrum belong to an "anomalous" rotational band based on the ground state (1/2−[521]),[9] as shown on Fig. 1. The rotational sequence of spin 1/2 through 9/2 de-excites via $M1+E2$ transitions between adjacent levels and by $E2$ transitions between every other level. The calculated energy values of the high spin states in the $K=1/2$ band of 241.9 kev (I_0+3) and 262.5 kev (I_0+4) tend to confirm the measured values of 241.9 and 262.0 kev. The associated rotational parameters are presented in Table II for comparison with available results for adjacent nuclei.

The activation yield of Ta^{173} was quite low due to the limited quantity and low enrichment of the target material, as well as to the short half-life. We report therefore only the low-energy, well-converted portion of the de-excitation spectrum, although the mass tables of Cameron[10] predict an energy of 2.8 Mev available for electron capture of Ta^{173}.

The presence of a low-lying (5/2−[512]) level is predicted by Mottelson and Nilsson. One may construct with these incomplete data a rotational band based on this level which de-excites to the $K=1/2$ band by a transition of 37 kev. This very tentative assignment is

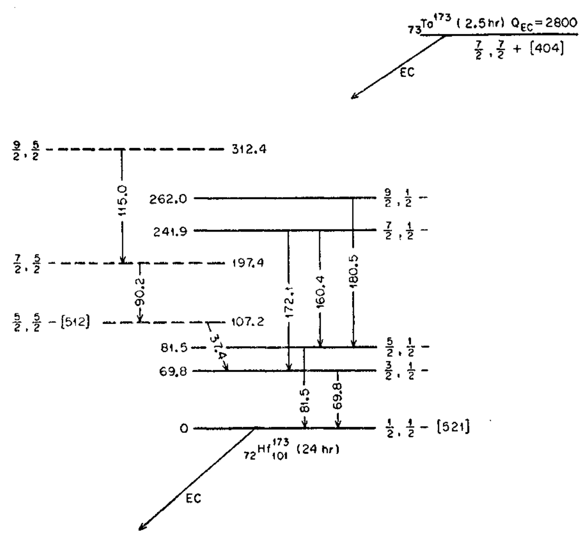

FIG. 1. Levels in Hf^{173} populated by electron-capture decay of Ta^{173}. The convention employed in the designation of intrinsic states is I, $K\pi[Nn_z\Lambda]$, as for all succeeding figures. Rotational sequences are aligned vertically. Excited states which are very uncertain are shown as dashed lines. All energy values are given in kev. The values of Q_{EC} are taken from the tables of Cameron (reference 10).

[7] K. P. Jacob, J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **117**, 1102 (1960).
[8] K. T. Faler, thesis, University of California Radiation Laboratory Report UCRL-8664, April, 1959 (unpublished).
[9] The notation used is ($K\pi[Nn_z\Lambda]$).
[10] A. G. W. Cameron, Atomic Energy of Canada, Limited, Report AECL-433, 1957 (unpublished).

TABLE II. Empirical constants for rotational energy formula,

$$E_I=E^0+(\hbar^2/2\mathcal{I})\{I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})\}+B\{I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})\}^2,$$

where E_I is the energy of state of spin I, $\mathcal{I}$ is the moment of inertia, E^0 is a constant, and "a" is the decoupling parameter which is nonzero only for $K=\frac{1}{2}$, $I_0=\frac{1}{2}$ cases.

Nucleus	Assigned orbital $K\pi[Nn_z\Lambda]$	$E(I_0)$ (kev)	"a"	B (kev)	$(3\hbar^2/\mathcal{I})_{\text{odd}}$ (kev)	$(3\hbar^2/\mathcal{I})_{e-e}$ (kev)	$(\Delta\mathcal{I}/\mathcal{I}_{\text{rigid}})\%$[a] Exper.	Theor.
Yb^{169}	1/2−[521]	24.3	+0.79	−0.008	70.4	87[b]	12	6
Yb^{171}	1/2−[521]	0	+0.85	−0.004	72.4	84.2	8	6
Hf^{173}	1/2−[521]	0	+0.82	−0.009	77.1	c		
Hf^{175}	1/2−[521]	125.9	+0.75	−0.010	81.0	90.9	6	6
W^{181}	1/2−[521]	746.1	+0.59		90.2	102	6	6
W^{181}	1/2−[510]	385.2	+0.48		87.8	102	7	7
W^{183} d	1/2−[510]	0	+0.19		78.1	100.1	10	7
Dy^{161}	5/2−[523]	25.6		−0.011	66.9	87.0	15	15
Yb^{169}	5/2−[523]	570.5			66.8	87	15	15
Yb^{169}	5/2−[512]	191.4		−0.010	75.4	87	8	7
Yb^{171}	5/2−[512]	122.4		−0.005	73.5	84.2	7	7
Yb^{173}	5/2−[512]	0		−0.003	67.6	78.7	7	7
Hf^{173}	5/2−[512]	107.2		−0.007	77.6	c		
Hf^{175}	5/2−[512]	0		−0.004	70.0	90.9	12	7
Hf^{177}	5/2−[512]	508.9			82.6	88.4	3	7
W^{181}	5/2−[512]	365.5			94.6	102	4	7
Yb^{171}	7/2−[514]	835.6			76.0	84.2	5	7
Hf^{175}	7/2−[514]	348.8		−0.034	86.0	90.9	3	7
Hf^{177}	7/2−[514]	0		−0.004	76.4	88.4	7	7
Yb^{171}	7/2+[633]	95.2			48.2	84.2	24	29
Yb^{169}	7/2+[633]	0			47.2	87	29	29
Hf^{177}	7/2+[633]	747.2			67.9	88.4	11	29
Hf^{179} e	9/2+[624]	0			67.0	93.2	14	21
W^{181}	9/2+[624]	0			61.8	102	20	21

[a] $\mathcal{I}_{\text{rigid}}=\frac{2}{5}MAR_0^2(1+0.33\delta)$ is given in reference 1, and $\Delta\mathcal{I}$ is obtained from columns 6 and 7. Theoretical values of $(\Delta\mathcal{I}/\mathcal{I}_{\text{rigid}})\%$ are quoted from reference 5 and O. Prior, Arkiv Fysik **14**, 451 (1958).
[b] Reference to possible 2+ state in Yb^{168} is given by R. G. Wilson and M. L. Pool in Bull. Am. Phys. Soc. **5**, 21 (1960).
[c] Energy of 2+ state of Hf^{172} is not known.
[d] J. J. Murray, F. Boehm, P. Marmier, and J. W. M. DuMond, Phys. Rev. **97**, 1007 (1955).
[e] See reference 5 and D. Strominger, J. H. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

suggested as an analog to the level scheme of Yb^{171}, a similar configuration of 101 neutrons, which will be discussed later.

B. Ta^{175}(11 hr)→Hf^{175}

Our experiments with Ta^{175} produced by the $Hf^{176}(p,2n)Ta^{175}$ reaction indicates the existence of a complex de-excitation spectrum, as listed in Table III. Faler[8] has recently reported on the decay of Ta^{175} and has listed a number of the more prominent transitions and a partial decay scheme. Comparison of the level structure in Yb^{173} and Hf^{175}, both 103-neutron nuclides, show striking similarities and good agreement with the predictions of Mottelson and Nilsson.[5]

Table IV summarizes the character and intensity of transitions incorporated in the decay scheme presented in Fig. 2. The procedure in the construction of this scheme was (1) the development of the (5/2−[512]) ground-state band; (2) the development of the anomalous band based on the level (1/2−[521]) at 126 kev above ground; (3) the population of the available orbital (7/2−[514]) at 348 kev and its associated rotational structure; (4) the postulation of spins of higher lying levels from the observed transitions to the lowest "band" (consistent with angular momentum selection rules); and (5) designation of parity for the higher states from intensity considerations.

The decay scheme that is drawn is consistent with transition intensity and multipole order determinations. Up to 350 kev, the K/L ratio and L subshell configuration generally indicate the multipolarity of the more prominent transitions. The multipole character of other transitions is often predictable either from assignment to a rotational band or from angular momentum selection rules. The total transition intensities are subsequently deduced by applying the proper theoretical internal conversion coefficient.[11] For transitions close to K-electron binding energies, a more accurate estimate of transition intensity may be obtained from use of L-subshell values. Figure 3 is a plot of theoretical K-shell internal conversion coefficients of Rose[11] for dipole and quadrupole radiation as a function of transition energy and for atomic number 72. In our tabulation of conversion data, it is presumed that $E1$ transitions are more likely to be unobserved as a result of their small conversion coefficients.

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

TABLE III. Conversion electron data for decay of Ta^{175}(11 hr) to Hf^{175}.

Transition energy (kev)	K	L_{I}	L_{II}	L_{III}	M	N	Remarks[a]
35.8			*w*	*w*	*w*		
50.5[b]		$\sim$295[c]	290	280	$\sim$200[d]	55	$M1/E2=8$
70.5		65	195	$\sim$185[c]	$\sim$90[d]		$M1/E2=1.1$
77.3[b]	>35	45			*w*		
81.5	>2500	1000	285	185	d	100	$M1/E2=17$
87.5	25	$\sim$10[c]	70[c]	65	*w*		$E2$
100.8[b]	20	*w*					
104.3	>1090	210	40	20	65	15	$M1/E2=19$
125.9[e]	$\sim$550[d]	$\sim$40[d]	$\sim$220[d]	220	$\sim$120[d]	$\sim$35[d]	$E2$
125.9[e]	d	d					
126.6	215[c]	$\sim$35[d]	20	20	d	d	$M1+E2$
132.0	<33[d]	d					
140.9	45	7					
162.0	40[c]	d					
162.5	240	<65[d]	d	4.5	17	5	
179.1	50	c	24[c]	17	13		$E2$
185.8	45	c	20[c]	15	<10[d]		$E2$
192.7	20	c	8[c]	d			$E2$
196.4	43	<9.5[d]			5		
207.4	165	32		c	7.5		$E1$
213.4	<10[d]						
230.8	20	c	6.5[c]	4.5	d		$E2$
266.9	540	90	d	5	23	d	

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
280.5[b]	23	4	475.0	9.5	1.6	867.2[b]	4	*w*
288.9	67	10	525.4[b]	$\sim$2.4		877.6	2	*w*
294.0	<3[d]		533.2[b]	$\sim$1.4		902.2[b]	2	
308.9	6.5		540.4	7.6	1.2	964.3	14	3
348.5	210	40	601.7[b]	$\sim$1.4		1000.1[b]	1.3	
361.4[b]	8.5		621.8[b]	*w*		1013.1	1.0	
365.7[b]	$\sim$1.5		694.5[b]	*w*		1037.7[b]	1.2	
386.0[b]	12		732.5	2.1	*w*	1121.0[b]	2.8	
393.2	43	6	751.4	1.2		1146.0	1.9	
404.1[b]	9	*w*	761.9[b]	$\sim$0.7		1252.2[b]	3.6	
432.8[b]	$\sim$4.4	*w*	809.9[b]	2		1376.4[b]	*w*	
436.4	55	8	814.6[b]	$\sim$0.5		1382.6[b]	*w*	
443.3[b]	$\sim$3		851.5	0.7		1469.8[b]	1.1	
450.5[b]	*w*		853.6[b]	$\sim$0.7		1639.0[b]	0.8	
461.9[b]	2		859.7	10	1.6	*KLL* Auger	$\sim$900[f]	

[a] Conversion line intensity data are internally consistent. "*w*" indicates a weak line. Multipole assignments are made on the basis of K/L or L ratios.
[b] Not assigned in decay scheme.
[c] Not completely resolved from a neighboring line.
[d] Composite of two or more lines.
[e] Anomalously high K-electron intensity is interpreted as an indication of a composite line.
[f] Total intensity of *KLL* Auger electron lines is tabulated.

Recent work[12] on the levels of Yb^{173}, an isotone of Hf^{175}, has established the existence of intrinsic states at 351 kev (7/2+[633]) and at 637 kev (7/2−[514]) above the ground state (5/2−[512]). It appears that the same orbitals are present in Hf^{175} at energies of 207 and 348 kev, respectively. Unique to Hf^{175} is an intense rotational band ($K=1/2$) including levels up to 9/2− at 406 kev. The deviation between the observed and predicted energy for the latter level is 0.9 kev. Five transitions which proceed from the anomalous band to the ground-state band help position the (1/2−[521]) state at 126 kev above ground.

At 348 kev above ground, there appears a probable (7/2−[514]) state which could be the base for a rotational sequence extending to $I=11/2$ at 622 kev. This 7/2− assignment is supported by the probable $E2$ character of a 36-kev transition de-exciting to the 312-kev level ($I=11/2-$). The rotational parameters for this band (shown in Table II) are somewhat higher than for other odd-A, odd-N nuclei in this region. One may note that all three levels of this band proceed to all levels (where $\Delta I\leq 2$) of the ground state (5/2−[512]) band. On the other hand, no transitions are observed to proceed to the levels of the base (1/2−[521]) band. This could be explained by the difference in K number.

[12] J. W. Bichard, J. W. Mihelich, and B. Harmatz, Phys. Rev. **116**, 720 (1959).

By comparing internally converted electron data with the photon data of Faler (Table IV, last column), a consistent assignment of multipole orders for the transitions of 207, 267, and 348 kev is possible (assuming pure dipole radiation). The conversion electron data (K/L and L ratios) indicate that the transitions are predominantly dipole. In this case the relative photon

TABLE IV. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Hf^{175} (Fig. 2).

Proposed excited states $(I,K\pi)$	(kev)	De-exciting transitions (kev)	Multipole[a] assignment	Deduced relative intensities $N_\gamma+N_{ce}$	N_γ[b]	Data of Faler N_γ[c]
(5/2, 5/2−)	0					
(7/2, 5/2−)	81.5	81.5	$M1+E2$	11 230[d]	1340	<1020
(9/2, 5/2−)	185.8	104.3	$M1+E2$	2620[d]	570	
		185.8	$E2$	310	225	
(11/2, 5/2−)	312.4	126.6	$M1+E2$	440	125	
		230.8	$E2$	215	180	
(7/2, 7/2+)	207.4	207.4	$E1$	3960	3750	2830
		125.9	$(E1)$	⩾1000	⩾830 }	3340
(1/2, 1/2−)	125.9	125.9	$E2$	1825[d]	770 }	
(3/2, 1/2−)	196.4	70.5	$M1+E2$	1100[d]	85	
		196.4	$(M1)$	140	90	
(5/2, 1/2−)	213.4	87.5	$E2$	250	35	
		132.0	$(M1)$	<60	<20	
		213.4	$(M1)$	<35	<25	
(7/2, 1/2−)	375.4	179.1	$E2$	325	215	
		294.0	$(M1)$	<20	<18	
		162.0	$M1$	100	50	
(9/2, 1/2−)	406.1	192.7	$E2$	150	110	
(7/2, 7/2−)	348.4	162.5	$(M1)$	600	285	790
		35.8	$E2$	w	w	
		140.9	$(E1)$	370	320	
		266.9	$(M1)$	3120	2455	2265
		348.5	$(M1)$	2300	2040	2040
(9/2, 7/2−)	474.8	126.6[e]	$(M1)$			
		162.5[e]	$(M1)$			
		266.9[e]	$(E1)$			
		288.9	$(M1)$	475	395	
		393.2	$(M1)$	610	560	
		475.0	$(E2)$	570	560	
(11/2, 7/2−)	622.0	308.9	$(M1)$	55	45	
		436.4	$(M1)$	980	920	
		540.4	$(E2)$	610	600	
(7/2, 7/2−)	1045.5	732.5	$(E2)$	335	333	
		859.7	$(M1)$	980	970	
		964.3	$(M1)$	1810	1790	
(9/2, 9/2−)	1226.7	751.4	$(M1)$	90	88	
		851.5	$(M1)$	70	69	
		877.6	$(M1)$	202	200	
		1013.1	$(E2)$	305	304	
		1146.0	$(M1)$	367	365	
K x-ray intensity[f]					~23 400	

[a] Multipolarities are assigned either from conversion electron data, as a member of a rotational band, or from consistency with angular momentum selection rules; latter assignments are in parentheses and are shown unmixed since we have no way of estimating mixing ratios.
[b] Estimates of photon and K x-ray intensity due to internal conversion are based on electron data and theoretical conversion coefficients.
[c] Photon data of Faler[8] are normalized relative to the 348-kev gamma ray.
[d] Photon and K-electron intensities are deduced from L-electron data.
[e] Recurring transition energy is previously listed.
[f] Total K-Auger intensity is estimated at 1.66 times the KLL-Auger intensity. The calculated value of K x-ray intensity is listed in column N_γ and is consistent with transition electron data, as in all succeeding tables.

and electron data fit reasonably well an assignment of $E1$ for the 207-kev transition and $M1$ for the other two. Furthermore, a very similar L-subshell structure was observed for the well-known 208-kev $E1$ in Hf^{177} and the 207-kev radiation in Hf^{175}, when one superimposed the two spectrograms. The 207-kev radiation is expected to depopulate the orbital (7/2+[633]) to the ground state. Among the many unassigned transitions is an intense 50.5-kev radiation of mixed $M1+E2$ character.

We have tabulated transition energies as high as 1.6 Mev in Table III, and Cameron[10] predicts 1.8 Mev available for the decay of Ta^{175} to Hf^{175}. A number of higher energy states in Hf^{175} are postulated at 1045 kev (7/2−[503]) and 1227 kev (9/2−[505]). The classifications of these states must be considered tentative.

The expected orbitals[5] for Ta^{175} are (7/2+[404]) or (9/2−[514]). The former is preferred on the basis of agreement with the selection rules proposed by Alaga.[13] The electron-capture decay proceeds strongly to the levels at 1227, 1045, 622, 475, 348, and 207 kev. The mode of population of the $K=1/2$ band is not known. These electron-capture branches are indicated by dashed arrows on Fig. 2, along with the appropriate

[13] G. Alaga, Phys. Rev. **100**, 432 (1955); and Nuclear Phys. **4**, 625 (1957).

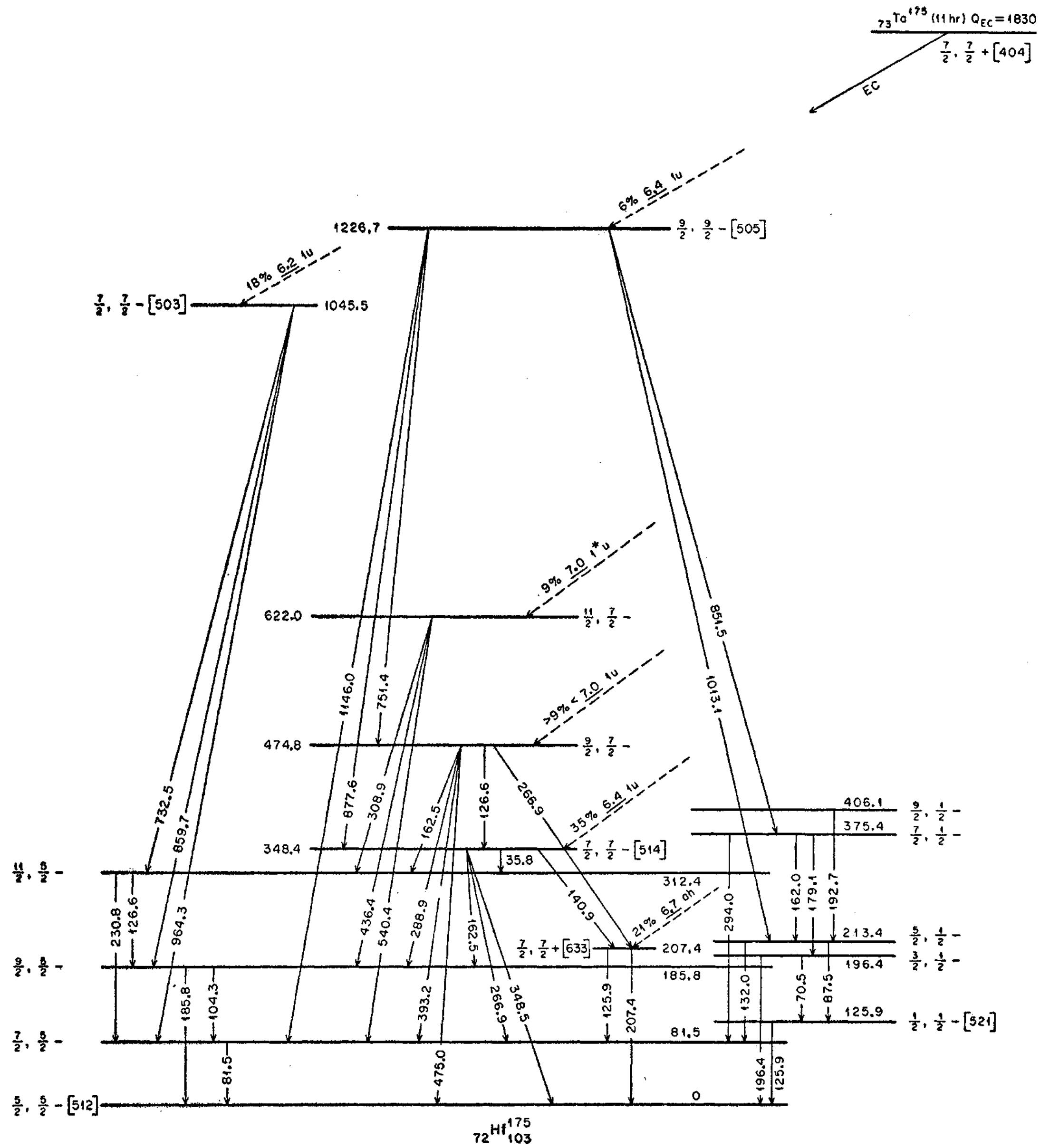

FIG. 2. Levels in Hf^{175} populated by electron-capture decay of Ta^{175}. Electron-capture branches to various levels are shown by dashed arrows with relative intensities in percent and $\log(ft)$ values underlined. The classification of these branches according to selection rules of Alaga (reference 13) follow the notation of Mottelson and Nilsson (reference 5): allowed (a), first-forbidden (1), unique first-forbidden (1*), hindered (*h*), and unhindered (*u*). See caption to Fig. 1.

$\log(ft)$ estimates,[14] as well as the classifications derived from selection rules associated with asymptotic quantum numbers. An extrapolation from the *KLL* Auger-electron intensity data to *K* x-ray intensity (using a *K*-fluorescence yield of 0.94) indicates that no appreciable amount of electron capture proceeds directly to the ground state of Hf^{175}. Asymptotic selection rules are probably impeding the first forbidden ground-state transition.

[14] S. A. Moszkowski, Phys. Rev. 82, 35 (1951).

A further exploration into the nature of the upper levels may be made by investigating the ratios of transition intensities between a single intrinsic state and members of a rotational band based on a different intrinsic state. The experimental and theoretical reduced transition probabilities for a number of nuclei in this region are compared in Table V. The experimental branching ratios for transitions de-exciting the 348 and 1045 kev to the ground-state band are consistent with a number of other determinations for similar transitions ($K_i=7/2$, $K_f=5/2$), all of which differ greatly from the

TABLE V. Branching ratios of dipole radiation between different intrinsic bands ($\Delta K=0, 1$).

Nucleus	Initial state $I(K\pi[Nn_z\Lambda])$	(kev)	Final states $I, I+1, I+2(K\pi[Nn_z\Lambda])$	Reduced trans.[a] prob., experimental
Yb^{169}	7/2(7/2−[503])	1465	5/2, 7/2, 9/2(5/2−[512])	0.4/2.2/1
Hf^{175}	7/2(7/2−[503])	1045	5/2, 7/2, 9/2(5/2−[512])	--/1.3/1
Hf^{177}	7/2(7/2−[503])	1060	5/2, 7/2, 9/2(5/2−[512])	1.1/1.0/-
W^{181}	7/2(7/2−[503])	807	5/2, 7/2, 9/2(5/2−[512])	0.4/1.0/-
Yb^{171}	7/2(7/2−[514])	836	5/2, 7/2, 9/2(5/2−[512])	1.1/1.1/1
Yb^{173}	7/2(7/2−[514])	637	5/2, 7/2, 9/2(5/2−[512])	3.4/1.4/1
Hf^{175}	7/2(7/2−[514])	348	5/2, 7/2, 9/2(5/2−[512])	0.7/2.0/1
Yb^{173}	7/2(7/2+[633])	351	5/2, 7/2, 9/2(5/2−[512])	0.03/3.3/1
				27/8/1 (theor.)[b]
Hf^{177}	7/2(7/2−[503])	1060	7/2, 9/2(7/2−[514])	3.7/1
Hf^{177}	7/2(7/2+[633])	747	7/2, 9/2(7/2−[514])	3.6/1
Yb^{169}	7/2(7/2−[514])	962	7/2, 9/2(7/2+[633])	3.2/1
				3.5/1 (theor.)[b]
Yb^{169}	7/2(5/2−[523])	648	5/2, 7/2, 9/2(5/2−[512])	0.35/0.8/1
				0.5/1.0/1 (theor.)[b]
Yb^{169}	5/2(5/2−[523])	570	5/2, 7/2(5/2−[512])	2.1/1
				2.5/1 (theor.)[b]
Hf^{175}	11/2(7/2−[514])	622	9/2, 11/2(5/2−[512])	7/1
				1.1/1 (theor.)[b]
Hf^{175}	9/2(7/2−[514])	475	7/2, 9/2(5/2−[512])	0.56/1
				1.9/1 (theor.)[b]
Hf^{177}	9/2(7/2+[633])	849	7/2, 9/2, 11/2(7/2−[514])	0.6/1.5/0
				0.38/1.1/1 (theor.)[b]
Hf^{177}	7/2(5/2−[512])	605	7/2, 9/2(7/2−[514])	0.18/1
Yb^{169}	7/2(5/2−[523])	648	7/2, 9/2(7/2+[633])	0.18/1
				0.28/1 (theor.)[b]
Hf^{175}	9/2(9/2−[505])	1227	7/2, 9/2(7/2−[514])	1.5/1
Yb^{171}	9/2(9/2+[624])	936	7/2, 9/2(7/2+[633])	3.5/1
				4.4/1 (theor.)[b]

[a] Reduced gamma-ray intensity is obtained from dividing the K-electron intensity by the theoretical K-conversion coefficient and by the energy dependence, E^3.
[b] The theoretical relation is given by the square of the ratio of Clebsch-Gordon coefficients compiled by A. Simon, Oak Ridge National Laboratory Report ORNL-1718, 1954 (unpublished).

predicted ratio. Lack of agreement with theoretical expectation is likewise found for branching from the high spin states at 475, 622, and 1227 kev. The ratios were obtained assuming pure dipole radiation. Besides the possibility of quadrupole admixture, one should consider the effects of retardation of the dipole radiation and the purity of K quantum numbers as well as the physical basis for asymptotic quantum numbers.

C. Ta^{177}(2.5 day)→Hf^{177}

The levels in Hf^{177} up to 321-kev excitation have been studied extensively[15] in the past employing β^--active sources of Lu^{177}. The electron-capture decay of Ta^{177} was studied by Mann, Nagle, and West,[16] who proposed a decay scheme with levels as high as 1060 kev. Mottelson and Nilsson[5] have made intrinsic state assignments consistent with the data of Mann et al.

We have studied both modes of decay but will discuss only the electron-capture spectrum produced by the Hf^{178}(p,2n)Ta^{177} activation. Table VI presents our complete transition data for this activity. Table VII summarizes data relevant to the decay scheme, including the relative photon intensities of Mann, Nagle, and West. These data corroborate the decay scheme of Fig. 4 proposed by Mann, et al., as well as the orbital assignments of Mottelson and Nilsson. The more precise energy measurements make the placing of certain transitions unique, and the K/L and L-subshell ratios confirm the multipolarities of the low-energy transitions.

We have normalized the photon data of Mann et al. to our electron data, utilizing the 1060-kev $M1$ transi-

TABLE VI. Conversion electron data for decay of Ta^{177} (55 hr) to Hf^{177}.

Transition energy (kev)	K	L_{I}	L_{II}	L_{III}	M	Remarks[a,b]
51.3		~15[c]	w	w	w	$M1+(E2)$?
96.4	>36	15	~3	w	w	$M1$
113.0	10 000	d	~8300[d]	7000	3520	$E2$
137.0	10.5	d	~5[d]	~3		$E2+(M1)$?
208.4	137	21[d]	d	4.4	7	$E1+(M2)$
250.0	11.4	2.1	3.2	1.9	w	$E2$

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
321.4	6.6	1.0	509.1	6.1	1.0	736.1	~0.4	
395.7	w		527.2	1.2		747.6	1.5	
421.5	5.2	1.0	550.7	0.5		849.6	~0.2	
425.4	18.3	3.0	599.0	~0.2		947.6	1.1	w
453.7	~0.4		605.5	0.7		1060.6	4.3	0.8
492.2	3.5	0.7	634.2	0.36		KLL Auger	~5700	

[a] Intensity data are normalized to 10 000 units for the most prominent line. "w" indicates a weak line.
[b] Multipole assignments are made on the basis of K/L and L ratios.
[c] Intensity is estimated visually due to dense blackening in the background.
[d] L_{I} and L_{II} lines not completely resolved.

[15] D. Strominger, J. H. Hollander, and G. T. Seaborg, Revs. Modern Phys. 30, 585 (1958).
[16] L. G. Mann, R. J. Nagle and H. I. West, Bull. Am. Phys. Soc. 2, 231 (1957).

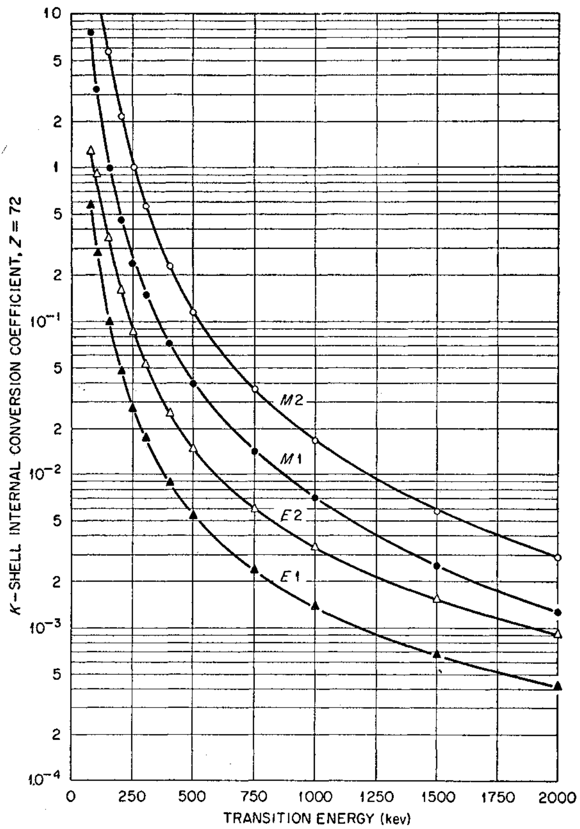

FIG. 3. K-shell internal conversion coefficients of Rose (reference 11) for $M1$, $M2$, $E1$, and $E2$ radiation as a function of energy for $Z=72$.

tion. The experimental K-conversion coefficient (α_K) for the 113-kev $E2$ transition is then in excellent agreement with the theoretical value. The value of α_K for the 321-kev transition is 0.3, in satisfactory agreement with the value of $\alpha_K=0.2$ obtained by Marmier and Boehm,[17] who studied the β^--decay of Lu^{177}. These values of α_K indicate an $E1$ transition with a considerable amount of $M2$ admixture ($\sim$55%). The value of $\alpha_K=0.06$ for the 208-kev $E1$ transition indicates an upper limit of 0.9% for any $M2$ admixture. Angular correlation measurements[18] have shown that the amount of $M2$ is 0.1%.

The intensity of the KLL Auger lines is consistent with the previously determined 70% electron-capture branch to the ground state of Hf^{177}. Figure 4 presents the electron-capture branching ratios to various levels in Hf^{177}. The consistency of the $\log(ft)$ values with the asymptotic selection rules proposed by Alaga[13] tend to support the level classifications of Mottelson and Nilsson.

A well-converted 421-kev transition is observed in the conversion-electron spectrum. This transition may conceivably be of $M3$ character depopulating a (1/2−[510]) isomeric state, in analogy to similar configurations in W^{179} and Hf^{179}. A mixed $M1+E2$ transition of 51 kev could then de-excite a rotational level ($I=3/2$) based on the isomeric state. An estimate of the order of magnitude of the half-life of this possible state may be obtained by comparison with the measured half-lives in W^{179} (222 kev, $T_{\frac{1}{2}}=7$ min) and Hf^{179} (160 kev, $T_{\frac{1}{2}}=19$ sec). On the other hand, there is not yet any experimental evidence to confirm this premise. Rotational excitations may possibly be based on states of intrinsic excitation at 509 and 747 kev. The inertial parameter, $3\hbar^2/\mathcal{J}$, assigned to these bands are 82 and 68 kev, respectively, as compared with $3\hbar^2/\mathcal{J}=76$ kev for the ground-state band.

The consistency of the orbital assignments may be examined by comparing the experimentally observed reduced transition probabilities with theoretical expectations, as shown on Table V. The relative de-excitation of the 1060- and 747-kev states to the 1st and 2nd excited states of the ground-state band are both in essential agreement with the expected 3.5/1 value. In both cases, the stated ratios are between intrinsic state $K_i=7/2$ and a rotational band, $K_f=7/2$. Branching from the rotational level at 605 kev to the ground-state band is experimentally 0.18/1 as compared to the theoretical value 0.28/1. The observed and calculated ratios for transitions from the 849-kev rotational level to the ground-state configuration are 0.6/1.5/1 and 0.4/1.1/1, respectively. The measured ratio for interband transitions between the 1060-kev state and the rotational structure based at 509 kev is 1.1/1, whereas the theoretical ratio is 3.1/1. The observed branching ratios are considered supporting (but not conclusive) evidence for the orbital assignments in Hf^{177}.

D. Re^{179}($\sim$20 min)$\rightarrow W^{179m}$(7 min)$\rightarrow$ W^{179}(40 min)$\rightarrow Ta^{179}$(600 day)

Targets enriched in W^{180} (6.6%) were irradiated with protons, and Re was extracted by distillation. An activity attributable to Re^{179} was observed, and a very approximate value of 20±5 minutes for the half-life was estimated from the rate of decrease of intensity of the conversion lines on successive films. Due to the short half-life and the intense background of conversion lines arising from the activities[15] of Re^{181} and Re^{182}, the obtaining of any data was difficult. However, we have observed an internally converted gamma-ray transition of 221.8 kev, converting in W with a very approximate value of 3.4 for the $K/L_{\rm I}$ ratio (a weak $L_{\rm III}$ line is discernible). Our intensity data is not incompatible with the $M3$ assignment of Mottelson and Nilsson.[5] It is likely that this is the 7-min isomeric transition observed by Rock[19] by a (p,3n) reaction on Ta^{181}. The 222-kev transition we observe is unique to the targets enriched in W^{180}.

In addition, a transition of 30.8 kev (converting in

[17] P. Marmier and F. Boehm, Phys. Rev. **97**, 103 (1955).
[18] E. Klema, Phys. Rev. **109**, 1652 (1958).
[19] T. J. Rock, Proc. Roy. Soc. (Canada) **50**, 28A (1956).

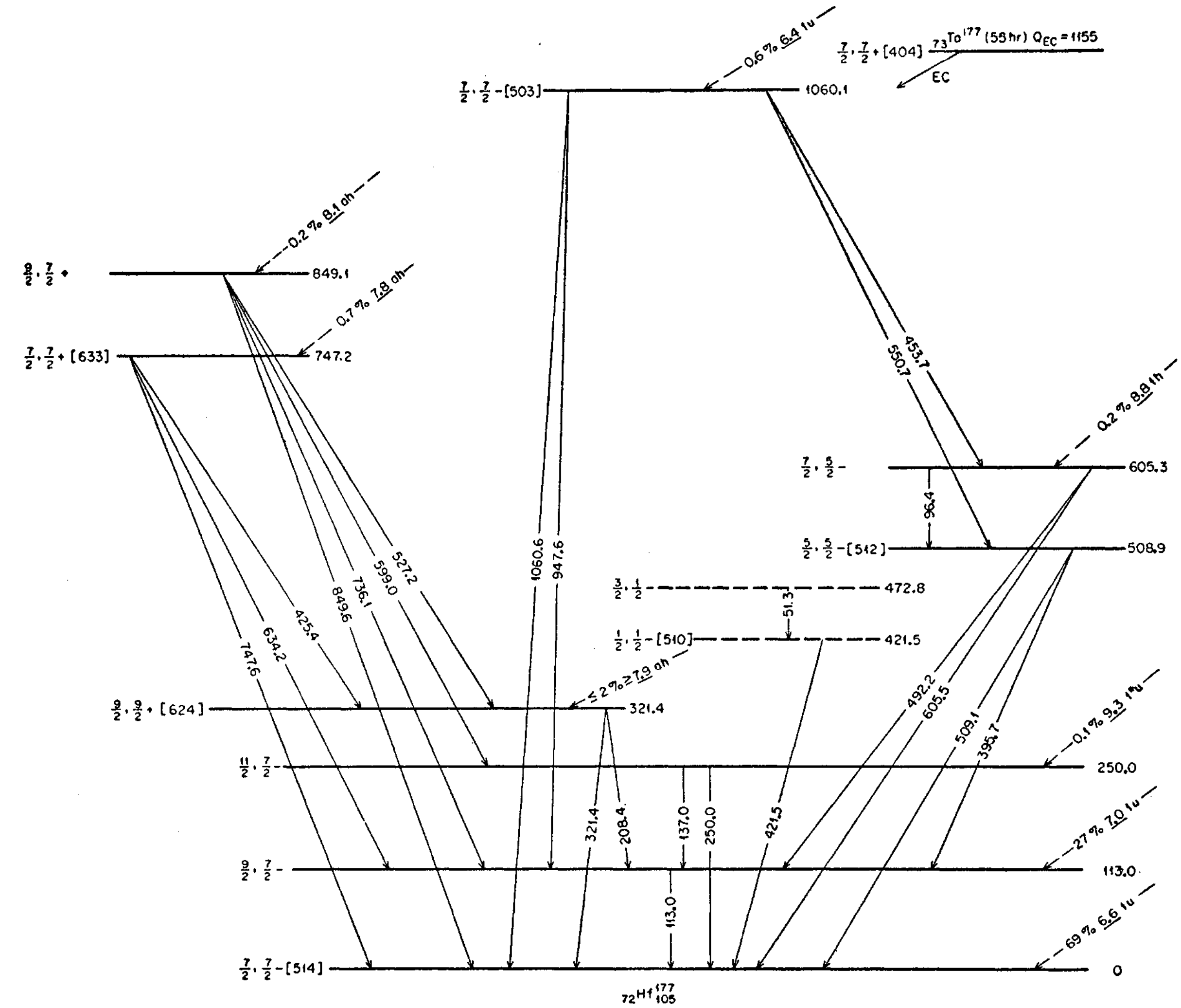

FIG. 4. Levels in Hf^{177} populated by electron-capture decay of Ta^{177}. See captions to Figs. 1 and 2 for meaning of notation.

Ta) was observed. This transition was also measured by Rock and is presumed to follow the 40-min electron-capture decay of W^{179}. The transition exhibits L_I (composite), L_{II}, L_{III} (very weak), and M lines. The multipolarity is probably dipole plus quadrupole, and the intensity is equal (within large experimental errors) to that of the 222-kev transition in W^{179}. Figure 5 displays the decay chain which has also been suggested by Mottelson and Nilsson.

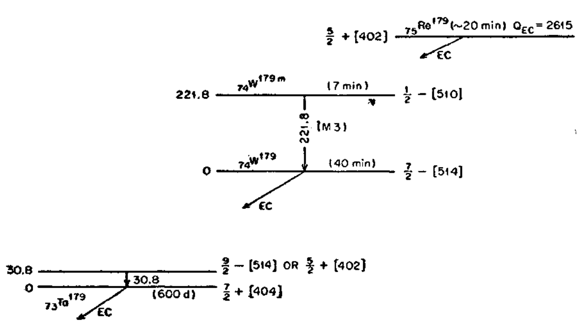

FIG. 5. Decay of Re^{179} to W^{179} to Ta^{179}. Our data confirms the energy measurements of Rock (reference 19) and clearly establishes the isotopic assignment.

Ta^{179} probably is in the (7/2+[404]) state, and one should expect a low-lying (9/2−[514]) orbital, according to Mottelson and Nilsson. This 30-kev level may be fed by an allowed, unhindered electron-capture decay of the ground state of W^{179} (7/2−[514]). Mottelson and Nilsson describe W^{179m} as a (1/2−[510]) orbital. It is likely that a large amount of energy is available for the decay of Re^{179}, so that there must be a number of as yet unobserved transitions.

E. Re^{181}(20 hr)→W^{181}

The preparation of 20-hr Re^{181} by the reaction $W^{182}(p,2n)$ resulted in a source which was a mixture of Re^{181} and Re^{182m}.[15] Since both activities have similar electron energies and half-lives, the spectrum of 13-hr

TABLE VII. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Hf^{177} (Fig. 4).

Proposed excited states $(I,K\pi)$	(kev)	De-exciting transitions (kev)	Multipole[a] assignment	Deduced relative intensities $N_\gamma+N_{ce}$	N_γ[b]	Photon data of Mann et al. N_γ[c]
(7/2, 7/2−)	0					
(9/2, 7/2−)	113.0	113.0	$E2$	44 000	14 000	13 130
(11/2, 7/2−)	250.0	137.0	$E2+(M1)$?	≤44	≤23	35
		250.0	$E2$	145	125	90
(9/2, 9/2+)	321.4	208.4	$E1/M2\geq 100$[d]	≤3325	≤3155	2210
		321.4	$E1/M2=0.8$[d]	33	25	21
(5/2, 5/2−)	508.9	395.7	($E2$)	w	w	
		509.1	($M1$	160	153	210
(7/2, 5/2−)	605.3	96.4	$M1$	175	32	
		492.2	($M1$)	85	80	
		605.5	($M1$)	28	27	
(1/2, 1/2−)?	421.5	421.5	($M3$)	14	8	
(3/2, 1/2−)?	472.8	51.3	$M1+(E2)$?	(25)?	(1)?	
(7/2, 7/2+)	747.2	425.4	($M1$)	307	285	280
		634.2	($E1$)	105	105	210
		747.6	($E1$)	627	625	550
(9/2, 7/2+)	849.1	527.2	($M1$)	33	32	30
		599.0	($E1$)	~50	~50	3.5
		736.1	($E1$)	~150	~150	70
		849.6	($E1$)	~100	~100	140
(7/2, 7/2−)	1060.1	453.7	($M1$)	~8	~8	
		550.7	($M1$)	16	16	<35
		947.6	($M1$)	131	130	140
		1060.6	($M1$)	690	685	685
K x-ray intensity					~148 000	

[a] Multipolarities are assigned either from conversion electron data, as a member of a rotational band, or from consistency with angular momentum selection rules; latter assignments are in parentheses and are shown unmixed, unless otherwise noted.
[b] Estimates of the photon and K x-ray intensities (due to internal conversion) are based on electron data and theoretical conversion coefficients.
[c] Photon data of Mann et al.[16] are normalized to the 1060-kev transition.
[d] Deviation of α_K from that for pure $E1$ is interpreted as an indication of $M2$ admixture.

Re^{182m} had to be subtracted. In Table VIII are listed 75 internally-converted transitions of energy up to 1.5 Mev following electron-capture decay of Re^{181}. A possible partial decay scheme for W^{181} which is most consistent with these experimental results is shown in Fig. 6.

The 365-kev transition accounts for about one-half of the total intensity of the electron-capture decay. This intense gamma ray has been studied in a number of laboratories[20,21] and is interpreted as $M2+(E1)$? from half-life ($t_{\frac{1}{2}}=14$ μsec) and K-conversion coefficient ($\alpha_k=0.30$) considerations. Our $L_{\rm I}/L_{\rm III}$ ratio is not incompatible with $M2$ multipole order. It has been suggested[5,21] that the 365-kev gamma-ray de-excites a (5/2−[512]) state to ground (9/2+[624]). A 252-kev ($E3$) transition is shown in Fig. 6 de-exciting the isomeric state; the observed branching is 2%. The assignment of $E3$ multipolarity for this radiation is based on experimental and theoretical K/L and L ratios. A comparison with the 229-kev $E2$ transition in W^{182} shows the relatively small K and $L_{\rm I}$ conversion coefficients, which are characteristic of $E3$, for the 252-kev transition. With regard to the 19.7-kev transition which proceeds to the 365-kev state, either $E2$ or $E3$ assignment are consistent with the observed L ratio. However, the relative magnitudes of M-subshell lines (i.e., the absence of appreciable M_V) makes an $E2$ assignment preferable.

For the levels postulated in W^{181}, nine intrinsic orbitals are indicated, four of which exhibit rotational excitation. A sequence of three levels may well be the expected low spin states: 385 kev (1/2−[510]), 560 kev (3/2−[512]), and 746 kev (1/2−[521]). A considerable number of transitions proceed between these states, and the 385-kev level is depopulated by the 19.7-kev $E2$ to the 365-kev (5/2−[512]) state. The mode of population of the 746-kev state is not apparent. Two anomalous ($K=1/2$) rotational bands are postulated for which the factors "a" and $3\hbar^2/\mathcal{J}$ are summarized in Table II. Two additional rotational excitations are indicated which are based on the 365-kev and ground states. One may conjecture that the transition of 109.9 kev, rather than the one of 110.3-kev, is the rotational excitation of the 365-kev state.

A number of intrinsic states of high spin are possible in W^{181} at 1469 kev (9/2−[505]), 953 kev (7/2+[633]), 807 kev (7/2−[503]), and 409 kev (7/2−[514]). The experimental branching ratio of 0.36/1 for transitions

[20] S. H. Vegors and P. Axel, Phys. Rev. **101**, 1067 (1956); and A. J. Bureau and C. L. Hammer, Phys. Rev. **105**, 1006 (1957).
[21] C. C. Gallagher, M. Sweeney, and J. O. Rasmussen, Phys. Rev. **108**, 108 (1957).

TABLE VIII. Conversion electron data for decay of Re^{181} (20 hr) to W^{181}.

Transition energy (kev)	K	$L_{\rm I}$	$L_{\rm II}$	$L_{\rm III}$	M	N	Remarks[a,b]
19.7			>400[c]	>400[c]	>200[c]	>45[c]	$E2$
31.1		40	d	*w*	∼10		
38.1		70	8	*w*	20		
43.5		420	75	<65[d]	d	35	$M1$
65.0		580	<330[d]	290	280	60	$E1$ or $M1/E2=15$
71.7		30	12	d	9		
72.7[e]		30	d	d	13		
93.7[e]	>50	10	d	4	d		
102.7	d	f	35	33	∼15[d]	5	$E2$
103.1	16	f	35	30	d		$E2$
109.9	1000	<200[d]	<80[d]	∼20[d]	40	12	
110.3	400	<80[d]	8	∼10[d]	16		
113.3	200	25	d	d	7		
137.2[e]	15	d					
144.3[e]	70	11[f]	f	3			$E1$ or $M1+E2$
154.4[e]	12	2					
163.9[e]	12	d					
164.6[e]	12	d					
165.8[e]	12	2					
175.2	15	f	5.5	∼5[d]	3.2		$E2$
177.4[e]	16	d					
186.2	5	*w*					
195.0	13	d					
197.0[e]	37	6.5			d		
252.2	35	f	30	15	d	4	$E3$
262.6[e]	5	d					
276.2[e]	15	*w*					
295.9	∼4[d]	d					
318.6	35	4.5			*w*		
331.9	32	4.5					
353.6[e]	∼8	f	∼3[f]	*w*	d		
356.1[e]	∼5	*w*					
360.7	160	24			8		
365.5	2750	520	f	40	125	40	($M2$)[g]

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
382.3[e]	∼2.5		668.2[e]	*w*		989.4[e]	1.2	0.17
398.0	10	*w*	693.9[e]	∼0.4[f]		993.7	∼0.14[f]	
408.7	∼2		738.1[e]	0.9	*w*	1000.2[e]	0.7	d
441.8	13	2.2	769.6[e]	∼0.3	*w*	1009.3[e]	<1.5[d]	d
475.6	∼2		791.4[e]	∼0.3	*w*	1075.6[e]	∼0.16[f]	*w*
487.2[e]	∼5[f]	<1.6[d]	803.6[e]	∼2[f]	d	1086.9[e]	0.27	∼0.04
489.0[e]	∼6[f]	<1.6[d]	805.2[e]	∼1[f]	d	1103.5	0.14	
515.7	∼0.5		822.6[e]	0.45		1383.7[e]	0.08	
522.2[e]	∼0.7		840.4	0.25		1440.6[e]	0.40	0.05
557.7[e]	<1.6[d]		854.5[e]	0.3	*w*	1469.1	0.14	
587.6	1.2	*w*	880.0[e]	0.9	*w*	1538.4[e]	0.06	
639.0[e]	3.6	∼0.5[f]	883.1[e]	0.44	*w*	*KLL* Auger		∼680
651.2[e]	0.7		907.5[e]	0.24	*w*			
661.8	1.4	0.4	953.7	4.6	<1.5[d]			

[a] Intensity data are normalized to 2750 units for the most prominent line; "*w*" indicates weak line.
[b] Multipole assignments are based on K/L and L ratios.
[c] Film sensitivity and source effects are very uncertain at these low energies.
[d] Conversion line is a composite of two different lines.
[e] Not assigned in decay scheme.
[f] Conversion lines not completely resolved.
[g] See references 20 and 21.

de-exciting the 807-kev ($K_i=7/2$) level to the $5/2-[512]$) rotational band is in rough agreement with some of the other cases shown in Table V.

F. Radioactivities of Mass 174

The electron-capture decay of Lu^{174} (165 days) to the first excited (2+) state in Yb^{174} has been known for some time.[4] Recent experiments[22,23] have shown that at least one other high-energy transition follows the electron capture of Lu^{174}.

We have measured a number of conversion lines in a source of Lu^{174m} produced by irradiating enriched Yb^{174} with protons. In addition to the previously reported 76.5-kev ($E2$) transition in Yb^{174}, three low-energy transitions for which the differences in energy of the L and M conversion lines are uniquely those of Lu are observed. Table IX displays this data.

The conversion data for the 59-kev transition are

[22] R. G. Wilson and M. L. Pool, Phys. Rev. **117**, 517 (1960).
[23] L. T. Dillman, R. W. Henry, N. B. Gove, and R. A. Becker, Phys. Rev. **113**, 635 (1959).

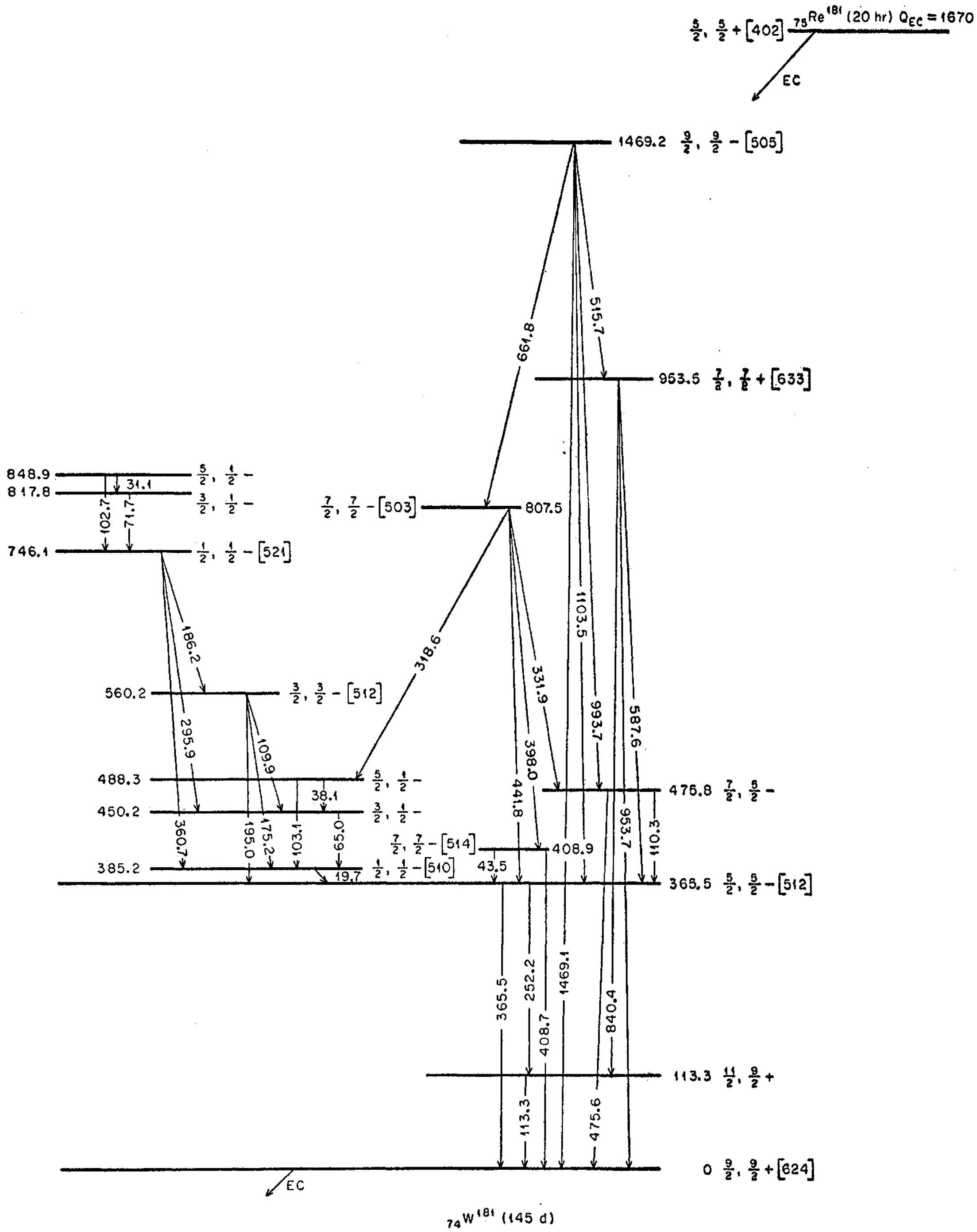

FIG. 6. Partial decay scheme of Re^{181}. See captions to Figs. 1 and 2 for discussion of notation.

consistent with an $M3$ multipole order assignment. The theoretical L-subshell ratio for $M3$ according to Rose[11] is $L_I:L_{II}:L_{III}=740:46:1600$, whereas the experimental determination is $780:<180:1610$. The experimental L_{II} intensity is somewhat high because it is coincident with a KL_IM Auger electron line. The observed M-subshell ratio ($M_I:M_{III}=190:480$) is in agreement with the theoretical value. However, the experimental L/M ratio is larger than the theoretical ratio by a factor of two.

We have made a qualitative check on the half-lives of the three transitions in Lu. In a number of spectrograms taken at various elapsed times, the ratio of the intensity of these transitions in Lu compared to the

TABLE IX. Conversion electron data for decay of Lu^{174m} and Ta^{174}.

Transition (kev) element	K	L_I	L_{II}	L_{III}	M	N	Remarks[a, b]	Rel. transition intensity[c]
Lu^{174m}(165 day) → Lu^{174} → Yb^{174}								
59.05(Lu)		780	<180[d]	1610	670	240	$M3(6-\rightarrow 3-)$	3480
67.05(Lu)		320	d	*w*	95	d	$M1(3-\rightarrow 2-)$	3050
44.65(Lu)		1290	160	~65	350	115	$M1(2-\rightarrow 1-)$	2270
76.5(Yb)	>210	e	1000[e]	950	510	150	$E2(2+\rightarrow 0+)$	3350
Ta^{174}(~1 hr) → Hf^{174}								
90.9(Hf)	~300	e	1000[e]	980	450	d	$E2(2+\rightarrow 0+)$	

[a] Conversion intensity data are internally consistent for lines in the Lu^{174m} decay chain. Comparison may not be made between data for Lu and Ta "*w*" indicates weak line.
[b] Multipole assignments are made on the basis of K/L and L and M ratios.
[c] Estimates of transition intensity are obtained from electron data and theoretical conversion coefficients.
[d] Electron line is a composite of two different lines.
[e] L_I and L_{II} lines are not completely resolved.

intensity of the 76.5-kev transition in Yb (following electron capture) is constant. One may say that the half-lives of the transitions in Lu are very similar, or identical to that of the electron-capture activity.

One may propose the following decay scheme as shown in Fig. 7. The 59.1-kev transition may be responsible for the 165-day half-life. In this case, the half-life of Lu^{174g} would be relatively short (< few days). However, 165 days is roughly 10^8 times the single-particle estimate for the half-life of an $M3$ transition of 59 kev. If one considers the sum and difference of probable spins of the two odd nucleons, one obtains the values of 6− and 1− for this "doublet." A spin sequence, as shown, of 6−, 3−, 2−, 1− is very reasonable and is consistent with estimates of transition intensity. The 44.6- and 67.1-kev transitions in cascade obey exactly the $I(I+1)$ interval rule for spin sequence 1, 2, 3. The ratio, however, may be coincidental. The 111.7-kev ($E2$) crossover is not observed.

The electron capture of Lu^{174g} proceeds to levels of 76.5 and 1320 kev in Yb^{174}. We have confirmed the existence of a 1245-kev transition[24] which is in prompt

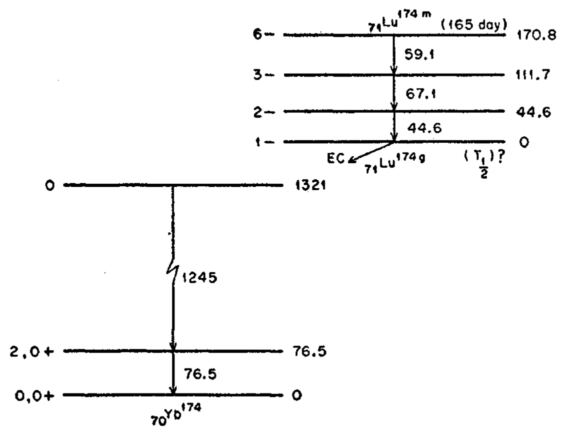

FIG. 7. Electron-capture decay of Lu^{174m} and Lu^{174}. No evidence of β^- decay was observed.

[24] Mr. J. W. Bichard of Notre Dame contributed to this phase of the work.

coincidence with the 76.5-kev transition. The absence of any transition to the 0+ ground state or expected 4+ level indicates that the spin of the level at 1320 kev is probably 0. This is of course consistent with the conjectured spin of Lu^{174g}.

No evidence of β^--decay of Lu^{174} to the 90.9-kev (2+) level in Hf^{174} was observed. The electron-capture decay of Ta^{174} (1.2 hr) to Hf^{174} has been reported by Faler,[8] who observed transitions of 90, 160, and 205 kev with a scintillation spectrometer. We have studied the internal conversion electron spectrum with a source of Ta^{174}, and for intensity reasons see only a 90.9-kev transition for which the L and M subshell ratios are those expected for an $E2$ transition.

An illuminating presentation of the systematics of first excited (2+) states in even-even nuclides is shown in Fig. 8 where the transition energies in kev are charted on a two dimensional display of proton number vs neutron number. The empirical evidence was obtained by Coulomb excitation experiments by Chupp et al.,[25] and by internal conversion studies.[4] Reference lines are drawn at 66 protons and 104 neutrons which are halfway between the closed shells. The lowest observed 2+ level (73 kev) occurs at 66 protons, and for the two cases available, minima for a given proton number occur at 104 neutrons. One may note that for $Z=66$, the energy decreases as the neutron number approaches 104, and that for neutron number of 104, the energy decreases as the proton number approaches 66.

G. Ta^{176}(8 hr)→Hf^{176}

Early experiments[2] with the Ta^{176} activity indicated two $E2$ transitions in Hf^{176} of 88 and 202 kev. These transitions have also been studied with the β^--decay activity of Lu^{176} [26] and by Coulomb excitation.[25] We observe an $E2$ transition of 88-kev energy for the 3.7-hr Lu^{176m} activity which was produced by the

[25] E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson, and H. Mark, Phys. Rev. **112**, 518 (1958).
[26] R. N. Glover and D. E. Watt, Phil. Mag. **2**, 699, (1957); J. R. Arnold, Phys. Rev. **93**, 743 (1954).

TABLE X. Conversion electron data for decay of Ta^{176} (8 hr) to Hf^{176}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a,b]
88.35	>310	c	1000[c]	950	460	$E2(2+\rightarrow 0+)$
91.3	>4	*w*	5.5	5.5	d	$E2+(M1)$?
201.9	57	7	16	12	8	$E2(4+\rightarrow 2+)$

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
99.6	3.3	d	611.9	1.9	*w*	1359.0	<0.3[d]	
103.4	2.3		616.5	~0.35		1489.5	*w*	
125.6	14	2	639.0	*w*		1504.3	0.12	
131.1	2.4		645.5	1.3		1556.9	~0.12	
146.7	11.5	*w*	677.6	0.55		1586.4	0.35	
156.8	8	*w*	686.3	*w*		1618.2	~0.15	
158.2	12	*w*	711.4	5.4	0.8	1632.6	0.28	
175.6	13	*w*	723.3	*w*		1672.3	0.22	
190.4	11.5	*w*	741.4	*w*		1681.0	*w*	
240.0	9	1.5	938.2	~0.15		1698.9	0.45	
366.5	0.4		1024.7	~0.25		1707.2	~0.08	
414.8	0.35		1140.2	0.8		1723.5	~0.08	
466.5	3.3	d	1161.5	3.0	0.44	1778.2	~0.14	
473.6	0.85		1192.3	1.0		1825.4	0.35	*w*
508.4	3	0.45	1203.1	~0.15		1863.7	0.27	*w*
513.1	1.1		1225.1	2.8	0.4	1907.7	*w*	
522.0	5.2	0.85	1254.8	0.43		1958.1	*w*	
533.1	0.6		1271.7	0.27		2045.1	0.12	
546.9	1.4	*w*	1295.7	3.3	0.45	2081.0	~0.08	
571.1	1.4	*w*	1343.5	0.3		Auger (KLL)	~156	

[a] Intensity data are normalized to 1000 units for the most prominent line; "*w*" indicates a weak line.
[b] Multipole assignments are based on K/L and L ratios.
[c] L_I and L_{II} lines not completely resolved.
[d] Conversion line is a composite of two different lines.

$Yb^{176}(p,n)Lu^{176}$ reaction. Our investigation of the decay of Ta^{176} to Hf^{176} with internal conversion spectrographs has revealed more than 60 transitions of energy up to 2 Mev, as shown in Table X. Gamma-ray studies of Rasmussen and Shirley[27] show a number of broad peaks up to 3-Mev energy. The predicted energy available for decay of Ta^{176} is 3.45 Mev.[10]

It is likely that the two $E2$ transitions of 88- and 202-kev energy are in cascade based on the ground state. For this rotational sequence, one obtains values of 88.9 and -0.015 for $3\hbar^2/\mathscr{I}$ and "B", respectively. The predicted energy for the $6+\rightarrow 4+$ transition is 303.5 kev, but such a transition is not observed. Transition intensities for the 88- and 202-kev radiations are 3700 and 470, respectively, based on conversion-electron data and theoretical conversion coefficients. The intensity of the Auger electron spectrum does not allow any appreciable electron-capture branch directly to the ground state. The above observations agree with those of Felber.[2]

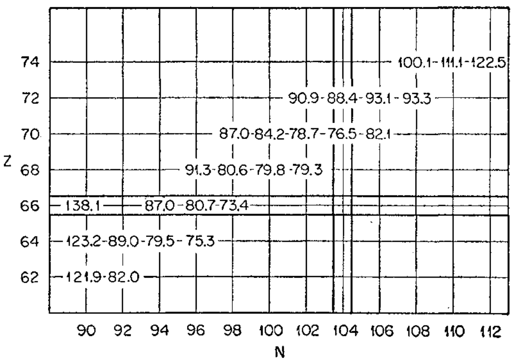

FIG. 8. First excited (2+) states in even-even nuclei are charted as a function of proton and neutron number with reference to $Z=66$ and $N=104$, the halfway marks between closed shells.

Not much may be said about higher energy states of Hf^{176} on the basis of the internal conversion study. Energy sums of transition data suggest very tentative levels at 611.2, 704.6, 799.3, 1343.5, 1675.5, and 1795.2 kev. These possible excited states are indicated solely as a guide for future experiments.

H. Ta^{178}(2.1 hr)$\rightarrow Hf^{178}$

The decay of the 2.1-hr activity in Ta^{178} has been reported by Felber.[2] Our more complete conversion electron data, as compiled in Table XI, shows good agreement with his results except for the multipolarity of the 331.7-kev transition which he designated as $E2$. The conversion lines of the 325.7-kev transition, also present, can serve as a convenient standard for $E2$ multipolarity. The K/L ratio and L-subshell structure of the transitions of 326 and 332 kev are very different and correspond to the theoretical conversion coefficients for pure $E2$ and $M1$, respectively. The value of the L-subshell ratio observed for the 88.8-kev isomeric transition of $E1$ multipole order is $L_I:L_{II}:L_{III}=1:0.32:0.42$. The theoretical conversion ratio[11] for an

TABLE XI. Conversion electron and photon for decay of Ta^{178}(2.1 hr) $\rightarrow Hf^{178}$.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a,b]	Rel. photon intensities Deduced[c]	Data of Felber
88.8	>450	115	37	48	d		$E1$	3200	3490 (88.8 + 93.1)
93.1	>400	~100[d]	1000[d]	950	500	150	$E2(2+\rightarrow 0+)$	750	
213.6	575	d	200[d]	120	85	28	$E2(4+\rightarrow 2+)$	4110	4110[e]
325.7	240	d	50[d]	18	20	5	$E2(6+\rightarrow 4+)$	5400	5550 (325.7 + 331.7)
331.7	220	32			9	2	$M1$	1880	
426.8	120	32[d]	d		9		$E2(8+\rightarrow 6+)$	5320	3700
KLL Auger	~190							~4920	~5750

[a] Multipole assignments are made on the basis of K/L and L ratios.
[b] Electron intensity data are internally consistent and normalized to 1000 units for the most prominent line.
[c] Deduced photon and K x-ray intensities are obtained from electron data and theoretical conversion coefficients.
[d] Partially resolved from a neighboring line.
[e] Photon intensities of Felber[2] are normalized relative to the 213-kev transition.

[27] J. O. Rasmussen and D. A. Shirley, University of California Radiation Laboratory Report UCRL-8618, 1959 (unpublished).

89-kev $E1$ is $L_I:L_{II}:L_{III}=1:0.33:0.39$. Our additional evidence supports the decay scheme proposed by Felber.

No data was obtained on the decay of the presumably low spin Ta^{178} (9.5 min).[2,28]

I. Lu^{170}(1.9 day)→Yb^{170}

The electron-capture decay of Lu^{170} has been studied with intense sources in the electron spectrographs. The Lu activity was produced by the $(p,2n)$ reaction on enriched Yb^{171} targets. Our previous data[4] consisted of two $E2$ transitions of 84.2 and 193.5 kev. The tabulation of the ninety internally converted transitions which have been observed in the Lu^{170} spectrum is presented in Table XII. Transitions of energy up to 3 Mev were recorded, this energy being the limiting range of the spectrographs. Cameron's mass tables[10] indicate 3.5-Mev energy for this decay.

Only a tentative and fragmentary level scheme for Yb^{170} is feasible at this stage. However, it is likely that the 2+ and 4+ levels of the ground-state rotational band are at 84.2 and 277.7 kev, with no evidence for the possible 6+ level. The energy constants $3\hbar^2/\mathcal{J}$ and "B" are 84.7 and −0.0114 kev, respectively.

There is some evidence of weakly populated levels at 1231.6 and 1308.6 kev on the basis of energy sums.

TABLE XII. Conversion electron data for decay of Lu^{170} (1.9 day) to Yb^{170}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a,b]
84.3	>340	c	1000[c]	1000	440	$E2(2+\rightarrow 0+)$
193.5	35	c	13[c]	6.6	5	$E2(4+\rightarrow 2+)$

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
152.8	18	3.5	689.1	0.3		1453.3	2.7	0.4
221.2	0.65	w	840.9	~0.5[d]		1458.4	~0.3[d]	
222.7	1.4	w	856.8	0.65		1483.0	1.7	0.27
223.8	0.6		940.2	0.8		1515.0	w	
228.5	2.1	0.3	955.2	0.2		1517.4	w	
236.1	0.75	d	986.8	1.7	0.25	1553.5	0.13	
241.7	5.3	0.8	988.9	~0.5[d]		1569.4	0.25	w
251.3	~0.57[c]		1001.5	~0.5[c]		1577.1	0.08	
283.4	3.2	0.6	1005.0	1.5	d	1688.1	w	
286.8	1.0	~0.2	1030.2	0.25		1815.9	w	
301.9	0.36		1056.3	1.0	0.17	1861.0	w	
323.9	3.5	0.6	1063.0	0.55	d	1939.1	w	
366.4	0.27		1103.0	0.3		1955.9	0.13	
369.9	0.23		1136.0	0.4		2039.0	0.27	
372.2	~0.3[d]		1141.4	0.75		2123.6	0.09	
382.8	~0.3[d]		1147.7	0.5		2359.1	0.06	
384.8	0.15		1225.0	0.55		2488.2	w	
389.1	0.65	0.1	1228.3	0.4		2512.1	w	
396.2	1.45	0.4	1231.2	0.3		2655.3	w	
410.6	~0.25[d]		1259.5	0.3		2684.5	0.05	
419.8	2.3	0.4	1265.5	w		2700.0	w	
443.6	0.24		1282.5	0.5	w	2740.4	0.03	
455.7	~0.45[d]	w	1297.8	0.2		2775.2	0.06	w
479.0	~0.25[d]	w	1310.0	0.3		2836.1	0.025	
492.3	0.4		1324.6	w		2872.3	0.03	
497.1	0.3		1344.0	0.3		2930.4	w	
540.4	0.45		1367.6	0.3		2955.2	0.065	w
544.6	1.75	0.35	1397.5	0.3		3022.8	0.03	
572.2	0.45	0.2	1407.6	0.17				
579.6	0.15		1430.9	0.25				

[a] Intensity data are normalized to 1000 units for the most prominent line; "w" indicates weak line.
[b] Multipole assignments are based on K/L and L ratios.
[c] L_I and L_{II} lines not completely resolved.
[d] Conversion line is a composite of two different lines.

[28] J. H. Carver and W. Turchinetz, Proc. Phys. Soc. (London) **71**, 618 (1958).

TABLE XIII. Conversion electron transitions which appear in decay scheme of Yb^{169} (Fig. 9).

Transition[a] energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[b,c]
24.23			>630	>630	>320	>80	$E3$
62.75		250	530	510	d	70	$M1/E2=2$
70.85	>260	~640[d]	<250[d]	210	200	50	$M1/E2\approx 14$
75.0	w		315	~320[d]	155	d	$E2$
87.4	>1000	480	130	90	180	35	$M1/E2=15$
92.0	340	~60[e]					
104.35	290	50			d		
110.9	>840	155	28	25	45	11	$M1/E2=17$
133.5	~80[e]	10					
144.6	140	20	e	w	d		
157.0	115	e	60[c]	40	d		$E2$
165.2	145	e	80[c]	50	30	d	$E2$
191.4	290	50	e	6	d		$E1$
198.4	30	d	d	d			

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
258.7	27	d	489.7	~1.7[d]	w	1075.9	~1.3	w
291.6	24	4	549.1	3.5	w	1173.5	~1.2	
369.6	24	d	577.1	6.6	1.2	1186.6	3.0	w
379.2	54	8	647.5	~1.3		1207.4	~0.5	
404.6	4		881.1	1.0		1272.8	~0.6	
456.8	11	~2	891.2	2.7		1380.2	~0.9	
470.8	~8[d]	~1.3	962.4	9.6	1.3	1394.1	~0.9	
484.0	3.7		1062.5	~2.8[d]		KLL Auger	<1400[f]	

[a] Conversion data for this nucleus not appearing in the decay scheme are reported in reference 6.
[b] Multipole assignments are made on the basis of K/L or L ratios. Population of M subshells for low-energy radiation is observed in experiment and is of use in multipole classification.
[c] Intensity data are internally consistent. "w" indicates a weak line.
[d] Conversion line is a composite of two different lines.
[e] Conversion line is partially resolved.
[f] A portion of the Auger intensity is attributed to the presence of Lu^{170} in the source.

There is also a possibility these states form a vibrational band of spins 2 and 3 ($K=2$). This could correspond to a γ-vibrational band as observed in Er^{168},[7] based at 822 kev. It might be expected from systematics that the γ-vibrational level in Yb^{170} would be at somewhat higher energies. The inertial parameter for the postulated band in Yb^{170} is 77 kev which corresponds well with 75 kev for the isotone, Er^{168}. Other evidence for a quadrupole vibrational assignment are the ratios of reduced transition probabilities for depopulation of the 1231- and 1308-kev levels to the ground-state band. The experimental ratios, assuming pure quadrupole radiation, are:

$$(2,2\rightarrow 0,0)/(2,2\rightarrow 2,0)=0.49$$

and

$$(3,2\rightarrow 2,0)/(3,2\rightarrow 4,0)=1.26.$$

In this connection, one may note the observed ratios for similar transitions in Er^{168} are 0.55 and 1.25. The theoretical branching ratios are somewhat higher, 0.7 and 2.5, respectively.

A number of other levels may be designated solely on the basis of energy fits at 1537.4, 1515.1, 1482.4, 1381.4, 1141.0, and 940.7 kev.

J. Lu^{169}(1.5 day)→Yb^{169}

We have presented the extensive conversion electron data for this activity previously[6] and have remarked on the existence of an anomalous rotational band ($K=1/2$) based on a postulated isomeric state ($I=1/2$)

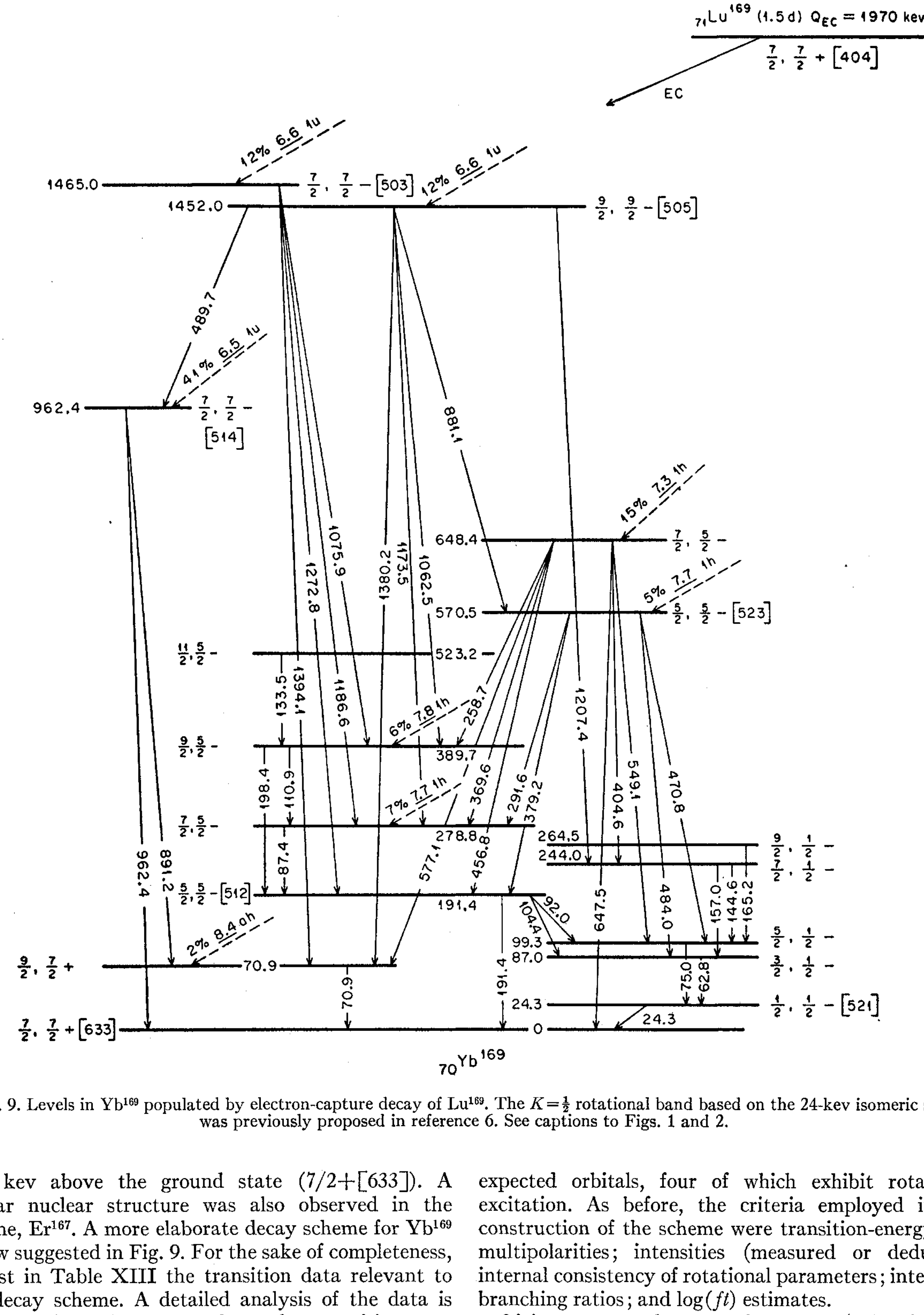

FIG. 9. Levels in Yb^{169} populated by electron-capture decay of Lu^{169}. The $K=\frac{1}{2}$ rotational band based on the 24-kev isomeric state was previously proposed in reference 6. See captions to Figs. 1 and 2.

24.3 kev above the ground state (7/2+[633]). A similar nuclear structure was also observed in the isotone, Er^{167}. A more elaborate decay scheme for Yb^{169} is now suggested in Fig. 9. For the sake of completeness, we list in Table XIII the transition data relevant to the decay scheme. A detailed analysis of the data is presented in Table XIV where the transitions are grouped according to the postulated initial level. The level scheme is consistent with the premise of seven expected orbitals, four of which exhibit rotational excitation. As before, the criteria employed in the construction of the scheme were transition-energy fits; multipolarities; intensities (measured or deduced); internal consistency of rotational parameters; interband branching ratios; and $\log(ft)$ estimates.

Of interest are the anomalous $K=1/2$ band based at 24.3 kev, a well-developed band based on a (5/2 −[512]) state at 191.4 kev, and an intrinsic state

(5/2−[523]) at 570 kev with a 7/2− rotational excitation at 648 kev. The values of the rotational parameter, $3\hbar^2/\mathscr{I}$, for these bands are 70, 75, and 67 kev, respectively. Using the rotational parameter values listed in Table II, one obtains a predicted value of 265.4 kev for the proposed 9/2(1/2−[521]) [29] state at 264.5 kev and a predicted value of 523.1 kev for the 11/2(5/2−[512]) state at 523.2 kev. The intrinsic structure implied above appears to be well founded as the "cross-feeding" between bands is extensive. It is, however, noteworthy that there is no feeding from the (5/2−[512]) band to the (7/2+[633]) ground state, except for the 191.4-kev ($E1$) transition to the ground state. This may be due to violation of the asymptotic selection rule ($\Delta n_z=0$) for $E1$ transitions where $\Delta K=1$ is involved. The transition probabilities of gamma-rays (assuming pure $M1$) which originate from the 648- and 570-kev levels of the (5/2−[523]) band and terminate at the several states of the (5/2−[512]) band show little variation from theoretical calculations. Quantitively, the comparison is: experimental 2.1/1; theoretical 2.5/1 for the 570-kev state; and experimental 0.35/0.8/1; theoretical 0.5/1.0/1 for the 648-kev state.

TABLE XIV. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Yb^{169} (Fig. 9).

Proposed excited states $(I,K\pi)$	(kev)	De-exciting transitions (kev)	Multipole[a] assignment	Deduced relative intensities $N_\gamma+N_{ce}$	N_γ[b]
(7/2, 7/2+)	0				
(9/2, 7/2+)	70.85	70.85	$M1+E2$	6480[c]	680
(1/2, 1/2−)	24.3	24.3	$E3$	>1700	0
(3/2, 1/2−)	87.0	62.75	$M1+E2$	3630[c]	240
(5/2, 1/2−)	99.3	75.0	$E2$	1080	110
(7/2, 1/2−)	244.0	144.6	$M1+E2$	310	140
		157.0	$E2$	610	360
(9/2, 1/2−)	264.5	165.2	$E2$	800	480
(5/2, 5/2−)	191.4	92.0	($M1$)	510	90
		104.4	($M1$)	470	112
		191.4	$E1$	5820	5470
(7/2, 5/2−)	278.8	87.4	$M1+E2$	5200[c]	850
(9/2, 5/2−)	389.7	110.9	$M1+E2$	2060[c]	600
		198.4	$E2$	230	182
(11/2, 5/2−)	523.2	133.5	$M1$	155	62
(5/2, 5/2−)	570.5	291.6	($M1$)	195	165
		379.2	($M1$)	835	770
		470.8	($M1$)	205	195
		484.0	($M1$)	105	100
(7/2, 5/2−)	648.4	258.7	($M1$)	165	135
		369.6	($M1$)	350	320
		404.6	($M1$)	70	67
		456.8	($M1$)	265	253
		549.1	($M1$)	130	127
		577.1	($E1$)	1745	1737
		647.5	($E1$)	435	433
(7/2, 7/2−)	962.4	891.2	($E1$)	1743	1740
		962.4	($E1$)	7010	7000
(9/2, 9/2−)	1452.0	489.7	($M1$)	48	45
		881.1	($E2$)	241	240
		1062.5	($M1$)	530	527
		1173.5	($M1$)	293	292
		1207.4	($M1$)	132	132
		1380.2	($E1$)	1250	1249
(7/2, 7/2−)	1465.0	1075.9	($M1$)	257	255
		1186.6	($M1$)	759	750
		1272.8	($M1$)	180	179
		1394.1	($E1$)	1270	1269
K x-ray intensity					<36 500[d]

[a] Multipolarities are assigned either from conversion electron data, as a member of a rotational band or from consistency with angular momentum selection rules; latter assignments are in parentheses and are shown unmixed since we have no way of estimating mixing ratios.
[b] Estimates of photon and K x-ray intensity are based on electron data and theoretical conversion coefficients.
[c] Photon and K-electron intensities are deduced from L-electron data.
[d] An upper limit only is available due to isotopic impurity.

[29] The symbolism used here is $I(K\pi[Nn_z\Lambda])$.

TABLE XV. Log(ft) estimates and asymptotic classifications for electron capture to levels in Yb^{169} (Fig. 9).

Final state in Yb $I(K\pi[Nn_z\Lambda])$	(kev)	Rel. branching (%)	Log(ft) estimate	Classification
7/2(7/2−[503])	1465.0	12	6.6	1st forb.-unhindered[a] allowed-hindered[b]
9/2(9/2−[505])	1452.0	12	6.6	1st forb.-unhindered[a] allowed-hindered[b]
7/2(7/2−[514])	962.4	41	6.5	1st forb.-unhindered[a] allowed-unhindered[b]
7/2(5/2−[523])	648.4	15	7.3	1st forb.-hindered-K forb.[a] allowed-hindered-K forb.[b]
5/2(5/2−[523])	570.5	5	7.7	1st forb.-hindered[a] 2nd forb.-hindered[b]
9/2(5/2−[512])	389.7	6	7.8	1st forb.-hindered[a] allowed-hindered-K forb.[b]
7/2(5/2−[512])	278.8	7	7.7	1st forb.-hindered-K forb.[a] allowed-hindered-K forb.[b]
9/2(7/2+[633])	70.9	2	8.4	allowed-hindered[a] 1st forb.-hindered-K forb.[b]

[a] Associated with the (7/2+[404]) ground state in Lu^{169}; $Q_{EC}=1970$ kev.
[b] Associated with the (9/2−[514]) ground state in Lu^{169}.

The postulation of a 70.8-kev rotational state ($I=9/2$) is consistent with the high moment of inertia expected for the ground-state orbital (7/2+[633]). Experimental branching ratios de-exciting the 648- and 962-kev states to the ground-state band also imply rotational character for the 70.8-kev state. This evidence is listed in Table V. From the experimental L ratio for the 70.8-kev radiation ($L_{\text{I}}/L_{\text{II}}/L_{\text{III}}=\sim 640/<250/210$), the multipole character cannot be determined since L_{II} is a composite line. If one assumes $M1+E2$ multipolarity, then the ratio $M1/E2=14$, derived from the $L_{\text{I}}/L_{\text{III}}$ ratio, is consistent with the rotational interpretation. There is the less likely possibility that the 70.8-kev state is associated with the (11/2−[505]) orbital and that the de-exciting radiation is $M2$.

Two close-lying levels are tentatively placed at 1465 kev (7/2−[503]) and at 1452 kev (9/2−[505]), both intrinsic states being expected. The choice for the $K=7/2$ assignment is based on a determination of transition probabilities de-exciting to various levels of the intrinsic band (5/2−[512]). For the 1465-kev state, the branching-ratio is comparable to similar determinations (see Table V), all of which show large deviation from theoretical expectations.

A very intense transition of 962.4-kev energy may de-excite a proposed 962-kev (7/2−[514]) state to ground. This radiation is interpreted as of $E1$ character based on a comparison of photon and conversion-electron intensities. The ratio of γ-ray transitions proceeding to the (7/2+[633]) band (see Table V) supports the orbital assignment.

On Fig. 9 we have indicated relative percentages of electron-capture decay from Lu^{169} to the various levels in Yb^{169}. These are of value in helping to classify the ground state of Lu^{169} which would be expected to be either the (7/2+[404]) or the (9/2−[514]) orbital.

TABLE XVI. Conversion electron transitions which appear in decay scheme of Yb^{171} (Fig. 10).

Transition[a] energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[b, c]
19.3		>120	>190	>200	>130	>40	$E1$
27.0		w	d	∼9	∼5		
46.45		20	5	4.5	∼7		$M1/E2=50$
55.65		115	∼10	∼3	32	∼8	$M1$
66.67		115	220	210	≥100		$M1/E2=2$
72.3	>50	90	30	22	d	8	$M1/E2=14$
75.9	>90	∼50[e]	950	1000	540	130	$E2$
85.5	85	∼18[e]	d	d	∼12	∼4	
91.3	42	d					
109.2	65	13	∼2	∼1.5	4	∼1	$M1/E2\approx 20$
122.2			w	w			
132.2	w						
141.3	w						
154.6	3	∼0.6	e	∼0.2			$M1/E2\approx 2.5$
163.8	7.5	∼0.5	2.3	1.8	1.4	w	$E2$
170.6	∼1.2[e]	∼0.2	∼0.35	d	∼0.2		$E2$
195.0	3	∼0.3	0.6	d	d		$E2$

Transition energy (kev)	K	L_I	Transition energy (kev)	K	L_I	Transition energy (kev)	K	L_I
518.2	1.2	0.2	713.6	1.6	w	782.0	1.1	w
627.4	1.5	w	740.9	14	1.9	827.3	w	
668.2	4.5	0.65	768.5	0.9	w	854.4	∼0.5	
690.0	0.7	d				841.6	3.3	0.5

[a] Conversion data for this nucleus not appearing in the decay scheme is reported in reference 6.
[b] Multipole assignments were made on the basis of K/L or L ratios. M subshell ratios are observed in low-energy transitions and are of use in multipole classification.
[c] Intensity data are internally consistent. "w" indicates a weak line.
[d] Conversion line is a composite of two different lines.
[e] Conversion line is partially resolved.

The possibility of (5/2+[402]) seems somewhat remote since the spins of the upper states of Yb^{169} appear to be relatively high. Relying on a disintegration energy of 2 Mev, as calculated from a semiempirical mass formula,[10] one may deduce $\log(ft)$ values from the various branches. Table XV presents this analysis. The last column lists the classifications of the electron-capture transition according to the interpretation of Alaga[13] for these two choices of spin and parity for Lu^{169}. This suggests that the more likely assignment is (7/2+[404]). We have neglected any electron capture to the ground state which should proceed as an allowed-hindered transition. The effect of this neglect is to increase the partial half-lives and $\log(ft)$'s of the branches to the upper state. This would make the choice of (7/2+[404]) for Lu^{169} even more preferable. The intensity of the KLL Auger lines is not sufficiently large to indicate an intense electron-capture branch to the ground state. Hence, the asymptotic selection rules are apparently greatly impeding the expected allowed ground-state transition.

K. Lu^{171}(8.1 day)→Yb^{171}

The Yb^{171} de-excitation spectrum has been analyzed to see if any level structure in addition to the previously reported[6] ground-state rotational band ($K=1/2$) was apparent. We are proposing a possible decay scheme on the basis of the preceeding information and a number of additional weak transitions (see Table XVI) and some scintillation-counter measurements.[30] Table XVII presents a detailed interpretation of these data in connection with the decay scheme. A number of Mottelson-Nilsson orbitals expected for this nucleus may be incorporated into this scheme as shown in Fig. 10.

A well-developed anomalous rotation band based on the ground state (1/2−[521]) is observed, with its highest level at 246.5 kev ($I=9/2$). The predicted value is 246.8 kev, as calculated from the rotational energy formula. The rotational parameters agree well with the isotone, Hf^{173}, and the isotope Yb^{169}, as shown in Table II.

Another rotational band is possibly based on a (5/2−[512]) level at 122 kev with rotational excitations of 85.5 and 109.2 kev in cascade and an $E2$ crossover of 195 kev. This band is depopulated by low-energy transitions (46.5 and 55.7 kev) of $M1+E2$ multipole order which proceed to the 5/2− and 3/2− levels of the ground-state band. The rotational sequence based at 122 kev may be fed by transitions from an intrinsic state at 836 kev (7/2−[514]). The resulting branching ratio is given in Table V. These transitions are interpreted as being predominantly $M1$ in order to preserve the intensity balance. One might expect to populate the orbital (7/2−[514]) since analogous states may occur at 962 and 637 kev in Yb^{169} and Yb^{173}, respectively. A possible rotational excitation of the 836-kev state is at

[30] A. I. Lebedev, A. N. Silant'ev, and I. A. Yutlandov, Izvest. Akad. Nauk S. S. S. R. Ser. Fiz. **22**, 839 (1958); Chem. Abstr. **52**, No. 19561c.

TABLE XVII. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Yb^{171} (Fig. 10).

Proposed excited states $(I,K\pi)$	(kev)	De-exciting transitions (kev)	Multipole[a] assignment	Deduced relative intensities $N_\gamma+N_{ce}$	N_γ[b]	Photon data of Lebedev et al. N_γ[c]
(1/2, 1/2−)	0					
(3/2, 1/2−)	66.7	66.7	$M1+E2$	1520[d]	110 }	1000
(5/2, 1/2−)	75.9	75.9	$E2$	3560[d]	350 }	
(7/2, 1/2−)	230.5	154.6	$M1+E2$	10	5	
		163.8	$E2$	40	25	
(9/2, 1/2−)	246.5	170.6	$E2$	5.5	3.5	
(5/2, 5/2−)	122.4	27.0	$(E1)$	35	10	
		46.45	$M1+E2$	45	5.5	
		55.65	$M1$	225	55	
		122.2	$(E2)$	*w*	*w*	
(7/2, 5/2−)	207.9	85.5	$M1+E2$	160	20	
		132.2	$(M1)$	*w*	*w*	
		141.3	$(E2)$	*w*	*w*	
(9/2, 5/2−)	317.1	109.2	$M1+E2$	115	30	
		195.0	$E2$	21	17	
(7/2, 7/2+)	95.2	19.3	$E1$	>780	>100	1860
(9/2, 7/2+)	167.5	72.3	$M1+E2$	860[d]	90	
		91.3	$(M2)$	72	1	
(7/2, 7/2−)	835.3	518.2	$(M1)$	39	38	
		627.4	$(M1)$	77	75	
		713.6	$(M1)$	112	110	
		668.2	$(E1+M2)$	<1615	<1610	
		740.9	$(E1)$	6235	6220	6220
(9/2, 7/2−)	949.6	740.9[e]	$(M1)$			
		782.0	$(E1+M2)$	<525	<524	
		827.3	$(E2)$	*w*	*w*	
		854.4	$(E1)$	295	294 }	1150
(9/2, 9/2+)	936.4	841.6	$(M1)$	350	347 }	
		768.5	$(M1)$	76	75	
		690.0	$(E1)$	271	270	

[a] Multipolarities are assigned either from conversion electron data, as a member of a rotational band or from consistency with angular momentum selection rules; latter assignments are in parentheses and are shown unmixed since we have no way of estimating mixing ratios.
[b] Estimates of photon intensity are based on electron data and theoretical conversion coefficients.
[c] Photon data of Lebedev et al. (reference 30) are normalized to the 740-kev transition, assuming pure $E1$ multipolarity. There probably is a considerable $M2$ admixture to the $E1$.
[d] Photon and K-electron intensities are deduced from L-electron data.
[e] Recurring transition energy is previously listed.

950 kev. The value of $3\hbar^2/\mathcal{J}$ would be 76.0 kev, which is comparable with the observed values of 72.4 and 73.5 kev for the low-lying $K=1/2$ and $K=5/2$ bands, respectively.

A pair of interesting levels are postulated at 95.2 and 167.5 kev. These levels are rather firmly placed with eight transitions proceeding to and from them. A very intense transition is the one of 19.3 kev proceeding to the 75.9 kev (5/2−) level of the ground-state band. The L conversion line spectrum is attenuated by the sharp cutoff in film sensitivity at ~10 kev. The M-subshell ratio is more reliable, and it resembles those for well-known $E1$ transitions of comparable energy in other rare earths nuclei. Additional evidence for the $E1$ assignment is the strong photon peak at 20 kev reported by Lebedev et al.[30] Photon data for four transitions attributed to mass 171 are included in Table X, normalized to the 740-kev radiation. The relatively intense photon peak for the 740-kev transition indicates it is of $E1+(M2)$? multipolarity. Hence, it is probable that the transition of 19 kev de-excites the expected (7/2+[633]) state. The rotational interpretation of the level at 167.5 kev appears less firm. The multipole-order data on the low-energy transition of 72.3 kev de-exciting this state are not conclusive, although the assignment as $M1+E2$ is preferable. Similar rotational energies are observed for the (7/2+[633]) orbital in Er^{167} and Yb^{169}. A number of $E1$ transitions proceeding to the 167-kev state are expected to have considerable $M2$ admixture in order to preserve an intensity balance.

In conjunction with the predictions of intrinsic level ordering, we provisionally associate the 936-kev state with the configuration (9/2+[624]). This level is not included in Fig. 10. Branching from the 936-kev ($K_i=9/2$) state to the (7/2+[633]) band is experimentally 3.5/1 as compared to the theoretical ratio 4.4/1. The relevant interband transitions of 841.6 and 768.5 kev are presumed to be $M1$.

The complex low-energy excitation of this nucleus make photon-photon coincidence measurements im-

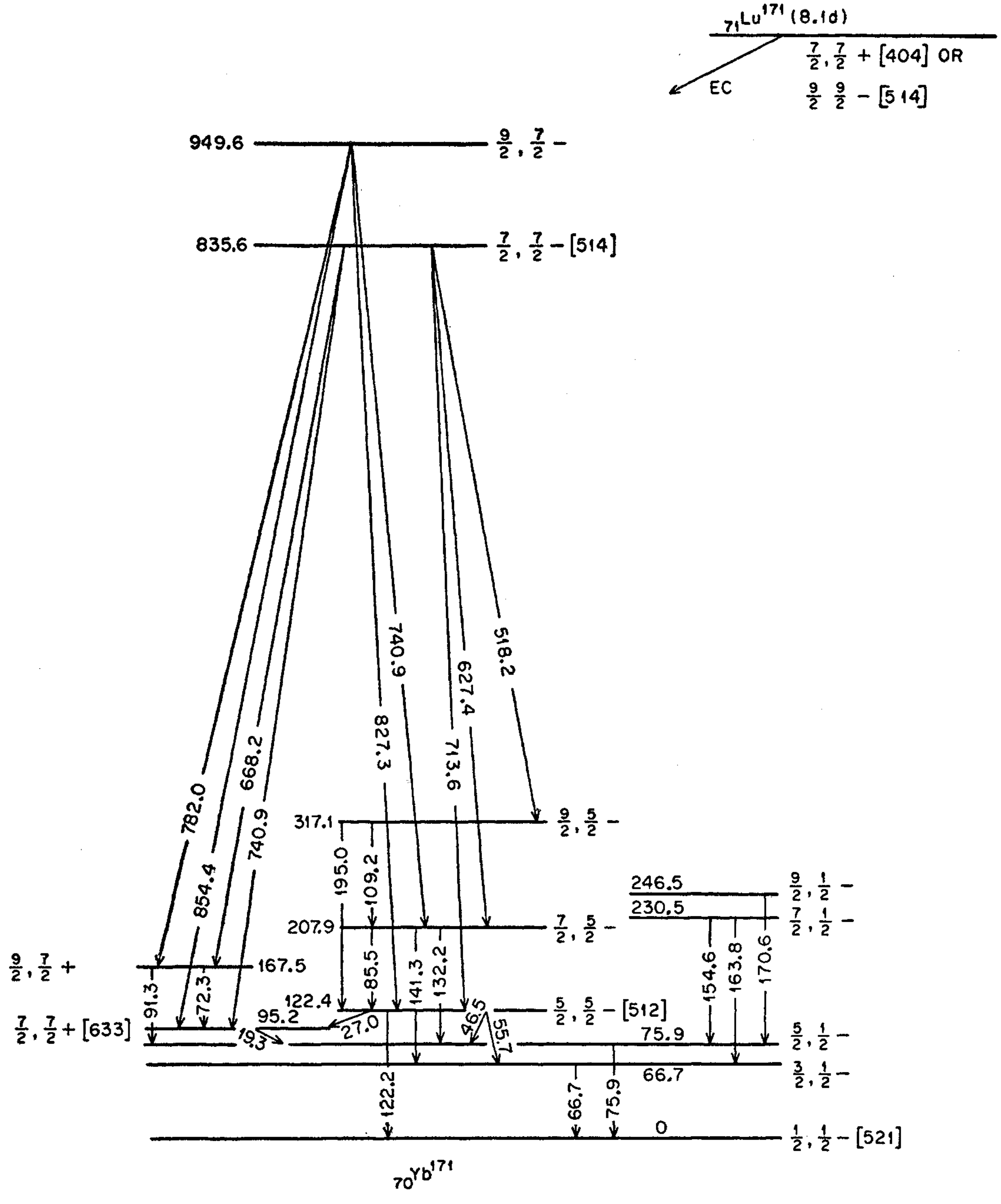

FIG. 10. Levels in Yb^{171} populated by electron-capture decay of Lu^{171}. In a previous paper (reference 6), the $K=\frac{1}{2}$ rotational sequence to $I=9/2$ was indicated. A very tentative level at 936 kev (9/2+[624]) may deexcite to the (7/2+[633]) band. See captions to Figs. 1 and 2.

practical. We have established that the transitions of 668 and 740 kev do not coincide to any appreciable extent with any photon of more than 100-kev energy.

Cameron's mass tables[10] predict an available energy of 884 kev for Lu^{171}. The actual value is somewhat higher. Lu^{171} would be expected to be in the (7/2+[404]) or (9/2−[514]) state.

III. DISCUSSION

In this investigation of odd-neutron nuclei in a region of high nuclear eccentricity ($\delta=0.28$), one should like to obtain data of two general types. First, one should like to learn something about the position and properties of intrinsic levels and also something about the transition probabilities, both beta and electromagnetic, be-

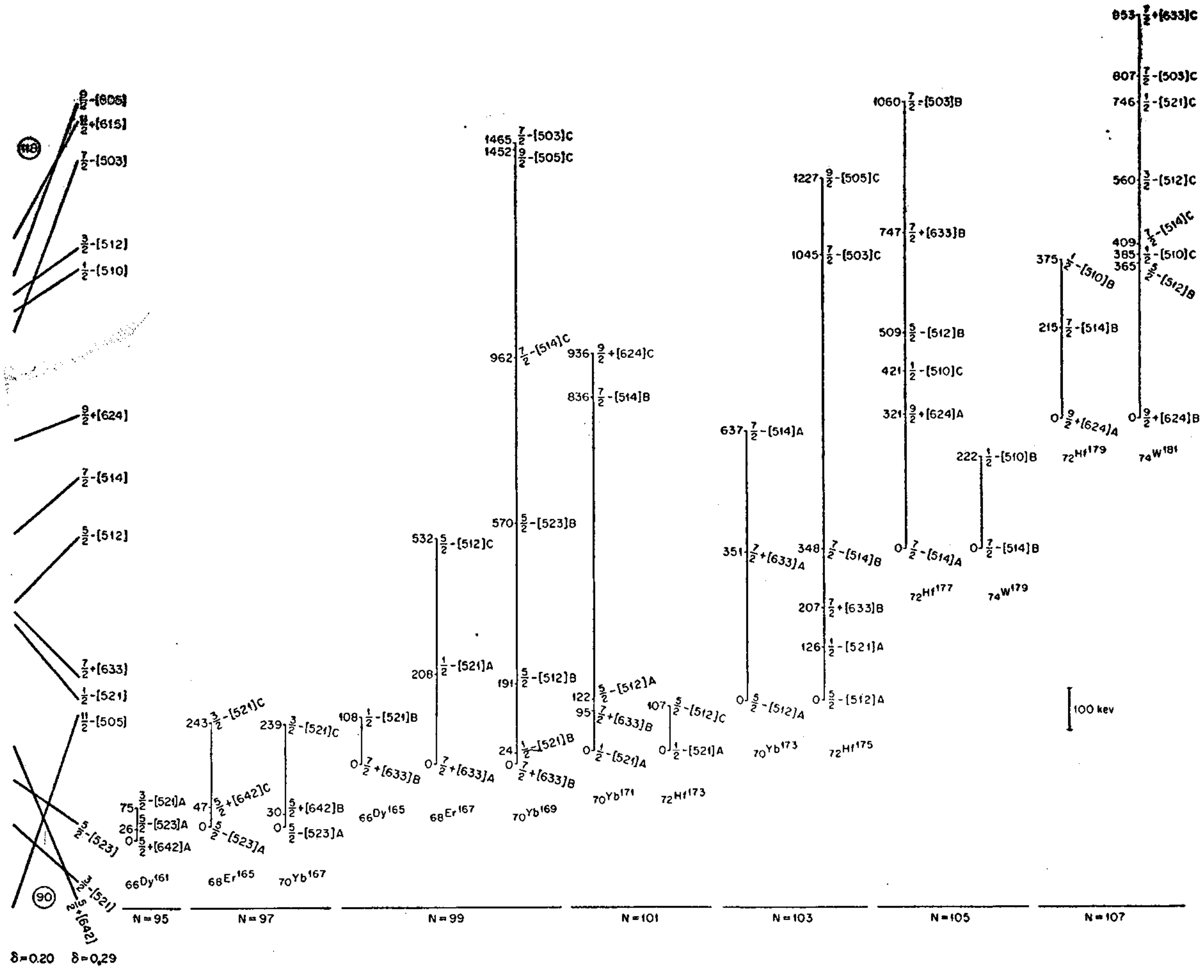

FIG. 11. Energies of postulated intrinsic states of odd-neutron nuclei as a function of neutron number (95 to 107, inclusive). To the left are shown the approximate positions of the Mottelson-Nilsson orbitals (reference 5) for $0.2 \leq \delta \leq 0.29$. We have designated the reliability of the level assignments by the letters A, B, or C, in order of decreasing certainty.

tween such levels. Second, the nature of the collective excitation which gives rise to the rotational bands is of interest. Relevant data are the moments of inertia, any deviation from the $I(I+1)$ energy ratio which may indicate a "rotation-vibration" type of interaction or centrifugal force effects, as well as the value of "a", the decoupling parameter appropriate for $K=1/2$ bands. The behavior of "a" for various nuclei is quite interesting because this parameter does depend on the wave function of the intrinsic motion. In addition to these energy parameters, data are needed on the electromagnetic parameters. Such data are those on the relative gamma-ray transition probabilities within a rotational band. These data may lead to estimates of the relative, or perhaps absolute, values of the intrinsic quadrupole moment Q_0, the gyromagnetic ratios g_K and g_R, and the parameter b_0 which influences the magnetic moment and hence the $M1$ transition probability in $K=1/2$ bands.

Figure 11 is a plot of possible intrinsic levels for odd A-odd N nuclei with neutron numbers of 95 to 107 (isotones are grouped together). An energy scale is preserved in the vertical direction, although the energy differences between different groups of isotones is unknown. At the far left are shown the approximate ordering of the Nilsson orbitals for nuclear eccentricities of 0.29 and 0.2. We follow the approach of Mottelson and Nilsson as to the characterization of the reliability of the level designation; e.g., A for the most certain, and B and C for those of decreasing reliability.

It must be kept in mind that the actual level designation is not yet certain; at best, the firm data consists of spins and parities. As to the validity of the asymptotic quantum number designations, more sensitive experiments must be performed. Such experiments are investigations of Coulomb excitation, dipole-quadrupole mixtures of transitions between intrinsic levels, reduced transition probabilities of intraband transitions, and $\log ft$ values for electron capture or beta decay. One may remark that we have tacitly ignored the possibility

TABLE XVIII. Mixed $M1+E2$ transitions and $E2$ branching ratios in rotational bands ($161 \leq A \leq 175$).

Nucleus	Initial → final state ($I_i \to I_f$)	($K\pi[Nn_z\Lambda]$)	Transition energy (kev)	$L_{\rm I}:L_{\rm II}:L_{\rm III}$	$M1:E2$[a]	Reduced transition[b] probability, experimental
Dy^{161}	(7/2 → 5/2)	(5/2−[523])	77.5	0.32:0.95:1	0.9:1	
Yb^{169}	(7/2 → 5/2)	(5/2−[512])	87.4	1:0.27:0.19	15:1	
Yb^{171}	(7/2 → 5/2)	(5/2−[512])	85.5	1:⋯:⋯	⋯	
Yb^{173}	(7/2 → 5/2)	(5/2−[512])	78.7	1:0.25:0.18	20:1	
Hf^{175}	(7/2 → 5/2)	(5/2−[512])	81.5	1:0.28:0.18	17:1	
Dy^{161}	(9/2 → 7/2)	(5/2−[523])	98.1	0.75:1.2:1	1.4:1	2.9
Yb^{169}	(9/2 → 7/2)	(5/2−[512])	110.9	1:0.18:0.16	17:1	~3.8
Yb^{171}	(9/2 → 7/2)	(5/2−[512])	109.2	1:0.15:0.11	20:1	3.3
Yb^{173}	(9/2 → 7/2)	(5/2−[512])	100.7	1:0.18:0.11	22:1	3.4
Hf^{175}	(9/2 → 7/2)	(5/2−[512])	104.3	1:0.19:0.10	19:1	~2.2
Er^{167}	(3/2 → 1/2)	(1/2−[521])	57.1	1:0.85:0.88	7:1	
Yb^{169}	(3/2 → 1/2)	(1/2−[521])	62.8	0.47:1:0.96	1.9:1	
Yb^{171}	(3/2 → 1/2)	(1/2−[521])	66.7	0.55:1:0.95	2:1	
Hf^{173}	(3/2 → 1/2)	(1/2−[521])	69.8	0.36:0.87:1	1.3:1	
Hf^{175}	(3/2 → 1/2)	(1/2−[521])	70.5	0.33:1:0.95	1.1:1	

[a] Ratios (of photon intensities) obtained from L ratios.
[b] Theoretical $B(E2:I \to I-1)/B(E2:I \to I-2) = 2K^2(2I-1)/[(I+1)(I-1+K)(I-1-K)] = 3.0$ for $I_i = 9/2$.

of vibrational excitation of the ground or higher lying intrinsic states. For example, for β vibrations, there should be a rotational band with $K=K_0$ and for γ vibrations a pair of bands with $K=(K_0\pm 2)$ where K_0 is the K number for the ground state.

A few remarks are in order for some of the levels not discussed above. The data on the levels in Dy^{161} populated by electron-capture decay have been discussed previously.[5,6] In the case of the $N=97$ isotones, a low-lying intrinsic state, possibly (5/2+[642]) is suggested. The data on these nuclei have been reported in an earlier publication.[6] The level assignment is proposed on the basis of intense $E1$ transitions of 29.7 and 47.1 kev in Yb^{167} and Er^{165}, respectively, proceeding to the (5/2−[523]) ground state. The $E1$ assignments were made on the basis of the observed L ratios. For the 29.7-kev transition, the experimental L ratio is 0.85/0.76/1 which is to be compared with the theoretical value of 0.77/0.6/1; while for the 47.1-kev transition, the experimental ratio is 1.5/<1/1 compared to the theoretical ratio of 1.6/0.7/1. (The 47.1−$L_{\rm II}$ conversion line is coincident with the $KL_{\rm I}L_{\rm I}$ Auger electron line.) The 243-kev transition in Er^{165} is of $M1+E2(<10\%)$ character and possibly depopulates a (3/2−[521]) level to ground. The transition of 239 kev in Yb^{167} may occur between similar levels.

With regard to the three isotones of $N=99$, we have discussed the level scheme of Yb^{169} above. We have postulated an intrinsic level (5/2−[512]) in Er^{167} at 532 kev. The experimental K-conversion coefficient for this transition[6] is compatible with an $E1+M2$ assignment. The 532-kev transition does not populate the 9/2+ level of the ground-state rotational band. If this transition proceeded to the level at 208 kev (1/2−) or 265 kev (3/2−), another transition, different in energy by 57 kev, should have been seen. Such a transition has not been observed. Therefore, the most reasonable interpretation is the one indicated.

The levels of nuclei of neutron number 101, 103, and 105 are discussed in the text of this paper. Regarding the isotones of $N=107$, Hf^{179} has been discussed by Mottelson and Nilsson,[5] and W^{181} is reviewed above.

In Table II are shown the empirical data on the values of B, the correction term for the simple rotational energy relationship, and $3\hbar^2/\mathcal{J}$ the inertial parameter, as well as "a", the decoupling parameter. One may note that the value of B is quite small, and that for the odd-neutron nuclei ($Z=70$ and 72) the value of B is somewhat smaller (1/2 or 1/3) than for the case of the odd-proton Tb ($Z=65$) and Tm ($Z=69$) isotopes.[6] Experimental decoupling parameters for orbital (1/2−[521]) exhibit a smooth variation as a function of mass number, indicating a maximum of +0.85 for a mass of 171.

In order to estimate the contribution of the odd nucleon to the moment of inertia, we have tabulated values of $3\hbar^2/\mathcal{J}$ for the even-even nuclei (where available), and in the last columns are listed the experimental and calculated[31] values of $\Delta\mathcal{J}/\mathcal{J}_{\rm rigid}$ (in percent). This follows the symbolism of Prior, where $\Delta\mathcal{J}$ represents the increase in $\mathcal{J}$ for the odd nucleon case over the value for the even-even nucleus with one less neutron, and $(\mathcal{J})_{\rm rigid}$ is the moment of inertia associated with rigid rotation about an axis normal to the symmetry axis. There is a good correlation between experimental results and the predictions of Prior for the related orbitals.

The $M1/E2$ mixing ratios for rotational transitions are listed in Table XVIII. One may observe that both transitions listed for Dy^{161} have a very low $M1/E2$ ratio. The remainder of the odd neutron ($K\neq 1/2$)

[31] O. Prior, Arkiv Fysik 14, 451 (1958).

transitions have $M1/E2$ ratios of $\sim$20. The $K=1/2$ transitions have low ratios ($\sim$1 or 2) except for the case of Er^{167}. This may be due to the effect of the magnetic decoupling parameter b_0 which is in a multiplicative factor to the $M1$ transition probability. This factor is $[1+(-1)^{I+1/2}b_0]^2$, where I is the spin of the initial (upper) state. It is perhaps too early to conjecture on the magnitude of b_0 since little is known of the quadrupole moments or gyromagnetic ratios.

The last column in Table XVIII displays, for a number of $K=5/2$ rotational bands, the experimental ratio of the $B(E2)$ for the cascade transition to the $B(E2)$ for the crossover transition. Satisfactory agreement is obtained with the theoretical value of 3.0. No conversion data are available on $5/2\rightarrow 3/2$ branching in $K=1/2$ bands. This is attributed to the low energy of the transition ($\sim$12 kev) and to the predicted low intensity relative to the $5/2\rightarrow 1/2$ branch.

In Table V was shown a number of branching ratios for reduced transition probabilities for transitions between a given intrinsic state and members of a lower rotational band. In all cases, no information is available as to the possible admixture of quadrupole radiation to the dipole radiation; we have assumed pure dipole radiation. The spins and parities of the levels under discussion are fairly well established; again, the intrinsic level assignment is only a postulate. The first group, all involving $K=7/2$ initial states and (5/2−[512]) rotational levels as final states, show a rough agreement among themselves, but a striking disagreement with the theoretical ratio. Most of the other tabulated ratios are in fair to good agreement with the predicted ratios, with the possible exception of the transitions in Hf^{175}.

It is gratifying that there is some systematic behavior of the very complex low-energy excitation spectra of the odd-A rare earths. Although very few of the level schemes presented have been studied rigorously, we feel that the direction for future experiments has been indicated. We have indicated in the tables of data the multipolarities which are assigned from internal conversion data (L or K/L ratios, or internal conversion coefficients); some of the other multipolarities (hence the photon intensities as obtained from the postulated internal conversion coefficients) are deduced.

IV. ACKNOWLEDGMENTS

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