Nuclear Levels in a Number of Even-Even Rare Earths ($150 \leq A \leq 184$)

B. HARMATZ AND T. H. HANDLEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee*

AND

J. W. MIHELICH†
University of Notre Dame, Notre Dame, Indiana‡

(Received April 17, 1961)

To obtain more data on the system of levels in even-even nuclei, a number of such nuclei ($150 \leq A \leq 184$) were studied with electron-capturing sources in permanent magnet spectrorgaphs. Some measurements were made with scintillation counters. Data confirming recently reported results on the decay of Tb^{152}, Tb^{156}, and Ho^{162} have been obtained. It was found that Eu^{150} has two isomeric states ($T_{\frac{1}{2}}=14$ hr and >5 yr). Levels at 740.7 (0+) and 773.3 (4+) kev in Sm^{150} are proposed. A study of the two isomeric activities of Tb^{154} indicated the existence of levels in Gd^{154} which may be described as a gamma-vibrational band (at 997.3 kev) and a beta-vibrational band (at 680.6 kev). The new data for Tm^{166} (7.7 hr) are consistent with levels in Er^{166} at 2137.3 and 2164.6 kev, both of which are probably 3 states and which exhibit considerably different branching ratios of the de-exciting transitions. The decay of Lu^{172} appears to populate a large number of even-parity levels in Yb^{172} which may be arranged in rotational bands corresponding to primary or base states at 1174.0 kev ($I=3+$), 1467.5 kev ($I=2+$), 1664.3 kev ($I=3+$), 1702.1 kev ($I=3+$), 2075.0 kev ($I=4+$), and 2287.3 kev ($I=4+$). The very complex decay of the two isomers of Re^{182} excite many odd-parity levels which may be arranged in seven or more bands. In addition, even-parity beta- and gamma-vibrational bands may be populated. Electron-capture decay of Re^{184} populates a gamma-vibrational band in W^{184} of spins 2, 3, and 4. Data relevant to the rotational energy parameters and ratios of gamma-ray transition probabilities from the various states are presented. As a corollary, data on the decay of Eu^{149} are presented since this activity was present in some of our composite sources.

1. INTRODUCTION

DATA on the excited levels of even-even nuclei are accumulating rapidly. Particularly in the region of the deformed nuclei, the nuclei possess a very complicated set of levels. Singular success in predicting and describing these excitations has been achieved by the use of the unified model based on the work of Bohr and Mottelson.[1] In this model, a large number of levels may be explained by means of vibrational excitations of various order λ, where the parity of the vibrational state is $(-1)^\lambda$, and ν is the projection of the vibrational angular momentum on the symmetry axis ($\nu=0, \pm 1 \cdots \pm\lambda$). For example, there are the quadrupole bands of two types: the gamma vibration where $\lambda=2$, $\nu=2$, $K=K_0+2=2$, and the beta vibration where $\lambda=2$, $\nu=0$, $K=K_0+0=0$. K_0 is the K quantum number for the ground state. At roughly twice this excitation energy, one may find a two-phonon beta-vibrational band with $K=0$, $I=0+$, $2+$, $4+$, and 2 two-phonon gamma-vibrational bands with $K=0$, $I=0+$, $2+$, $4+\cdots$ and $K=4$, $I=4+$, $5+$, $6+\cdots$. In addition, pair excitations are possible when two decoupled nucleons are lifted to an excited state.

Each of the bands may possess rotational excitation describable by the familiar relationship

$$E_I=E_0+(\hbar^2/2\mathfrak{g})I(I+1)+BI^2(I+1)^2,$$

where E_0 is the energy of the base of the band, $\mathfrak{g}$ is the moment of inertia, and B is a measure of the deviation from the strong coupling limit (rotation-vibration interaction). Some care must be taken in the evaluation of the energy parameters since, in general, two levels of the same spin and parity will repel each other. The amount of interaction is dependent on the energy difference between the interacting levels. Some evidence for such an interaction is presented below.

Considerable success has been achieved by Griffin and Rich[2] in the computation of moments of inertia for ground-state bands of a number of rare each nuclei. This calculation was based on the work of Belyaev,[3] who applied the formalism of the superconductor theory to the problem of nuclear matter, and on the Nilsson model[4] to describe the self-consistent field.

Another important facet of the unified model is the prediction[5] of the ratios of gamma-ray (and beta-decay) transition probabilities. In fact, one of the important criteria in constructing a decay scheme is the premise that decay-branchings to a given band are describable as ratios of the squares of vector angular momentum coefficients. It has become clear that, although exact agreement with the theory is not obtained, there is great consistency in the branching ratios for similar sets of transitions in different nuclei.

A considerable amount of data has accumulated for the so-called gamma-vibrational bands ($K=2$, $I=2+$, $3+\cdots$). The presence of beta-vibrational levels is now firmly established. These levels ($K=0$, $I=0+$, $2+\cdots$) have been, in general, established by angular correlation measurements. Marklund *et al.*[6] have tabulated the

* Operated for U. S. Atomic Energy Commission by Union Carbide Corporation.
† Oak Ridge National Laboratory temporary employee, summer 1957 to 1960.
‡ Work supported in part by U. S. Atomic Energy Commission.
[1] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd. **27**, No. 16 (1953).
[2] J. J. Griffin and M. Rich, Phys. Rev. **118**, 850 (1960).
[3] S. T. Belyaev, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **31**, No. 11 (1959).
[4] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).
[5] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).
[6] I. Marklund, B. Van Nooijen, and Z. Grabowski, Nuclear Phys. **15**, 533 (1960).

TABLE I. Conversion electron data for Re^{184} (38 day) → W^{184}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a,b]
111.2	>29 900	[c]	46 760	41 330	23 520	7020	$E2(2+\rightarrow 0+)$
252.8	1290	[d]	370[d]	135	180		$E2(4+\rightarrow 2+)$
539.8	14.4						
642.5	94	19.4					
770.5	24						
783.1[e]	~8						
793.4	1000	190			50		
896.0	330	62					
899.2	[c]						
904.4	765	149			36		
995.0	w						
1002.7[e]	w						
1011.0	~5						
1023.8	9						
1106.0	w						

[a] Intensity data are normalized to 1000 units for the 793.4 kev K-electron line; "w" indicates weak line.
[b] Multipole assignments are based on K/L and L ratios.
[c] Conversion line not completely resolved.
[d] Conversion line is a composite of two different lines.
[e] Not assigned in decay scheme.

available data on such levels, and Sheline[7] has recently published a review article on the subject of vibrational states.

Data on negative parity states are much more sparse. The four expected octupole bands are those with $K=0$, 1, 2, 3 with a monotonic sequence of spins except for the $K=0$ band where only odd-spin values are permitted. Sheline has reviewed this matter, and it is clear that the number of well-established odd-parity states in rare earth nuclei is small.

An alternate approach to the problem of excitation in even-even nuclei is that of Davydov and Filippov[8] who calculated the energy states and gamma-ray transition probabilities for rotations of an axially asymmetric nucleus without changes in its internal state. Van Patter[9] has published a review of the experimental data (up to July, 1959) and a comparison of these data with the Davydov-Filippov restricted asymmetric rotor theory. More recently Davydov *et al.*[10] have considered an adiabatic general asymmetric rotor theory with no restrictions on the moments of inertia, and they concluded that agreement with experiment is not markedly improved. They suggested that a vibration-rotation interaction might improve the agreement. Using this model, Mallman[11] has just completed such a calculation, finding good agreement with experimental results for nuclei with $40\leq A\leq 250$. In particular, he has analyzed 30 nuclei, of which only 14 have more than four levels known (the requisite number to determine the parameters of the model).

There is no question that the asymmetric rotor approach is an interesting one. Unfortunately, it does not explain the negative parity levels, of which a large number are postulated in this work.

The experimental decay schemes proposed are subject, of course, to the uncertainties which must always be considered. The energies, spins, and parities of levels, properly determined, will be independent of the model attempting to explain them. Our analysis, in the main, consists of the postulation of existence of rotational bands, along with the relevant energy parameters, and decay branching ratio considerations.

The experimental procedure has been described in detail previously.[12] Separated isotopes[13] (20 to 50 mg of the oxide) were irradiated in the ORNL 86-inch cyclotron with proton beams of 70 μa and varying in energy from 12 to 22 Mev. Ion exchange columns were used to isolate the carrier-free activity which were electrodeposited onto a 10-mil Pt wire, 2 cm long. With this method of preparing sources for the permanent-magnet, conversion-electron spectrographs, it has been possible to record electron lines up to energies of 3 Mev. The relative transition energies of the conversion lines are measured precisely. The isotope assignment is based on relative activation with enriched isotopes and on the decay rate of the lines observed in a series of exposures.

The photographic detectors were Eastman "AA" x-ray film. The electron lines which cover a wide range of energy and intensity are read on a series of spectrograms which must be normalized to each other. Only peak heights (corrected for radius of orbit and film response) of the photometrically determined intensities were measured. The errors which should be assigned to our energy and intensity measurements have been discussed previously.[12] For electron energies of <50 kev. the uncertainties become greater, depending on the quality of the source. Gamma-ray intensities have been

[7] R. K. Sheline, Revs. Modern Phys. **32**, 1 (1960).
[8] A. S. Davydov and C. F. Filippov, Nuclear Phys. **8**, 237 (1958).
[9] D. M. Van Patter, Nuclear Phys. **14**, 42 (1960).
[10] A. S. Davydov, N. S. Rabotnov, and A. A. Chaban, Nuclear Phys. **17**, 169 (1960).
[11] C. A. Mallman, Nuclear Phys. 24, 535 (1961). We wish to thank the author for the preprint.
[12] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **114**, 1082 (1959).
[13] Enriched isotopes were made available by the Isotopes Division of ORNL.

TABLE II. Branching ratios in de-excitation of gamma-vibrational levels of W^{184}, Er^{166}, and Er^{168} (assuming pure $E2$ radiation).

Nucleus	Initial state $(K, I\pi)$	Initial state (kev)	Final states $(K, I\pi)$	Reduced transition[a] probability ratios
Er^{166}	(2, 2+)	787.1	(0, 0+), (0, 2+), (0, 4+)	0.56/1/w[b]
Er^{168}	(2, 2+)	822.4	(0, 0+), (0, 2+), (0, 4+)	0.58/1/w[c]
W^{184}	(2, 2+)	904.4	(0, 0+), (0, 2+), (0, 4+)	0.53/1/0.04[b]
W^{184}	(2, 2+)	904.4	(0, 0+), (0, 2+), (0, 4+)	0.58/1/0.05[d]
				0.7/1/0.05 (theor.)[e]
Er^{166}	(2, 3+)	860.4	(0, 2+), (0, 4+)	1.35/1[b]
Er^{168}	(2, 3+)	897.0	(0, 2+), (0, 4+)	1.2/1[c]
W^{184}	(2, 3+)	1006.8	(0, 2+), (0, 4+)	1.42/1[b]
W^{184}	(2, 3+)	1006.8	(0, 2+), (0, 4+)	3.6/1[d]
				2.5/1 (theor.)[e]
Er^{166}	(2, 4+)	957.3	(0, 2+), (0, 4+)	0.17/1[b]
Er^{168}	(2, 4+)	996.3	(0, 2+), (0, 4+)	0.17/1[c]
W^{184}	(2, 4+)	1134.7	(0, 2+), (0, 4+)	0.16/1[b]
				0.34/1 (theor.)[e]

[a] Reduced gamma-ray intensity is obtained by dividing the K-electron intensity by the theoretical K-conversion coefficient and by the energy-dependent term, E^{2L+1}.
[b] This work.
[c] K. P. Jacob, J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **117**, 1102 (1960).
[d] C. G. Gallagher, D. Strominger, and J. P. Unik, Phys. Rev. **110**, 725 (1958).
[e] The theoretical relation is given by the square of the ratio of Clebsch-Gordan coefficients compiled by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

obtained for the less complex spectra, and in other cases data available in the literature and compiled in Nuclear Data Sheets[14] have been used.

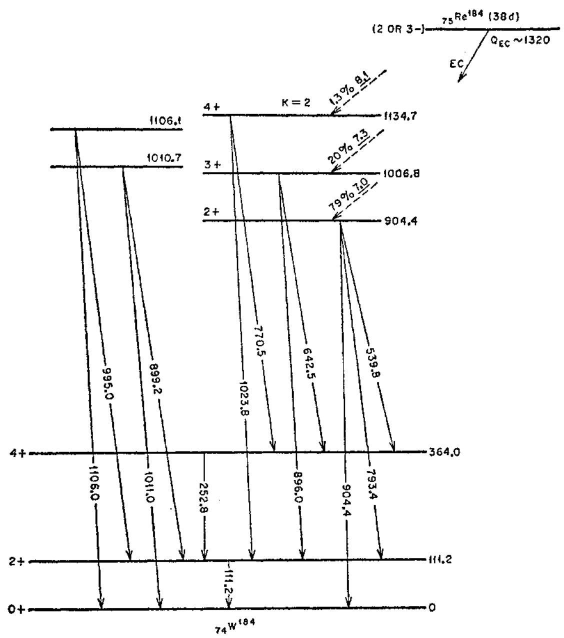

FIG. 1. Levels in W^{184} populated by electron-capture decay of Re^{184}. Rotational sequences are aligned vertically. Level and transition energies are given in kev, including estimates of available decay energy (Q_{EC}) taken either from Nuclear Data Sheets[14] or A. G. W. Cameron, Atomic Energy of Canada, Limited, Report AECL-433, 1957 (unpublished). Electron-capture branches to various levels are shown by dashed arrows with relative intensities in percent and log(ft) values underlined. The enclosing of any number in parentheses implies that this quantity is tentative.

[14] *Nuclear Data Sheets*, compiled by K. Way, F. Everling, G. H. Fuller, N. B. Gove, J. B. Marion, R. Nakasima, and C. L. McGinnis, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C. 1958 to 1961).

In general, what we are trying to determine are the position and movements of the base or primary levels[15] of possible vibrational bands, the details of the electromagnetic de-excitation of these levels, and the quantitative description of any rotational excitation of these levels, with the view in mind of detecting any rotational-vibrational interaction, level repulsions, and possible Coriolis force effects.[16]

One is faced with the difficulty of establishing the nature or character of these high-lying states. The main criteria for such assignments are the effects of collective excitation (level half-life or Coulomb excitation cross section, and of course rotational energies) as well as the effects on the ratios of electromagnetic transitions proceeding to or from members of a rotational family.

In the cases where no photon data were available, photon intensities were calculated using the measured conversion line intensities and the theoretical internal conversion coefficients.[17] Here again, an important consideration is the balance between the intensities of populating and depopulating transitions. Multipole assignments (other than $M1$) are indicated for the more intense transitions in the range of 20 to 350 kev based on K/L ratios and L and M subshell ratios.

II. EXPERIMENTAL RESULTS

A. Re^{184} (38 day) → W^{184}

The electron-capture decay of Re^{184} has been investigated by Gallagher *et al.*[18] They proposed a level

[15] In the following discussion, the term "primary level" refers to a state of intrinsic or vibrational nature, as contrasted to the states above it which are due to rotational excitation of the "primary" state.
[16] A. Kerman, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 15 (1955).
[17] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).
[18] C. G. Gallagher, D. Strominger, and J. P. Unik, Phys. Rev. **110**, 725 (1958).

scheme which included a ground-state rotational band ($K=0+$) and a possible gamma-vibrational band ($K=2+$) based at 904 kev. In addition, they made tentative assignments for negative parity levels at 1150 and 1230 kev based on coincidence measurements.

The internal conversion electron spectrum with sources of Re^{184} which contained some Re^{183} has been studied. Table I shows the transition energy and intensity measurements. Figure 1 presents a decay scheme based on these determinations. The data indicate the populating of a 4+ state (at 1134.7 kev) of the postulated $K=2+$ band for which the rotational energy constants $3\hbar^2/\mathscr{I}$ and B are, respectively, 105 and -0.077 kev. The 4+ assignment is supported by experimental branching ratios for the gamma rays to the members of the $K=0+$ band (see Table II).

Bodenstedt *et al.*[19] have redetermined the half-life of Re^{184} as 38 ± 1 days and have performed directional correlation measurements on the gamma-ray depopulation of the vibrational band. The results are consistent with spin of 2 and 3 for the levels of 904 and 1006 kev and the assignment of pure $E2$ character to the transitions of 793 and 896 kev. All the available data are consistent, therefore, with the designation of these levels as members of a $K=2$ band. The branching ratios of Table II for the de-exciting transitions are not in extreme disagreement with the theoretical values, although there appears to be a systematic difference between the experimental values for a number of nuclei (consistent among themselves) and the theoretical value. The previously reported value[18] for the de-excitation of the 1006.8-kev (3+) state was considerably different from experimental results for other nuclei; the value we obtain is quite consistent with other observed transitions between similar states: e.g., Er^{166} and Er^{168}.[20]

In the proposed decay scheme (Fig. 1), a good intensity balance between excitation and de-excitation for the low-lying 2+ and 4+ levels was obtained. No evidence was obtained for the previously reported levels at 1150 and 1230 kev. A pair of levels at 1010.7 and 1106.1 kev are possible, feeding the low-spin states of the ground-state band. Virtually all the electron capture proceeds to the levels of the gamma-vibrational band. Assuming an available decay energy[18] of 1320 kev, the $\log(ft)$ values shown on the diagram are obtained. A spin assignment of either 2− or 3− for Re^{184} would be acceptable. The coupling rule of Gallagher and Moszkowski[21] predicts that the proton orbital[22] 5/2+ [402] will couple with the neutron orbits 1/2− [510] to form a 3− state.

No attempt was made to resolve those transitions following the 165-day isomer of Re^{184}.[23]

B. $Re^{182}\rightarrow W^{182}$

One of the most interesting disintegration schemes is that leading to levels in W^{182} by β^- decay of Ta^{182} and the electron-capture decay of the two isomers of Re^{182} (half-lives of 60 hr and 13 hr). We should like to report at this time on some of our results of the conversion electron study of the two Re isomers. The activities were produced by proton irradiation of enriched W targets. The sources were composite, and the lines were classified by means of such criteria as decay rate and yields with different activation procedures. The spectra were too complex to undertake any scintillation counter analysis.

Previous studies employing high-resolution spectrographs were conducted by Gallagher *et al.*[24] on the 13-hr Re^{182} activity and by Gallagher and Rasmussen[25] on the 60-hr Re^{182} activity. Certain features are obvious at first glance. The Re^{182} isomers are able to populate higher-lying levels in W^{182} than is Ta^{182} in its β^- decay.[26] Re^{182} (13 hr) populates all of the levels fed by Ta^{182} and presumably is the isomeric state with lower spin. (The parallel and antiparallel arrangements of the proton and neutron orbitals for this odd-odd nucleus would give rise to spins of 7 and 2.)[21,22] The 60-hr Re^{182} which has the higher spin populates a large number of states with relatively large spins, several of which exhibit a possible rotational excitation.

1. Re^{182} (13 hr) $\rightarrow W^{182}$

Our transition data up to 2-Mev energy for 13-hr Re^{182} are compiled in Table III. This listing includes all radiation previously reported by Gallagher *et al.*[24] Several transitions which are not common to either 60-hr Re^{182} or to β^- decay of Ta^{182} [26] are indicated in Table III. Most of these transitions originate at nuclear levels above 2 Mev as shown in Fig. 2.

The main feature of 13-hr Re^{182} decay is the level structure identical to that observed in Ta^{182} decay up to 1553.7 kev. In addition to the well-known $K=2+$ gamma-vibrational band based at 1221.8 kev and the spin sequence of 2, 3, and 4 of the $K=2-$ band based at 1289.7 kev, there are some other interesting levels.

The level at 1258.0 kev is rather well fixed having a total of five transitions beginning or ending with it. The nature of the state is not yet certain; the 2+ state of a $K=0$ beta-vibrational excitation is a good possibility. There is evidence in the decay of the 60-hr isomer for the existence of higher members of the band.

[19] E. Bodenstedt, E. Matthias, H. J. Korner, E. Gerdau, F. Frisius, and D. Hovestadt, Nuclear Phys. **15**, 239 (1960).
[20] K. P. Jacob, J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **117**, 1102 (1960).
[21] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).
[22] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **1**, No. 8 (1959).
[23] N. R. Johnson, Bull. Am. Phys. Soc. **6**, 73 (1961).
[24] C. J. Gallagher, J. O. Newton, and V. S. Shirley, Phys. Rev. **113**, 1298 (1959).
[25] C. J. Gallagher and J. O. Rasmussen, Phys. Rev. **112**, 1730 (1958).
[26] J. J. Murray, F. Boehm, P. Marmier, and J. W. DuMond, Phys. Rev. **97**, 1007 (1955).

TABLE III. Conversion electron data for decay of Re^{182} (13 hr) → W^{182}.

Transition[a] energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[b]
31.7		10.5	8.5	12.5	[d]	w	$E1$
42.0		w					
42.7				w			
65.8		25	3.5	[d]	7.5		$M1/E2 \approx 70$
67.85		228	82	110	93	25	$E1$
84.7	>200	80	32.5	24	37	11	$M1/E2=9$
100.1	>500	[c]	~1000[c]	~900	~475	~160	$E2$
113.7	10	2	0.65	[d]			$M1/E2=7.5$
116.4	[d]						
152.5	32	~5[d]	[d]	1.5			$E1$
156.4	~1.4						
179.4	8	1.4	0.6	0.5			$M1/E2=2$
198.4	1.2		[d]	<0.6[d]	<0.3[d]		$E2$
222.0	1.3						
229.25	19	[d]	[c]	4	3		$E2$
264.0	2	[c]	0.6	[d]			$E2$
470.0[e]	16	2.4					
514.3[e,f]	w						
536.1[e]	<1.1[d]						
598.5[e,f]	1.8	w					
649.5[e]	0.85						
734.5[e]	0.85						
786.6[e]	0.6						
810.3[e]	~0.6						
836.2[e]	0.7	[d]					
894.9[e]	2.9	0.6[d]					
900.7[e]	0.75						
928.0	0.26						
960.4	~0.36[d]						

Energy (kev)	K	L	Energy (kev)	K	L
1002.2	0.09		1273.8	~0.22	
1044.7	~0.075		1289.2	~1.4[d]	
1121.7	8.8	1.5	1373.8	~0.15	
1158.2	0.43		1386.8	w	
1189.5	5.6	0.8	1437.8	0.055	
1221.8	5.8	0.9	1954.7[e]	0.18	
1231.4	0.3		2013.6[e,f]	0.21	
1257.2	~0.33		2023.5	w	
			2054.3[e]	0.21	

[a] Conversion line energy calibration is based on precise transition energy measurements for Ta^{182} decay (reference 26).
[b] Multipole assignments are made on the basis of K/L ratios and L subshell ratios. Intensity data are normalized to 1000 units for the most prominent line; "w" indicates weak line.
[c] Conversion line is partially resolved.
[d] Conversion line is a composite of two different lines.
[e] Not observed in decay of Re^{182} (60 hr) → W^{182}.
[f] Not placed in decay scheme.

A 31.7-kev transition, of $E1$ multipolarity on the basis of $L_I/L_{II}/L_{III}$ ratios, apparently proceeds to the 1258-kev (2+) state from the 1289-kev (2−) level which confirms a change in parity. Relative transition probabilities (RTP) for de-excitation of the 1258-kev level to the ground-state band are in fair agreement with the theoretical ratios listed in Table IV. Both the 2+ → 0+ and 2+ → 2+ transitions (1257 and 1158 kev) are $E2$ according to available conversion coefficient data.[14] There probably is an $E0$ admixture to the 1158-kev gamma ray proceeding between the two 2+ ($K=0$) states.

The rotational nature of the 1374-kev (3−) and 1488-kev (4−) states in the $K=2-$ series is established in part on the basis of the $I(I+1)$ energy spacing, and in part on the nature and intensity of the de-exciting radiation. The existence of the $E2$ admixture to $M1$ radiation ($M1/E2=8$ and 9) was observed in intraband transitions where $\Delta I=1$. Within the band, $E2$ branches from the 1488-kev (4−) state yield

$$B(E2:4\rightarrow 2):B(E2:4\rightarrow 3)=0.8.$$

The calculated ratio is 0.5. Intensities of low-energy $E1$ radiation branches from this $K=2-$ band to the 1258 kev $K=0$, $I=2+$ state are very small or zero, but relatively intense $E1$ transitions are found to de-excite to the $K=2+$ band. K-selection rules are probably impeding the forbidden $E1$ transitions to the $K=0$ band. As for the $K=2$, $I=4-$ state, Gallagher and Rasmussen[25] prefer the level of 1553.7 kev. Our study does not support this but agrees with the interpretation of Alaga *et al.*[5] The RTP ratio for transitions from the $K=2-$ state at 1289 kev to the $K=0+$ ground-state series is in satisfactory agreement with that expected (see Table IV).

With the placing of the $K=2-$ band at energies of

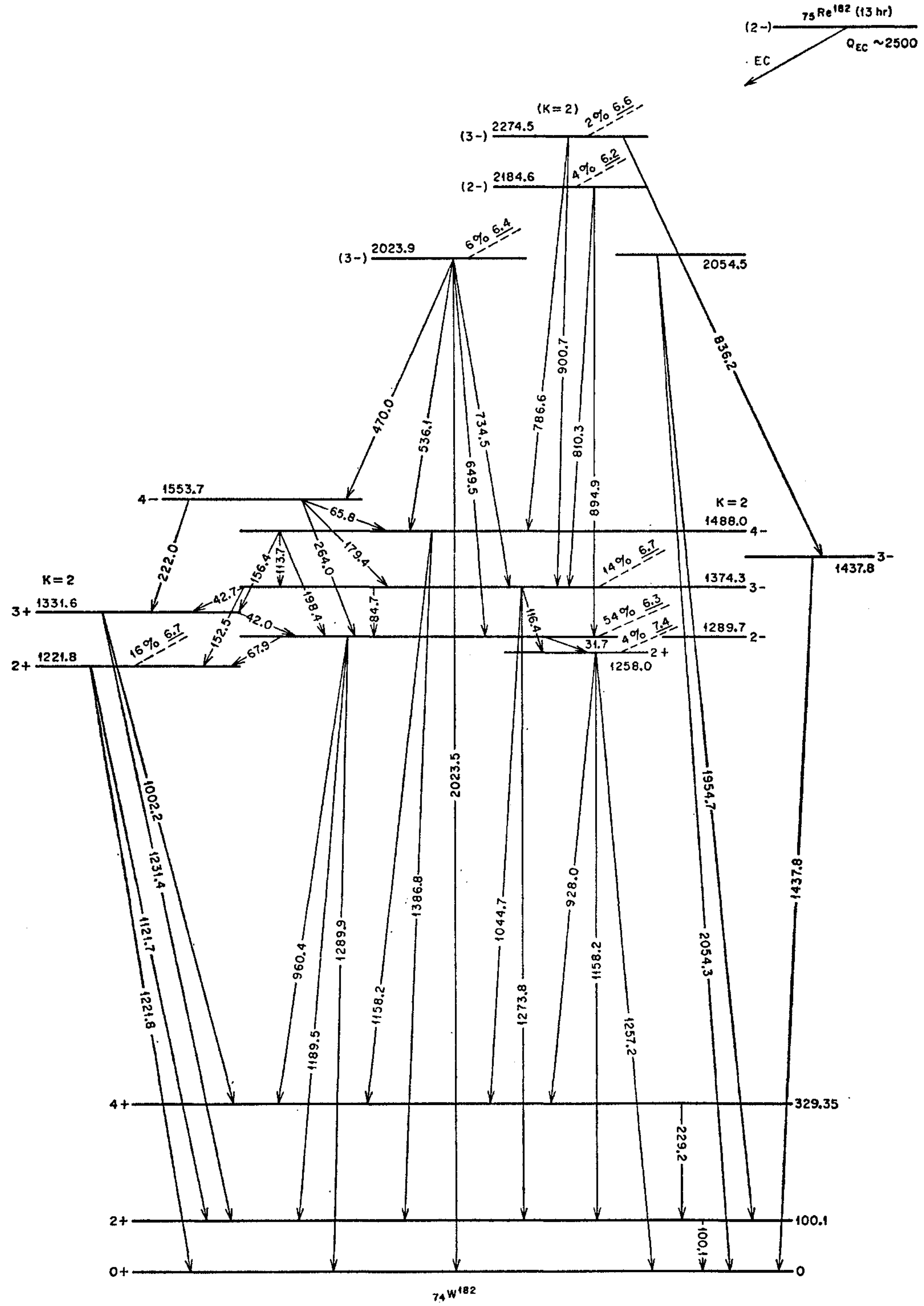

FIG. 2. Partial decay scheme of Re^{182} (13 hr) based on studies of β^- decay of Ta^{182} (reference 26) and on this work.

1289, 1374, and 1488 kev, certain features of the higher excitation become clear. Beta decay of Ta^{182} populates the level at 1553 kev which is given a $K=I=4-$ assignment.[5] This level is also established in Re^{182} decay, and $E2$ branching ratios to the $K=2-$ band are obtained (see Table IV). The level of 2023.9 kev is depopulated by four transitions to the three levels of the $K=2-$ band and to the aforementioned 1553.7-kev (4−) level. The intensity of the electron lines are consistent with $M1$ $(+E2)$ assignments. Transitions in-

TABLE IV. Ratios of reduced transition probabilities in de-excitation of levels of W^{182}.

Initial state I, π	(kev)	Final states $(K, I\pi)$	Assumed multipolarity	Reduced transition[a] probability ratios
2+	1258.0	(0, 0+), (0, 2+), (0, 4+)	$E2$	0.57/1/1.2 0.7/1/1.8 (theor.) $K_i=0$[b]
2+	1221.8	(0, 0+), (0, 2+), (0, 4+)	$E2$	0.69/1/[c]
2−	1289.7	(0, 0+), (0, 2+), (0, 4+)	$M2$	0.26/1/0.13 0.7/1/0.05 (theor.) $K_i=2$[b]
3+	1331.6	(0, 2+), (0, 4+)	$E2$	1.7/1 2.5/1 (theor.) $K_i=2$[b]
4+	1443.0[d]	(0, 2+), (0, 4+), (0, 6+)	$E2$	0.2/1/[c] 1.1/1/0.09 (theor.) $K_i=0$[b]
4−	1488.0	(2, 2−), (2, 3−)	$E2$	1/1.2 1/2.2 (theor.) $K_i=2$[b]
4−	1553.7	(2, 2−), (2, 3−)	$E2$	1/1 1.8/1 (theor.) $K_i=4$[b]
5−	1660.8[d]	(2, 3−), (2, 4−)	$E2$	1/0.27 1/0.16 (theor.) $K_i=3$[b]
6+	1757.5[d]	(0, 4+), (0, 6+)	$E2$	0.17/1 1.3/1 (theor.) $K_i=0$[b]
2−	2184.6[e]	(2, 2−), (2, 3−)	$M1$	4.7/1 2/1 (theor.) $K_i=2$[b]
3−	2274.5[e]	(2, 3−), (2, 4−)	$M1$	1/0.85 1/1.3 (theor.) $K_i=2$[b]
3−	2023.9[e]	(2, 2−), (2, 3−), (2, 4−)	$M1$	0.9/1/<0.5 2.8/1/0.14 (theor.) $K_i=3$[b]
5−	1621.7[d]	(2, 3−), (2, 4−)	$E2$	1/0.46 1/0.9 (theor.) $K_i=2$[b]

[a] Reduced gamma-ray intensity is obtained by dividing the K-electron intensity by the theoretical K-conversion coefficient and by the energy-dependent term E^{2L+1}.
[b] The theoretical relation is given by the square of the ratio of Clebsch-Gordon coefficients compiled by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).
[c] Transition unobserved.
[d] Levels unique to 60-hr decay of Re^{182}.
[e] Levels unique to 13-hr decay of Re^{182}.

volving a parity change would be too intense to preserve an intensity balance in the proposed decay scheme. The photon intensities are obtained by dividing the K-conversion line intensity by the theoretical conversion coefficient.[17] A tentative assignment for the 2023.9-kev level, then, is 3− ($K=3$) which indicates a possible octupole excitation.

The levels at 2184.6 and 2274.5 kev may have negative parity and spins of 2 and 3, respectively. This premise is based on the intensity of ($M1$) transitions to the $K=2-$ band (see Table IV). The energy difference of these two levels is not inconsistent with that expected for a rotation sequence. Two rather prominent transitions of 1954 and 2054 kev imply the existence of a 2054-kev state of low K quantum number.

A check on the internal consistency of the level scheme may be made by comparing the photon intensities predicted above with those few peaks which Gallagher *et al.*[24] were able to resolve. They report intensities for the photopeaks corresponding to energies of K x-rays and 470, 900,[27] and 2000[27] kev. Normalizing the photon data to the 470-kev K-conversion line (taking the transition as $M1$), one obtains satisfactory agreement with the premise that the transitions of 1954.7 and 2054.3 kev are of $M2$ multipolarity. The intensity of the composite 900-kev photopeak is consistent with the $M1$ multipolarities assumed above. In addition, the intensity of the K x-rays required for this level scheme is within 10% of the measured value.

[27] These photopeaks are composite.

2. Re^{182} (60 hr) → W^{182}

Since the spins of the two isomeric states of Re^{182} are presumably quite different, one should expect a dissimilar spectrum of transitions following electron capture since a different set of level in W^{182} would be populated. As mentioned previously, Gallagher and Rasmussen[25] reported on the decay scheme. They, too, used high-resolution, permanent-magnet spectrographs. Their data, in general, are in agreement with this work (see Table V). Our somewhat more complete data, however, in some cases lead to somewhat different conclusions. Figure 3 shows our proposed level scheme, and the relevant transition data are listed in Table VI. One feature which is worth pointing out at this time is that there appears to be a relatively large number of levels possessing a possible rotational excitation.

Let us discuss the evidence for some of these "bands." The 2+ and 3+ levels of the gamma-band at 1221.8 kev needs no further elaboration here. Directional correlation measurements by Hickman and Wiedenbeck[28] confirmed the spin assignments and established the mixing ratios for the transitions between the $K=2+$ and $K=0+$ bands. The (2, 2+ → 0, 2+)[29] transition is 94–99% quadrupole or 89–97% dipole on the basis of the correlation function. A somewhat surprising result is the indication from the angular correlation that the (2, 3+ → 0, 2+) transition is 2±0.5% quadrupole.

[28] G. D. Hickman and M. L. Wiedenbeck, Phys. Rev. **118**, 1049 (1960).
[29] The symbolism used here is $(K_iI_i \rightarrow K_fI_f)$.

One may note that Bodenstedt[19] concluded that the interband transitions in W^{184} were pure quadrupole. Theoretically, of course, dipole radiation is forbidden.

In agreement with Gallagher and Rasmussen, a rotational ($K=2-$) sequence up to $I=6$ based on the $2-$ state of 1289.7 kev is assigned; however there is disagreement as to the positions of the $4-$, $5-$, and $6-$ levels. Their energies for these levels are 1553, 1660, and 1830 kev, respectively. The energies we assign are 1488.0, 1621.7, and 1811.3 kev, respectively. Table VII presents the comparison of the experimental data with the predicted energies. One may note that the $5-$ level is lowered by 10 kev while the $6-$ level is raised by 6.5 kev from predicted values. Of course, if levels are being elevated or depressed due to the mutual repulsion of two levels of the same spin and parity, then it is difficult, indeed, to say what the true moments of inertia are. Intraband branching ratios (see Table IV) and $M1/E2$ ratios for rotational ($\Delta I=1$) transitions help place the 1621-kev state in the $K=2-$ band.

Another level of considerable interest is that at 1258.0 kev. Gallagher and Rasmussen have assigned it as a $K=1, I=1-$ state of a possible octupole excitation. It is quite possible that this is actually the $2+$ state of a $K=0$ beta-vibrational band. The possible existence of the $4+$ and $6+$ levels at 1443.3 and 1757.5 kev help to strengthen this assignment. The $(0, 0+)$ state apparently is not populated, a point which is not too surprising. Theoretically, the $2+$ level of the beta-band should decay primarily to the $4+$ level of the ground-state band, which is the case. The K assignment for the 1443-kev state is reasonable in view of the fact that there is negligible feeding to levels other than those of the $K=0$ band. The experimental branching ratio for the transitions de-exciting the state (assuming pure $E2$) is 0.2/1 as compared with the theoretical value of 1.1/1. This deviation is explainable if one admits the possibility of $E0$ or K admixtures. A similar situation exists for the transitions between the $6+$ level of the beta band and the ground-state band.

The energy constants for the three excited levels of the beta band are $3\hbar^2/\mathscr{I}=77$ kev and $B=+0.029$ kev. Based on these values, the unobserved $0+$ level is expected to be at 1180 kev. It is possible that the rota-

TABLE V. Conversion electron data for decay of Re^{182} (60 hr) $\rightarrow$ W^{182}.

Transition[a] energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[b]
18.05[f]			$M_I:M_{II}:M_{III}\approx 8:1:0.2$			80[c]	$M1$
19.85[f]		∼200[c]	∼70[c]	∼45[c]	∼75[c]	∼25[c]	$M1+(E2)$
23.1		w					
31.7		13	10	15	d	w	$E1$
39.1[f]		230	30	d	65	<27[d]	$M1$
42.0		w					
42.7		d	d	<10[d]			
44.7		<10[d]					
60.65[f]		27	w		d		$M1$
65.8		630	85	d	160	d	$M1/E2\approx 70$
67.85		∼220[d]	80	110	95	25	$E1$
79.5[f]	>30	w					
84.7	>740	330	135	100	∼150	45	$M1/E2=9$
100.1	>1000	∼200	2000	1800	1000	d	$E2$
107.1[f]	225	50	75	d	35	10	$M1/E2=1.2$
108.6[f]	180	∼30[e]	d		9		$M1$
113.7	1000	200	65	d	70	25	$M1/E2=7.5$
116.4	d						
130.8[f]	1000	200	78	55	80	25	$M1/E2=5$
131.4[f]	w						
133.8[f]	350	d	17	∼7	30	10	$M1/E2\approx 9$
145.35[f]	12						
147.7[f]	100	20[e]	e	d	d		
148.9[f]	200	45	d		<27[d]		
149.3[f]	∼50[e]	<30[d]					
149.5[f]	∼85						
151.2[f]	∼50	d					
152.5	90	d		∼5			
156.4	75	d					
160.0[f]	35	<33[d]					
169.1[f]	∼1100[d]	<380[d]	w		70		
172.8[f]	430	85[e]	e	4.7	24	8	$M1/E2\approx 15$
178.4[f]	25	d					
179.4	235	40	17	13	∼15		$M1/E2=2$
188.4[f]	w						
189.6[f]	60	d					
191.35[f]	∼730[d]	140[e]	e	∼3	<60[d]	10	
198.4	120		d	<60[d]	<30[d]		$E2$
203.3[f]	12						
208.2[f]	45	<30[d]					
209.45[f]	50	∼8.5					

TABLE V (*continued*).

Transition[a] energy (kev)	K	L_{I}	L_{II}	L_{III}	M	N	Remarks[b]
214.3[f]	83	15.5[e]	[e]	~4.5			$M1/E2\approx 1.2$
217.5[f]	~26[d]	[d]					
221.65[f]	~50[d] }	16[d]					
222.0	~36[d] }						
226.2[f]	<380[d]	40		[d]	9		
229.25	530	[d]	[e]	115	80	24	$E2$
247.4[f]	105	[e]	30[e]	14			$E2$
256.4[f]	550	97		~4	<42[d]	6	
264.0	66	[e]	19[e]	[d]			$E2$
276.25[f]	140	[e]	34[e]	14			$E2$
281.35[f]	86		[d]	~5.5	~8		$E2$
286.4[f]	[d]	[e]	24[e]	12	11		$E2$
299.9[f]	~35[d] }	12[d]					
300.4[f]	~35[d] }						
323.35[f]	<42[d]	[e]	5[e]	1.7			$E2$
339.05[f]	65	[e]	11[e]	4			$E2$
342.0[f]	4.4						
351.0[f]	78	[e]	19[e]	5.7			$E2$

Energy (kev)	K	L	Energy (kev)	K	L
928.0	0.75		1231.4	6.8	[d]
960.4	~0.45[d]		1257.2	~0.95	w
1002.2	2.1		1273.8	0.9	
1044.7	~0.3		1289.2	~1.7[d]	w
1076.8[f]	7.8	1.3	1342.7[f]	1.1	
1113.8[f]	3.1		1373.8	0.6	
1121.7	13	2.4	1386.8	w	
1158.2	1.3		1427.5[f]	3.2	w
1189.5	6.8	1.1	1437.8	~0.5	
1221.8	8.2	1.35			

[a] Conversion line energy calibration is based on precise transition energy measurements for Ta^{182} decay (reference 26).
[b] Multipole assignments are based on K/L ratios and L and M subshell ratios. Intensity data are normalized to 2000 units for the most prominent line. "w" indicates weak line.
[c] Film sensitivity and source effects are uncertain at these low energies.
[d] Conversion line is a composite of two different lines.
[e] Conversion line is partially resolved.
[f] Not observed in decay of Re^{182} (13 hr) $\rightarrow W^{182}$.

tional parameters for the beta-vibrational band may not be the correct values since there is present a 2+ level at 1221.8 kev. The repulsion between the two (2+) levels would tend to decrease the moments of inertia of the lower (gamma) band and increase it for the upper (beta) band. The relatively small energy separation between these two levels would be consistent with the rather marked effect. It has been remarked previously that inertial parameter for the gamma band was 10% larger than that for the ground state.

It is interesting to note that if one uses a value for B of -0.015 kev, which is the value for the ground-state band, then this would place the unperturbed 2+ level 22 kev lower than 1258 kev. This would place the unperturbed 0+ level at 1146 kev, and establish the inertial constant $(3\hbar^2/\mathscr{I})$ as 90 kev.

By substituting the experimental values of the beta- and gamma-vibrational state energies in the expression[1]

$$B=-\tfrac{1}{2}(\hbar^2/\mathscr{I})^3[3/E_\beta^2+1/E_\gamma^2],$$

one obtains a value of $B=-0.053$ for the ground-state band, which is to be compared with the experimental value of -0.015 kev. This is a rather large discrepancy, and the correction factor $b=2.12$ suggested by Sheline[7] does not seem sufficient to account for it.

The next possible band of interest is a sequence of three levels at 1437.8, 1660.8, and 1983.7 kev which have negative parity. The energies of the excited levels obey almost exactly if $I(I+1)$ interval rule for spin sequence 3, 5, and 7. It is worth remarking here that there are other possible bands interspersed with the band under discussion. These sequences consist of the following sets of levels (energies in kev): (1) 1553.7(4−) and 1829.9 (6−); (2) 1769.4 (6−) and 1960.7 (7−); and (3) 1810.1 (5−) and 1978.8 (6−). Very tentative levels are at 1961.3 kev (5−) and 1633.3 kev (5−). Table VII lists the rotational energy parameters for these bands. The values of $3\hbar^2/\mathscr{I}$ for the proposed odd-parity bands are observed to be 15 to 25% less than for ground-state band. In constructing the odd-parity bands, comparison was made of reduced gamma rays which go between states of the same spin and parity to observe the effects of ΔK.

Returning to the negative-parity band based at 1437.8 kev, one may postulate that 3−, 5−, 7− sequence is a $\lambda=3$ octupole vibration with $\nu=0$ (where ν is the projection of the vibrational angular momentum on the symmetry axis). In this mode, the axial symmetry of the nuclear shape is preserved. A $\nu=0$ vibration represents a nucleus with a paired nucleonic con-

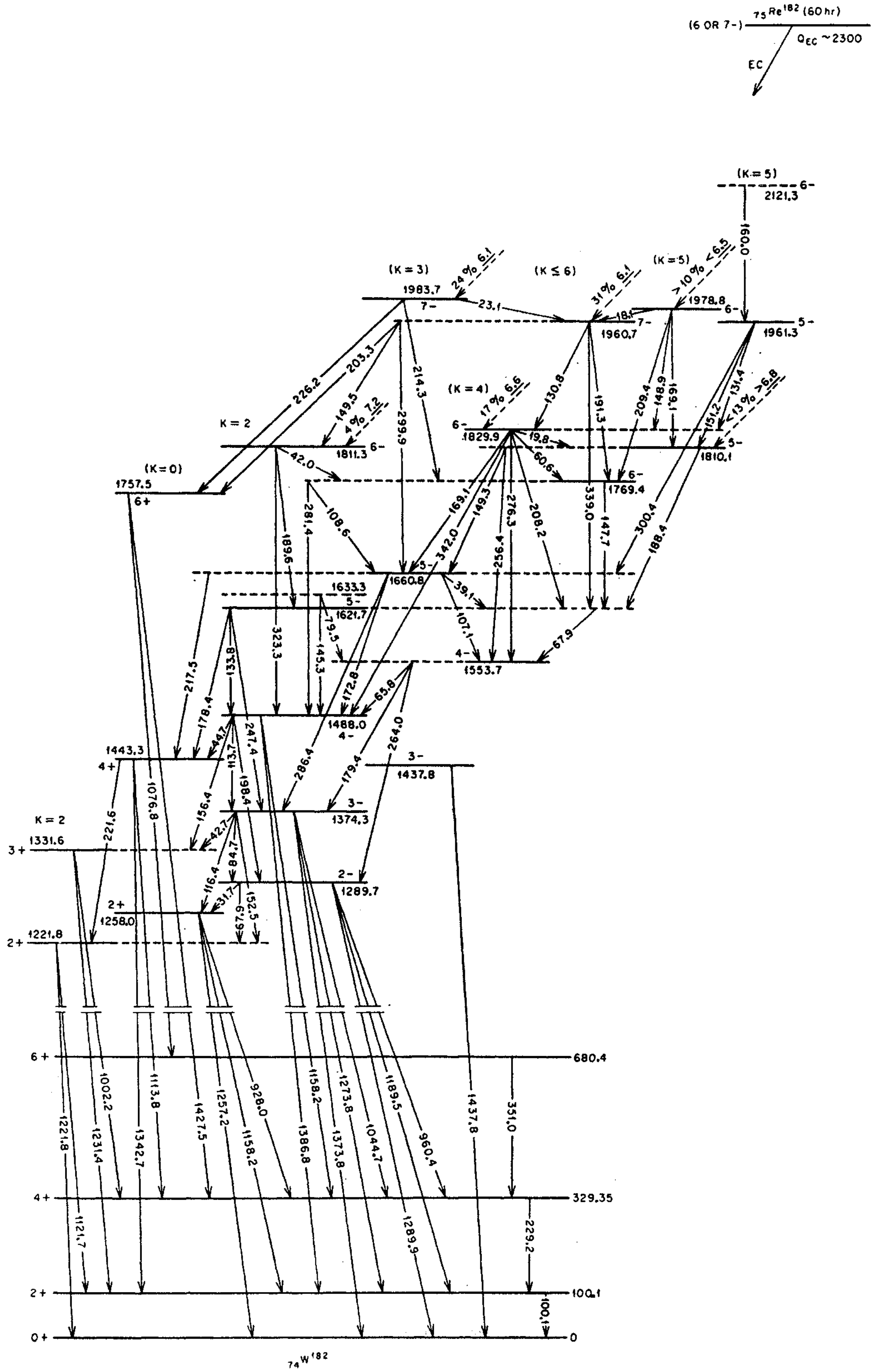

FIG. 3. Proposed decay scheme of Re[182] (60 hr) to W[182]. *All* observed transitions are placed in the scheme.

TABLE VI. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Re^{182} (60 hr) $\rightarrow W^{182}$ (Fig. 3).

Proposed excited states I,π	Proposed excited states (kev)	De-exciting transitions (kev)	Multipole[a] assignment	Calculated relative intensities $N_\gamma+N_{ce}$	Calculated relative intensities N_γ[b]
2+	100.1	100.1	$E2$	8600[c]	1750[c]
4+	329.3	229.2	$E2$	5360	4420
6+	680.4	351.0	$E2$	2110	2000
2+	1221.8	1121.7	$E2/M1=5.2$	3690	3675
		1221.8	($E2$)	3260	3250
3+	1331.6	1002.2	($E2$)	573	570
		1231.4	($E2$)	2730	2720
2+	1258.0	928.0	($E2$)	181	180
		1158.2	($E2$)	465	464
		1257.2	($E2$)	401	400
4+	1443.3	221.6	($E2$)	435	375
		1113.8	($E2$)	1035	1032
		1342.7	($E2$)	531	530
6+	1757.5	1076.8	($E2$)	2450	2440
		1427.5	($E2$)	1670	1666
2−	1289.7	31.7	$E1$	80	28
		67.9	$E1$	3350	2820
		960.4	($M2$)	~21	~20
		1189.5	$M2/E1=0.35$	1700	1692
		1289.9	($M2$)	~172	~170
3−	1374.3	42.7	($E1$)	<90	<50
		84.7	$M1/E2=9$	2840[c]	420[c]
		116.4	($E1$)	...	...
		152.5	$E1$	940	825
		1044.7	($M2+E1$)	<220	<220
		1273.8	$M2/E1\approx0.2$	361	360
		1373.8	($E3$)	150	150
4−	1488.0	44.7	($E1$)	<90	<50
		113.7	$M1/E2=7.5$	1815	435
		156.4	($E1$)	845	750
		198.4	$E2$	905	685
		1158.2[d]	($M2$)	...	...
		1386.8	($M2$)	w	w
5−	1621.7	133.8	$M1+E2$	720	230
		178.4	($E1$)	385	350
		247.4	$E2$	1235	1070
6−	1811.3	42.0	($M1$)	w	w
		189.6	($M1$)	165	92
		323.3	$E2$	705	666
3−	1437.8	1437.8	($E3$)	136	135
5−	1660.8	39.1	$M1$	380	27
		107.1	$M1/E2=1.2$	580	130
		172.8	$M1+E2$	1100	550
		217.5	($E1$)	637	605
		286.4	$E2$	1715	1562
7−	1983.7	23.1	($M1$)	w	w
		214.3	$M1+E2$	285	175
		226.2	($E1+M2$)	<6600	<6310
4−	1553.7	65.8	$M1+E2$	1300	350
		179.4	$M1/E2=2$	730	405
		264.0	$E2$	906	805
6−	1829.9	19.85	$M1$	~420	~6
		60.65	$M1$	52	12
		169.1	($M1$)	2660	1250
		208.2	($M1$)	145	90
		276.3	$E2$	2145	1940
		342.0	($E2$)	115	110
6−	1769.4	108.6	($M1$)	290	67
		147.7	$M1+E2$	210	80
		281.4	$E2$	1390	1265
7−	1960.7	130.8	$M1/E2=5$	2105	665
		149.5	($M1$)	~170	~68
		191.35	($M1$)	~2060	~1140
		203.3	($E1$)	~255	240
		299.9	($E2$)	~660	~615
		339.05	$E2$	1670	1585
5−	1810.1	149.3	($M1$)	~100	~40
		188.4	($M1$)	w	w
		256.4	$M1$	2610	1930
6−	1978.8	18.05	$M1$	~1120	~15
		148.9	($M1$)	420	160
		169.1[d]	($M1$)	...	...
		209.45	($M1$)	160	100
(5−)	1961.3	131.4	($M1$)	w	w
		151.2	($M1$)	~100	~40
		300.4	($M1$)	~230	~190
(6−)	2121.3	160.0	($M1$)	78	35

[a] Multipolarities are assigned either from conversion electron ratios of Table V, from conversion coefficients listed in Nuclear Data sheets (reference 14), or from consistency with angular momentum selection rules; latter assignments are in parentheses and are shown unmixed if we have no way of estimating mixing ratios.

[b] Estimates of photon intensity are based on internal conversion electron data and theoretical conversion coefficients (reference 17).

[c] Photon and K-electron intensities are deduced from L-electron data.

[d] Recurring transition is previously listed.

figuration, and alternate spins in the rotational sequence appear (the most usual example of this, of course, being the $K=0$, $\nu=0$ ground-state band).

TABLE VII. Empirical constants for rotational energy formula $E=(\hbar^2/2\mathcal{I})[I(I+1)]+BI^2(I+1)^2$ for possible rotational bands in W^{182} and predicted next levels.

Base state $I_0\pi$	Base state (kev)	$3\hbar^2/\mathcal{I}$ (kev)	B_{kev}	Higher rotational states (kev) Predicted	Higher rotational states (kev) Experiment
0+	0	100.6	−0.015	677.4(I_0+6)	680.4
2+	1221.8	109.8		1478.2(I_0+2)	
2+	1258.0	77.0	+0.029	2231.1(I_0+6)	
2−	1289.7	84.5	+0.007	1631.4(I_0+3)	1621.7
				1804.8(I_0+4)	1811.3
3−	1437.8	74.3	+0.001	2407.4(I_0+6)	
4−	1553.7	75.4		2206.8(I_0+4)	
6−	1769.4	82.0		2179.3(I_0+2)	
5−	1810.1	84.3		2175.4(I_0+2)	

Some remarks may be made about the gamma-ray de-excitation of this band: (1) The proposed $I=K=3-$ primary state at 1437.8 kev is observed to de-excite only to ground. The mode of population of this state is not known. (2) The value of $K=3$ for the 1660 kev (5−) state is indicated when one compares the RTP ratios to the $K=2-$ band. The experimental ratio of $B(E2:5-\rightarrow3-)$ to $B(E2:5-\rightarrow4-)$ is 1:0.27 as compared to the theoretical ratio for $K_i=3$ of 1:0.16. Theoretical values for $K_i=2$ or 4 show much greater deviation. (3) Some possible evidence for an impurity in K number is seen in the observation that both levels of 1660 and 1983 kev ($K=3$) decay with rather intense transitions to levels of the $K=0$ beta-vibrational band.

With regard to the levels at 1553.7 and 1829.9 kev, of spin assignments 4− and 6−, it is not clear how

valid the designation of a rotational sequence is. The intraband transition of 276.3 kev is $E2$ and corresponds to a value of $3\hbar^2/\mathfrak{g}$ of 75.4 kev. As can be seen by reference to Table IV, the ratio of RTP's are not inconsistent with the $K=4$ assignment. Another observation is that these levels de-excite preferentially to levels of K number one less than $K_i=4$. (The rotational transition is intense, as well.) The gamma-gamma directional correlation measurements[28] are consistent with a spin of 3, 4, or 5 for the 1553.7-kev level.

The possible rotational level sequence based at 1769.4 kev ($I=6-$, $7-$) would have a value of $3\hbar^2/\mathfrak{g}=82$ kev. Here, de-excitation to levels of $K_f=2$, 3, 4, as well as rotations appear to be favored, except that there is a not inappreciable amount of radiation proceeding to the $K=0$ beta-band. A pair of levels at 1810.1 and 1978.8 kev have been tentatively assigned as the 5− and 6− members of a $K=5$ band.

In Fig. 3 are indicated the relative percentages of electron-capture decay from Re^{182} to the various levels. It appears that this decay proceeds mainly to the 6− and 7− states of the $K=3$, 4, 5, and 6 bands.

It is clear that the density of levels in W^{182} in the region of excitation just under 2 Mev is quite high. It is also clear that these are high-spin states, and that negative parity is most reasonable. In fact, the only two positive bands are the beta- and gamma-vibrational bands (except for the ground state, of course).

TABLE VIII. Conversion electron data for decay of Lu^{172} (6.7 day) → Yb^{172}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a,b]
78.7	>200	[c]	1100[c]	1100	600	170	$E2(2+\rightarrow 0+)$
90.6	>195	50	225	220	110	40	$E2/M1=3$
112.7	53	6	24	21	11	3	$E2/M1=3.6$
134.3	2.3	[c]	0.83[c]	0.55	0.3		$E2/M1=3.2$
145.9[e]	3.4	<1.2[d]					
155.7[e]	1.1	0.15					
163.0	3.0	0.45					
181.4	210	[c]	59[c]	46	28	8	$E2(4+\rightarrow 2+)$
196.7	<1.2[d]						
199.8	0.3						
203.3	37	[c]	9[c]	6.7	4.5		$E2$
210.3	1.7	0.2					
228.9[e]	4.6	[d]					
247.0	2.8	[c]	0.8[c]	0.5			$E2$
264.9[e]	1.5	0.25					
269.9	17.5	2.9			<1.4[d]		
279.7	4.5	1.2	[d]	0.4	0.33		$E2(6+\rightarrow 4+)$

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
319.0[e]	0.9	w	594.3[e]	0.4	w	1194.4[e]	w	
323.8	9	1.3	607.1[e]	0.19		1290.2	0.03	
329.0[e]	<1.4[d]	0.11	622.4	0.19		1324.4[e]	w	
337.4	0.2		630.6	0.42	[c]	1388.7	0.05	
352.4[e]	0.17		682.0	0.6	w	1399.6	w	
358.2[e]	0.48		685.2[e]	w		1404.1	0.048	
366.3[e]	0.22		697.8	4.5	0.54	1433.8[e]	w	
372.3	7.2	1.1	709.0[e]	0.37		1441.7	0.042	
373.3	0.5	[d]	715.0[e]	w		1467.6	0.04	
377.3[e]	1.6	0.25	722.8[e]	0.3		1471.3	0.04	
399.5	1.9	0.23	810.6	8.2	1.3	1480.2[e]	w	
410.1	4.9	0.8	816.9	0.65		1490.2	0.08	
415.2[e]	w		901.4	11.2	1.8	1544.5	0.07	w
416.3[e]	0.2		913.4	3.5	0.6	1585.7	0.145	0.02
427.0	0.3		930.0	1.13	0.16	1604.2	0.025	
432.3[e]	0.7		968.8[e]	w		1623.5	0.11	<0.034[d]
437.3	0.6		1004.4	1.05	0.15	1672.0[e]	<0.034[d]	
442.6[e]	~0.1		1023.7	0.46	0.08	1726.0	0.04	
482.1	0.87	[c]	1042.4[e]	0.12		1769.0[e]	w	
486.0	1.05	<0.72[d]	1082.3[e]	0.24	w	1786.9[e]	w	
490.2	3.6	<2.4[d]	1095.3	7.6	1.2	1814.0	~0.013	
512.4[e]	0.28		1114.2	0.41	0.07	1851.3[e]	w	
528.1	6.0	0.85	1117.3	w		1869.2[e]	0.015	
535.9	<0.72[d]		1126.6[e]	~0.04		1915.8[e]	0.05	
540.2	<2.4[d]	0.25	1150.4[e]	w		1995.7	~0.01	
550.7[e]	0.5	w	1161.8[e]	w		2025.8[e]	w	
576.4	~0.33		1176.3[e]	~0.03		2083.5[e]	~0.01	
584.5	0.33	w	1186.0	~0.044				

[a] Multipole assignments are based on K/L and L-subshell ratios.
[b] Intensity data are normalized to 1100 units for the most prominent line. "w" indicates weak line.
[c] Conversion line is partially resolved.
[d] Conversion line is a composite of two different lines.
[e] Not placed in decay scheme.

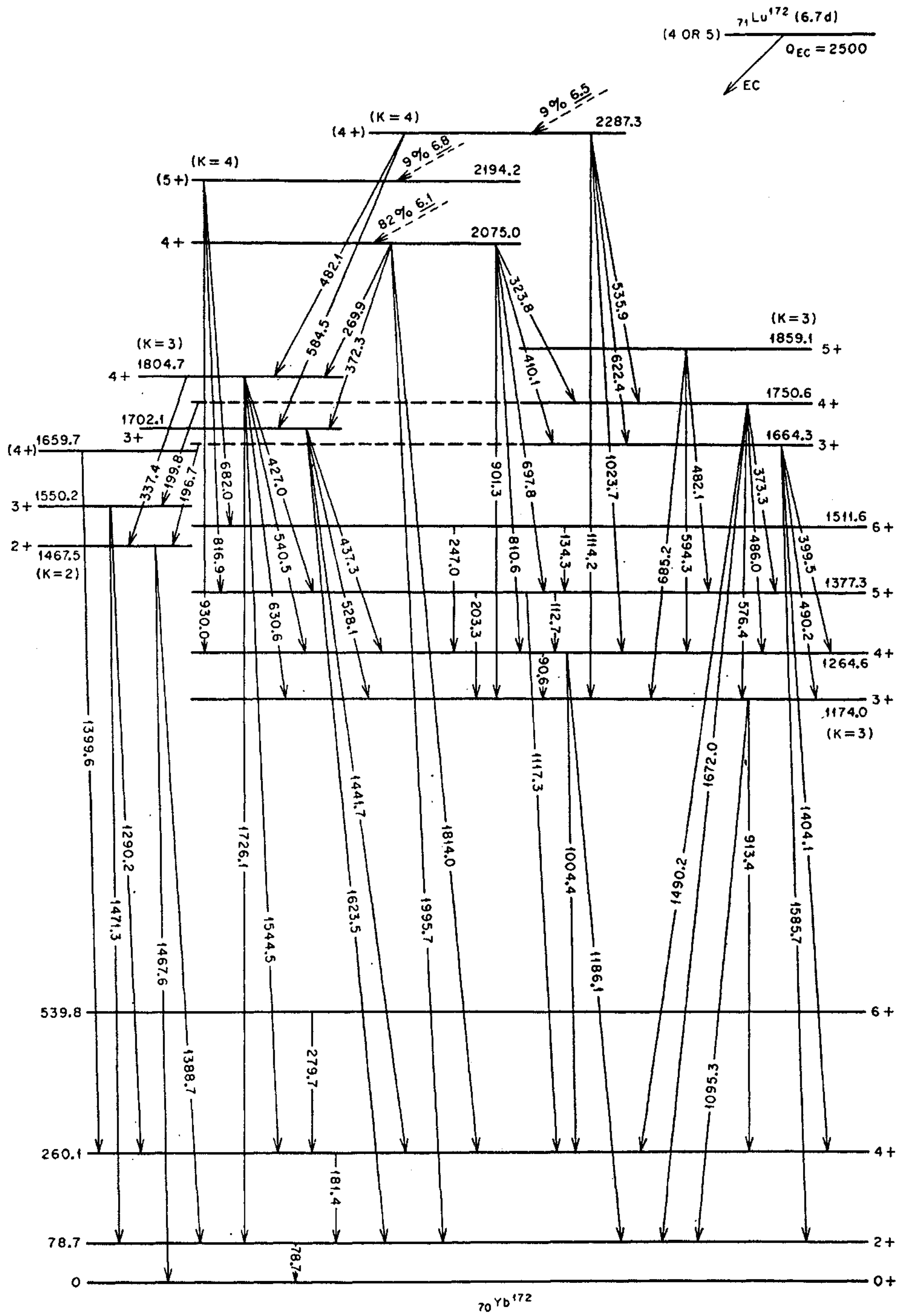

FIG. 4. Levels in Yb[172] populated by electron-capture decay of Lu[172] (6.7 day). A tentative state at 1864.3 kev is not shown.

C. Lu^{172} (6.7 day) → Yb^{172}

Lu^{172} (6.7 day) decays (primarily by electron capture) to levels in Yb^{172}. Although empirical mass tables[30] predict a relatively small available energy (2500 kev), an extremely complex de-excitation spectrum of 95 transitions is observed ranging in energy from 79 to 2083 kev. In a previous publication,[31] the internally converted gamma rays of this activity were reported, noting the existence of five intense $E2$ transitions of energies between 79 and 203 kev. Table VIII lists the complete internal-conversion electron data. Meanwhile some scintillation-counter and gamma-gamma coin-

[30] A. G. W. Cameron, Atomic Energy of Canada Limited Report AECL-433, 1957 (unpublished).

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

TABLE IX. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Lu^{172} (6.7 day) → Yb^{172} (Fig. 4).

Proposed excited states (I,π)	Proposed excited states (kev)	De-exciting transitions (kev)	Multipole[a] assignment	Relative photon intensities Calculated[b]	Relative photon intensities Experimental[c]
2+	78.7	78.7	$E2$	440	373
4+	260.1	181.4	$E2$	970	970
6+	539.8	279.7	$E2$	70	<184[d]
3+	1174.0	913.4	($E2$)	945	415
		1095.3	($E2$)	2920	2305
4+	1264.6	90.6	$E2/M1=3$	235	~138
		1004.4	($E2$)	340	
		1186.0	($E2$)	20	
5+	1377.3	112.7	$E2/M1=3.6$	46	≤46
		203.3	$E2$	237	>230
		1117.3	($E2$)	w	
6+	1511.6	134.3	$E2/M1=3.2$	3.4	
		247.1	$E2$	31	
2+	1467.5	1467.6	($E2$)	27	
		1388.7	($E2$)	30	<92[e]
3+	1550.2	1290.2	($E2$)	16	
		1471.3	($E2$)	27.5	
(4+)	1659.7	1399.6	($E2$)	w	
3+	1664.3	196.7	($M1$)		
		399.5	($M1$)	31	
		490.2	($M1$)	98	46
		1404.1	($E2$)	30	<92[e]
		1585.7	($E2$)	114	138
4+	1750.6	199.8[f]	($M1$)	0.7	
		373.3	($M1$)	6.8	
		486.0	($M1$)	28.5	
		576.4	($M1$)	13.2	
		1490.2	($E2$)	56	
		1672.0	($E2$)	<30	
(5+)	1859.1	482.1[f]	($M1$)	23	
		594.3	($M1$)	17.4	
		685.2	($E2$)	w	
3+	1702.1	437.3	($M1$)	12.6	
		528.1	($M1$)	197	138
		1441.7	($E2$)	27.5	
		1623.5	($E2$)	91	
4+	1804.7	337.4	($E2$)	~5	
		427.0	($M1$)	5.7	
		540.5	($M1$)	~62	
		630.6	($M1$)	21	
		1544.5	($E2$)	53	
		1726.0	($E2$)	37	
	1864.3	163.0	($M1$)	4	
		199.8[f]	($M1$)	0.7	
		1324.4	($E2$)	w	
		1604.2	($E2$)	20	
4+	2075.0	210.3	($M1$)	5	
		269.9	($M1$)	99	<184[d]
		323.8	($M1$)	83	<46
		372.3	($M1$)	97	138
		410.1	($M1$)	85	
		697.8	($M1$)	294	184
		810.6	($M1$)	812	784
		901.4	($M1$)	1454	1291
		1814.0	($E2$)	13	
		1995.7	($E2$)	12	
(5+)	2194.2	682.0	($M1$)	37	
		816.9	($M1$)	66	
		930.0	($M1$)	159	
(4+)	2287.3	482.1[f]	($M1$)	23	
		535.9	($M1$)	~19	
		584.5	($M1$)	14	
		622.4	($M1$)	9	
		1023.7	($M1$)	81	
		1114.2	($M1$)	88	

[a] Multipolarities are assigned either from conversion electron ratios of Table VIII 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 obtained from internal conversion electron data and theoretical conversion coefficients.
[c] Photon data of R. G. Wilson and M. L. Pool (reference 35) are normalized to the 181.4-kev transition.
[d] Composite photon peak of 279- and 269-kev transitions.
[e] Composite photon peak of 1404-, 1388-, and 1399-kev transitions.
[f] Recurring transition is listed twice.

cidence measurements[32,33] have become available. These data lead to the postulation of the level scheme shown in Fig. 4. Complementary data are now available from the studies of the β^- decay of Tm^{172}.[34]

The rather complete internal-conversion electron data allows one to expand the scheme based on coincidence measurements and to postulate levels consistent with the energies, intensities, and multipolarities of the newly included transitions (see Table IX). It is felt that the resulting scheme is almost unique. The exact interpretation of the levels may be somewhat in doubt, of course. Checks have been made on the validity of the proposed scheme employing the rotational energy criteria as well as the ratio of intensities of de-exciting transitions.

In addition to the ground-state rotational band ($I=0$, 2, 4, 6+), five primary states, each exhibiting rotational excitation levels are possible. One additional state at 2287.3 kev ($I=4+$) is shown in Fig. 4. As regards the 6+ → 4+ transition of the ground-state band, the 279.7-kev gamma ray appears to be of $E2$ multipolarity on the basis of the ratio of intensities of conversion lines and therefore seems to be the correct

TABLE X. Empirical constants for rotational energy formula $E=(\hbar^2/2\mathcal{J})[I(I+I)]+BI^2(I+1)^2$ for possible rotational bands in Yb^{172} and predicted next levels.

Base state $I_0\pi$	Base state (kev)	$3\hbar^2/\mathcal{J}$ (kev)	B_{kev}	Higher rotational states (kev) Predicted	Higher rotational states (kev) Experiment
0+	0	79.0	−0.008	538.9(I_0+6)	539.8
2+	1467.5	83.2	−0.007	1796.5(I_0+3)	
3+	1174.0	68.1	−0.003	1511.7(I_0+3)	1511.6
				1667.4(I_0+4)	
3+	1664.3	64.6	+0.003	1990.2(I_0+3)	
3+	1702.1	77.0		1933.0(I_0+2)	
4+	2075.0	71.5		2337.2(I_0+2)	

[32] K. P. Jacob, thesis, University of Notre Dame, 1958 (unpublished).
[33] R. G. Wilson and M. L. Pool, Phys. Rev. **118**, 1067 (1960).
[34] R. G. Helmer and J. B. Burson, Bull. Am. Phys. Soc. **5**, 425 (1960), Argonne National Laboratory Report ANL-6270, 1961 (unpublished).

one. The 18 levels above the ground state are quite firm, each being fixed by a number of accurately measured transition energies. Table X lists the observed and predicted energies for the rotational excitation of each of the several primary states along with the inertial constant of $3\hbar^2/\mathscr{I}$ and B (the coefficient appropriate for the rotation-vibration correction). It is clear that the excitation energies indeed do follow the $I(I+1)$ interval rule, and it is unlikely that this is merely fortuitous. The spins of the various states are fairly well determined in this fashion. (Of course, the spins are also highly consistent with the observed population and depopulation of the levels in question.) The value of quantum number K is also then very likely the value of I_0 (the spin of the base state). The checks on the K-number assignments will be discussed shortly.

The band based at 1174.0 kev displays the proper energy intervals for a spin sequence of 3, 4, 5, and 6. The parity designation is more difficult. The decay scheme, displayed as Fig. 4, was constructed with the following restriction: the parity of the 1174-kev state is positive, and the multipolarity of the transitions is as listed in Table IX. This is the most reasonable scheme; any negative parity bands would require some unexpected multipole mixtures and branching ratios to make the intensities of transitions feeding and depopulating various levels correct.

The rotational sequence based at 1174 kev, for which a level of spin as high as 6 is observed, has an inertial term 14% lower than that for the ground-state band. Another striking feature of the band is the presence of intense intraband transitions. These level spacings are determined to within 0.1 kev. For those transitions proceeding between levels of spin difference one, the multipolarities are $E2+M1$ ($E2/M1\sim3$), and all possible $E2$ crossovers are present, thus indicating the rotational character of the levels. Table XI displays the experimental ratio of the value $B(E2)$ for the cascade transition to the value of $B(E2)$ for the crossover transition de-exciting the 1377-kev (5+) and 1511-kev (6+) rotational states. Better agreement with the theoretical value is obtained by assuming quantum number $K=3$ rather than $K=2$; also the $E2$ intraband transitions are much more probable than the $E2$ interband transitions to $K=0+$ states of the same spin and parity. This is probably due to K-forbiddenness.

Two other possible bands based on $I=3+$ ($K=3$) states at 1664 and 1702 kev are indicated in Fig. 4. The base states de-excite to states of spin 2, 3, and 4. The

TABLE XI. Ratios of reduced transition probabilities in de-excitation of levels in Yb^{172}.

Initial state I, π	Initial state (kev)	Final states $(K, I\pi)$	Assumed multipolarity	Reduced transition[a] probability ratios
2+	1467.5	(0, 0+), (0, 2+)	$E2$	0.68/1
				0.7/1 (theor.) $K_i=2$[b]
3+	1174.0	(0, 2+), (0, 4+)	$E2$	1.3/1
	1550.2	(0, 2+), (0, 4+)	$E2$	0.9/1
	1664.3	(0, 2+), (0, 4+)	$E2$	2.1/1
	1702.1	(0, 2+), (0, 4+)	$E2$	1.8/1
				2.5/1 (theor.) $K_i=2$[b]
4+	1264.6	(0, 2+), (0, 4+)	$E2$	0.03/1
	1659.7	(0, 2+), (0, 4+)	$E2$	c/1
	1750.6	(0, 2+), (0, 4+)	$E2$	<0.3/1
	1804.7	(0, 2+), (0, 4+)	$E2$	0.4/1
	2075.0	(0, 2+), (0, 4+)	$E2$	0.57/1
				0.34/1 (theor.) $K_i=2$[b]
5+	1377.3	(0, 4+), (0, 6+)	$E2$	1/c
				1/0.57 (theor.) $K_i=2$[b]
3+	1664.3	(3, 3+), (3, 4+)	$M1$	1.7/1
	1702.1	(3, 3+), (3, 4+)	$M1$	8.8/1
				3/1 (theor.) $K_i=3$[b]
4+	1750.6	(3, 3+), (3, 4+), (3, 5+)	$M1$	0.3/1/0.5
	1804.7	(3, 3+), (3, 4+), (3, 5+)	$M1$	0.2/1/0.2
				0.4/1/0.8 (theor.) $K_i=3$[b]
4+	2075.0	(3, 3+), (3, 4+), (3, 5+)	$M1$	1.3/1/0.57
	2287.3	(3, 3+), (3, 4+), (3, 5+)[d]	$M1$	3.2/1/[c]
	2287.3	(3, 3+), (3, 4+), (3, 5+)[e]	$M1$	0.84/1/[c]
				3.9/1/0.22 (theor.) $K_i=4$[b]
5+	2194.2	(3, 4+), (3, 5+), (3, 6+)	$M1$	1/0.6/0.6
				1/0.6/0.24 (theor.) $K_i=4$[b]
5+	1377.3	(3, 4+), (3, 3+)[f]	$E2$	2.9/1
				1.7/1 (theor.) $K_i=3$[b]
6+	1511.6	(3, 5+), (3, 4+)[f]	$E2$	1.8/1
				0.5/1 (theor.) $K_i=3$[b]

[a] Experimental reduced gamma-ray intensity is obtained by dividing the K-electron intensity by the theoretical K-conversion coefficient and by the energy-dependent term, E^{2L+1}.
[b] The theoretical relation is given by the square of the ratio of Clebsch-Gordan coefficients compiled by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).
[c] Transition unobserved.
[d] Associated with the 1664-kev base-state band.
[e] Associated with the 1174-kev base-state band.
[f] Branching ratios are for the $E2$ cascade transition to the $E2$ crossover transition in the rotational band.

rotational levels are shown feeding lower states of spin 3, 4, and 5; however intraband transitions were not observed. The experimental reduced transition probabilities of the 1664-kev base-state band to the 1174-kev sequence are in essential agreement with theoretical prediction as shown in Table XI. In both cases, the stated ratios are between $K_i=K_f=3$ bands, and pure dipole radiation is assumed. Similar determinations for the 1702-kev base-state band show rougher agreement.

With the assumption of rotational excitation, one obtains $3\hbar^2/\mathfrak{I}=65$ and 77 kev, respectively, for the 1664- and 1702-kev bands. These values are to be compared with a value of 68 kev for the 1174-kev base band; however the interaction term "B" appears in Table X as slightly positive only for the 1664-kev band. Perhaps this is due to repulsion of the 1664-kev (3+) and 1750-kev (4+) levels by nearby (40-kev separation) states of the same spin and parity. Quantitatively, the deviation of the 1859-kev (5+) state from the $I(I+1)$ energy law is +0.6 kev compared to −0.6 kev for the 1377-kev (5+) state in the 1174-kev band.

There is some evidence for a gamma-vibrational band ($K=2+$) in Yb^{172} beginning at 1467.5 kev. The ratios of branching to the ground-state band (see Table XI) are consistent with the postulated existence of a gamma-vibrational structure. The inertial constant for this band, which is 5% greater than the ground-state band, may be influenced by interaction with close-lying 3+ states.

Additional evidence for the parity of the postulated states at 1174.0 and 1467.5 kev is now available from the study of the beta decay of Tm^{172} by Helmer and Burson.[34] Tm^{172} is most likely in a 2− state since the β^- spectrum to the ground state of even-even Yb^{172} is unique first-forbidden. The $\log(ft)$ values for the transitions to the two states in question are 7.6 and 6.7, respectively. It is certainly reasonable to assign positive parities to these states, an assignment we have arrived at independently using as a criterion the intensity balance of the various gamma-ray transitions. On the basis of their energies, it would appear that, in addition to the ground-state band, the Tm^{172} decay populates the levels assigned at 1174 (3+), 1467.5 (2+), 1550.2 (3+), and possibly 1664.3 (3+) kev.

The transition intensities indicate that most, if indeed not all, of the electron-capture decay of Lu^{172} proceeds to states above 2 Mev in Yb^{172}. A consistent level scheme is indicated if one takes the predicted total decay energy (2.5 Mev)[30] and a spin of 4 or 5 for Lu^{172}. The appropriate Nilsson orbitals here are 1/2− [521] for the neutron and either 9/2− [514] or 7/2+ [404] for the proton.

The 2075-kev state is shown in Fig. 4 feeding 9 lower-lying states of spin assignments 2, 3, 4, and 5. Conversion coefficient data which are available for a number of these transitions (see Table IX) are most consistent with a spin and parity of 4+. A 2194-kev state populates the $I=4$, 5, and 6 members of the rotational band associated with the 1174-kev state. Possibly the 2194-kev level is a rotational excitation (5+) of the primary state of 2075 kev. The relevant inertial parameter, $3\hbar^2/\mathfrak{I}=71.5$ kev, is close to values for other bands listed in Table X. The branching ratio of the 2194-kev level to the members of the 1174-kev band yields $B(M1{:}5\rightarrow4)/B(M1{:}5\rightarrow5)/B(M1{:}5\rightarrow6)=1/0.6/0.6$, assuming pure $M1$ radiation and $K_i=4$, $K_f=3$. The corresponding theoretical ratio is 1/0.6/0.24.

A 2287-kev level may decay to 6 different states of spins 3 and 4. This level is designated as $I=K=4+$. Both of the postulated (4, 4+) states at 2075 and 2287 kev are found to exhibit similar RTP ratios to $I=K=3+$ states at 1702, 1664, and 1174 kev. The experimental ratios, assuming pure $M1$ radiation, are:

$$E_i=2075\text{ kev}:\quad 372\gamma/410\gamma/901\gamma=0.9/0.6/1,$$

and

$$E_i=2287\text{ kev}:\quad 584\gamma/622\gamma/1114\gamma=1.1/0.6/1.$$

Branching ratios for dipole radiation between the (4, 4) states and $I=4$, $K=3+$ rotational levels at 1804, 1750, and 1264 kev are:

$$E_i=2075\text{ kev}:\quad 269\gamma/323\gamma/810\gamma=3.3/1.6/1,$$

and

$$E_i=2287\text{ kev}:\quad 482\gamma/535\gamma/1023\gamma=2.7/1.6/1.$$

There is a surprising consistency in the above ratios.

It is interesting to note that the de-excitation of the high-energy states of $K>2$ proceeds mainly through the 1174 (3+) state; this is probably due to K-selection rules.

D. Tm^{166} (7.7 hr) → Er^{166}

Certain features of the level scheme of Er^{166} as populated by the decay of Tm^{166} (7.7 hr) are now quite clear. The existence of a ground-state rotational series up to a 6+ level at 545.3 kev and a gamma-vibrational sequence with states of 787.1 (2+), 860.4 (3+), and 957.3 (4+) kev have been discussed previously.[20] Other workers[35,36] have reported on studies of Tm^{166} with internal conversion, scintillation counter, and gamma-gamma coincidence techniques which confirm the above states and their assignments.

More data were obtained on the internal-conversion electron spectrum of this activity (see Table XII). Attempts were made to obtain multipole order data by comparing the internal-conversion electron intensities of Table XII with the relative photon intensities, normalizing to the $E2$ conversion coefficient of the 184-kev transition. The low-energy photon data (<1 Mev) of Gromov *et al.*[36] which are more detailed and the high-energy values of Wilson *et al.*[35] which appear more reliable are employed. Table XIII summarizes the

[35] R. G. Wilson and M. L. Pool, Phys. Rev. **119**, 262 (1960).
[36] K. Ya. Gromov, B. S. Dzhelepov, and V. N. Pokrovskii, Bull. Acad. Sci. USSR **23**, 821 (1959).

TABLE XII. Conversion electron data for decay of Tm^{166} (7.7 hr) $\rightarrow$ Er^{166}.

Transition energy (kev)	K	L_{I}	L_{II}	L_{III}	M	N	Remarks[a,b]
73.4	w		w	w			$E2+(M1)$
80.6	>400	~ 110[c]	1120	1100	515	145	$E2(2+\rightarrow 0+)$
84.1	>4.4	1.8					
90.7[d]	w	w					
96.6	[c]	w	w	w	w		$E2+(M1)$
131.0	4.3	~ 0.6					
147.2[d]	1.7						
154.3[d]	6.0	0.8		w			
170.1	1.1						
184.4	165	[c]	35	28	19	4	$E2(4+\rightarrow 2+)$
194.8	15.5						
215.1	9.4						
269.8[d]	w						
280.2	1.0						
320.0[d]	w						
345.5[d]	2.6						
403.8[d]	1.85	0.28					
429.0[d]	~ 0.3						
459.3[d]	4.6	0.7					
521.3	w						
595.0	1.1						
599.2	0.2						
672.9	0.56						
675.6[d]	~ 0.3						
692.4	1.6	0.27					
706.3	2.4	0.4					
712.1[d]	0.2						
729.7[d]	w						
759.0	0.9						
780.0	3.15	0.55					
787.1	1.8						
812.1[d]	w						
877.0	0.5	0.1					

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
1060.1[d]	~ 0.05		1304.3	0.14		1636.2	w	
1074.1[d]	w		1308.7[d]	w		1829.3[d]	0.05	
1081.6	0.05		1350.4	0.08		1843.4[d]	w	
1155.1[d]	0.21	0.07	1377.6	0.45	~ 0.09	1873.0	0.10	
1180.0	1.05	0.13	1434.3	0.08		1899.4	w	
1194.5	w		1451.2	0.055		2057.3	0.36	0.06
1207.1	~ 0.09		1461.2[d]	w		2068.1[d]	w	
1239.1	~ 0.06		1498.2[d]	0.055		2083.0	0.115	
1266.7[d]	w		1508.5	0.075		2095.7[d]	w	
1276.8	1.4	0.2	1603.1[d]	w				

[a] Multipole assignments are based on K/L and L-subshell ratios.
[b] Intensity data are internally consistent. "w" indicate weak line.
[c] Conversion line is partially resolved.
[d] Not placed in decay scheme.

character and intensity of transitions incorporated in the decay scheme presented in Fig. 5.

Two states are clearly established at 2137 and 2164 kev which populate all proposed levels of spins 2, 3, and 4 in the ground-state and gamma-vibrational bands. Results of gamma-gamma coincidence studies[35] also indicate a level at 2137 kev. This state is assigned a spin of 3 and odd parity, since gamma rays of 1873 and 2057 kev which de-excite to the 2+ and 4+ levels have internal conversion coefficients which are most consistent with $E1$ assignments for these transitions. The 2164-kev level is assigned $I=3$ and odd parity. If the spin were 2, then the ground-state transition probably would have been observed. The electron-capture decay of Tm, of measured spin 2−,[37] proceeds primarily to the two levels in question with $\log(ft)$ values which are indicative of allowed transitions.

The nature of the 3− states may be investigated by comparing reduced transition probability ratios with Alaga[5] intensity rules. The experimental branching ratio from the 2164 kev (3−) level to the gamma-vibrational band ($K=2+$) is:

$$B(E1:3\rightarrow 2)/B(E1:3\rightarrow 3)/B(E1:3\rightarrow 4)=3/1/0.7,$$

assuming pure $E1$ radiation. The predicted ratio calculated for $K_i=3$ is 2.9/1/0.14. The theoretical ratio

[37] J. C. Walker and D. L. Harris, Phys. Rev. Letters **5**, 453 (1960).

for $K_i<3$ is quite different, predicting relatively weak feeding of the $I=2$ members of the $I=2$, 3, 4 series. Hence $K_i=3$ is favored.

In the case of the 2137-kev state, the transitions proceeding to the $K=2+$ gamma-vibrational band are probably of $M2$ character, otherwise the calculated photon intensity is too large. The observation that transitions between the 2137-kev state and the $K=2+$ band ($\Delta I=0$, 1) appear to be mainly of $M2$ type may be interpreted as evidence of K-forbiddenness for $E1$ radiation. The branching ratio of the 2137-kev level to the gamma-band gives

$$B(M2:3\to2)/B(M2:3\to3)/B(M2:3\to4)=0.05/1/0.9,$$

TABLE XIII. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Er^{166} (Fig. 5).

Proposed excited states I,π	(kev)	De-exciting transitions (kev)	Multipole[a] assignment	Photon intensities Calculated[b]	Experimental[c]
2+	80.6	80.6	$E2$	580[d]	645
4+	265.1	184.4	$E2$	825[d]	825
6+	545.3	280.2	$E2$	17	21
2+	787.1	521.3	($E2$)	w	
		706.3	$E2$	405	660
		787.1	$E2$	390	410
3+	860.4	780.0	$E2$	670	900
		595.0	($E2$)	130	
		73.4	$E2+M1$	w	
4+	957.3	96.6	$E2+M1$	w	
		170.1	($E2$)	4	
		692.4	$E2$	260	380
		877.0	$E2$	140	250
3−	2137.3	1081.6	($M1$)	12	
		1180.0	$M2$	125	165
		1276.8	$M2$	200	235
		1350.4	$M2$	13	45
		1873.0	$E1$	250	700
		2057.3	$E1$	1000 }	1610
3−	2164.6	2083.0	$E1$	350 }	
		1207.1	($E1$)	110	
		1304.3	($E1$)	190	
		1377.6	($E1$)	670	
		1899.4	($E1$)	w	
(−)	1055.4	194.8	$E1$	320	190
(−)	1459.7	403.8	($M1$)	36	
		599.2	$E1$	62	50
		672.9	($E1$)	224	≈600
		1194.5	($E1$)	w	
(−)	1716.3	759.0	$E1$	450	1290
		1451.2	($E1$)	90	
		1636.2	($E1$)	w	
(2+)	2295.3	131.0	($E1$)	32	
		1239.1	($E1$)	75	
		1434.3	($M1$)	36	
		1508.5	($M1$)	38	
(3+)	2379.3	84.1	($M1$)	4	
		215.1	$E1$	270	337

[a] Multipolarities are consistent with angular momentum selection rules and with conversion coefficients where photon intensity measurements are available. Multipolarities are shown unmixed since we have no way of estimating mixing ratios.

[b] Estimates of photons intensity are based on internal conversion K-electron data (Table XII) and theoretical conversion coefficients of Rose.[17]

[c] Photon data are taken from reference 36 for transitions of <1-Mev energy and from reference 35 for transitions >1 Mev. All photon data are normalized to the 184-kev ($E2$) radiation.

[d] Total intensity of the 80.6- and 184-kev transitions are, respectively, 3650 and 1080 units.

to be compared with the theoretical ratio of 0.2/1/1.3 for $K_i=0$. The theoretical ratio for $K_i=3$ would favor branching to the $I=2$ rather than $I=4$ level of the $K=2+$ band. Hence, there is some evidence that $K_i=0$ may be the proper assignment.

The 2137-kev ($K<3$) state is observed to de-excite more strongly to members of the $K=0+$ series than to corresponding spin states of the $K=2+$ band. In the case of the 2164-kev ($K=3$) state, the converse is true. This is consistent with the assigned K values; however, the radiation to the $K=0+$ band from the 2164-kev level is apparently $E1$. Admittedly, this involves a ΔK of 3 or a K-forbiddenness of order 2. The possibility of admixtures of K numbers must be considered.

One may note that states of spin 3− were proposed in the isotope Er^{168} at 1095.4 and 1543.1 kev. Both states are probably fed by allowed electron-capture transitions which are consistent with a 3− or 4− assignment for Tm^{168}. The $\log(ft)$ values are 7.7 and 6.2, respectively, for branching to the 1095 and 1543-kev states, using a decay energy[30] of 1630 kev. It would appear that branching to the latter level is preferred due to operation of the K-selection rule.

The experimental $E1$ branching ratio from the 1543-kev (3−) level to the members of the $K=2+$ sequence yields

$$B(E1:3\to2):B(E1:3\to3):B(E1:3\to4)=4.3/1/2,$$

to be compared with the theoretical ratio of 2.9/1/0.14 for $K_i=3$. The analogous branching from the 1095 kev (3−) level to states of the $K=2+$ band yields an experimental ratio

$$B(E1:3\to2):B(E1:3\to3):B(E1:3\to4)=0.02/1/0.4.$$

The theoretical ratio for $K_i=1$ is 0.1/1/1.3. Again, there is no question but that the reduced transition probabilities from the two 3− levels are strikingly different. Hence, $K=3$ is preferred for 1543-kev state and $K<3$ for the 1095-kev state.

The intraband transitions, both cascade and crossover, have been observed among the members of the $K=2+$ gamma-vibrational bands of Er^{166} and Er^{168}. The cascade transitions are observed to convert in the K, L_{II}, and L_{III} shells indicating $E2+(M1)$ multipole order. At present, no reliable intensity data are available. The energy measurements of these transitions determine the rotational level spacing of the $K=2+$ sequence with a precision comparable to that of the $K=0+$ ground-state band. The experimental value of the rotational perturbation term B is -0.0124 kev for both the $K=0+$ and $K=2+$ bands in Er^{166}. Similar determinations for the rotational series in Er^{168} yield $B=-0.0064$ kev for the $K=0+$ band and $B=-0.0041$ kev for the $K=2+$ band. The larger value of B for the ground-state band in Er^{166} is consistent with the lower energy of the $K=2+$ sequence as compared to Er^{168}.

A number of other features of the decay scheme of

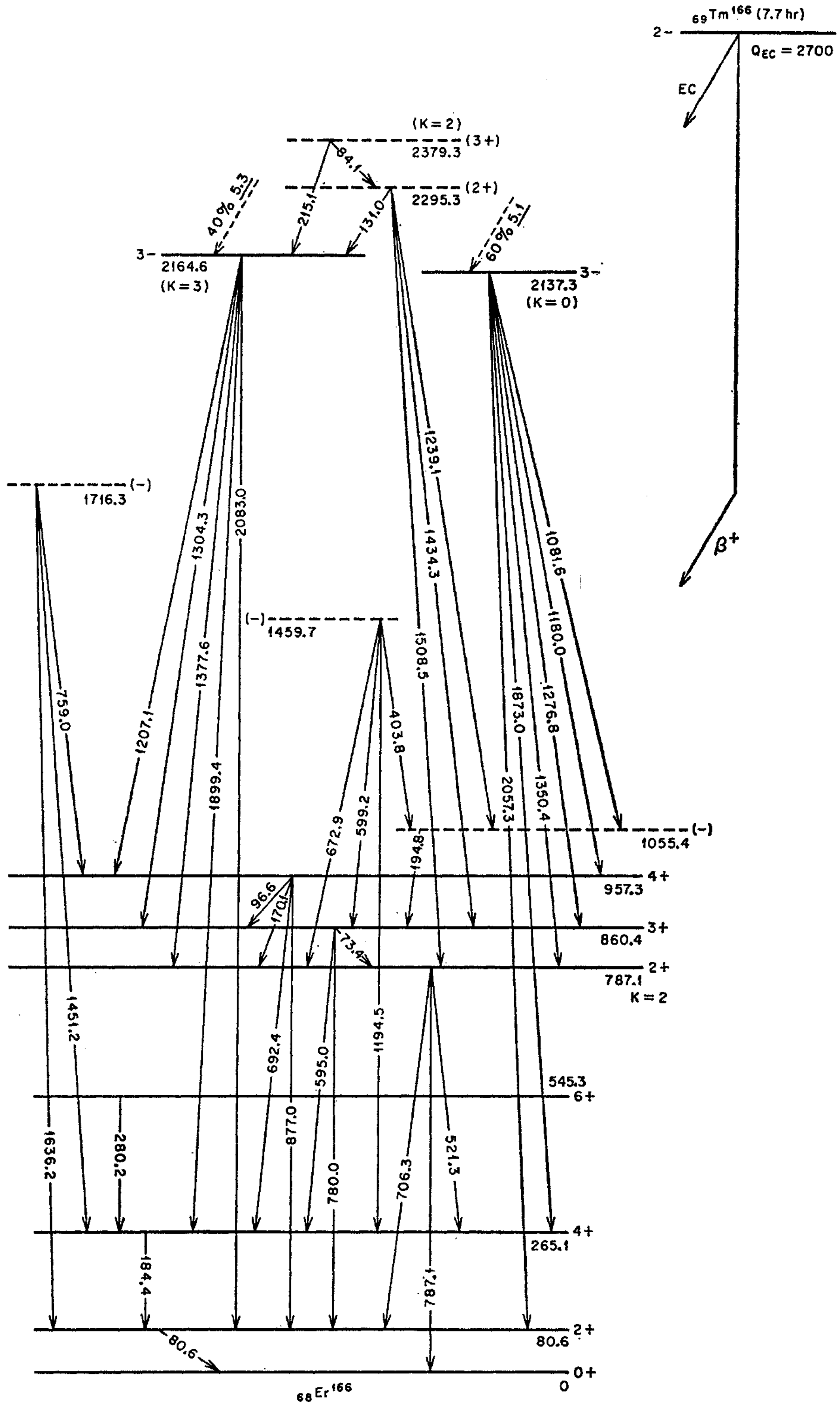

Fig. 5. Levels in Er^{166} populated by decay of Tm^{166} (7.7 hr).

Tm^{166} are not yet certain. A level is present at 1459.7 kev, but this is probably not the same level as the 0+ state populated in the β^- decay of Ho^{166}.[6] An odd parity assignment for this level and two others at 1055.4 and 1716.3 kev is probable. There are two tentative states at 2295.3 and 2379.3 kev for which even parity is indicated. The energy spacing suggests a rotational sequence of $I=2$ and 3, but this is very tentative.

TABLE XIV. Conversion electron data for decay of Ho^{162m} (67 min) and $Ho^{162} \rightarrow Dy^{162}$.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a,b]
Conversion in Ho							
38.3		1300[c]	140[c]	60[c]	430[c]	[d]	$M1$
57.8		380	40	~15	90	25	$M1$
Conversion in Dy							
80.7	>540	110	980	1000	490	110	$E2(2+\rightarrow 0+)$
89.9	[d]		~12	~12	8	w	$E2+(M1)$
95.2	55	[d]					
185.2	340	25	75	65	45	15	$E2(4+\rightarrow 2+)$
188.8	4.5						
265.5	~0.5						
276.0	3.5	~0.8					
283.2	50	[d]	12[d]	[d]	3.8		$E2(6+\rightarrow 4+)$

Energy (kev)	K	Energy (kev)	K	Energy (kev)	K
303.7	0.55	940.4	1.4	1232.7	~0.2
386.9	~0.17	999.8	w	1241.1	~0.2
393.2	0.33	1023.2	~0.2	1251.1	w
425.4	0.45	1034.7	w	1294.1	w
446.0	~0.2	1114.8	~0.2	1334.9	w
558.8	w	1133.6	w	1341.2	~0.4
798.7	w	1223.8	1.44		

[a] Intensity data are internally consistent for lines of the same activity. "w" indicates a weak line.
[b] Multipole assignments are made on the basis of K/L and L-subshell ratios.
[c] Film sensitivity and source effects are uncertain at these low energies.
[d] Conversion line is a composite of two different lines.

E. Ho^{162} (67 min) $\rightarrow Dy^{162}$

Earlier work on this nuclide[31] has shown intense $E2$ transitions in cascade decaying through rotational states ($I=2+$, $4+$, $6+$) based on the ground state. In addition, two low-energy transitions of 38.3 and 57.8 kev were remeasured, and the energy difference of the conversion lines are uniquely those of Ho, as was reported in a previous paper.[38] A check of the decay rate of the isomeric transitions was made. In a number of spectrograms taken at various elapsed times, the ratio of the intensity of these transitions in Ho compared to the intensity of the $E2$ transitions in Dy (following electron capture) is constant.

More complete internal-conversion electron data (see Table XIV) and gamma-ray scintillation spectra (see Fig. 6) were obtained. Table XV lists the gamma-ray intensities and multipolarities for the more prominent radiation in Dy. The internal-conversion coefficients for the transitions of 940.4 and 1223.8 kev are consistent only with $E1$ multipolarity. Since these transitions (on the basis of energy fit) proceed to the $4+$ and $6+$ levels of the postulated ground-state sequence, an assignment of $5-$ for the level at 1489.6 kev is indicated. The calculated partial half-life for the electron-capture decay to this level, using the energy prediction of Cameron ($Q_{EC}=1.9$ Mev),[30] is consistent with an allowed electron-capture transition [$\log(ft)\sim 4.1$]. A spin of $6-$ for Ho^{162m} may be obtained by employing the coupling rules[21] if the odd-neutron orbital $5/2-$ [523] is used rather than the very close $5/2+$ [642].[22] A spin of $1+$ is predicted in this manner for Ho^{162g}.

[38] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **119**, 1345 (1960).

The low-energy states of the odd-odd nuclide Lu^{174} ($Z=71$) were recently studied,[38] and an apparent similarity to Ho^{162} ($Z=67$) is observed. In the former case, $M1$ transitions of 44.1 and 67.1 kev may be arranged in cascade terminating at the ground state ($I_0=1$). The energy spacing obeys the $I(I+1)$ interval rule exactly for a rotational spin sequence of 1, 2, and 3.

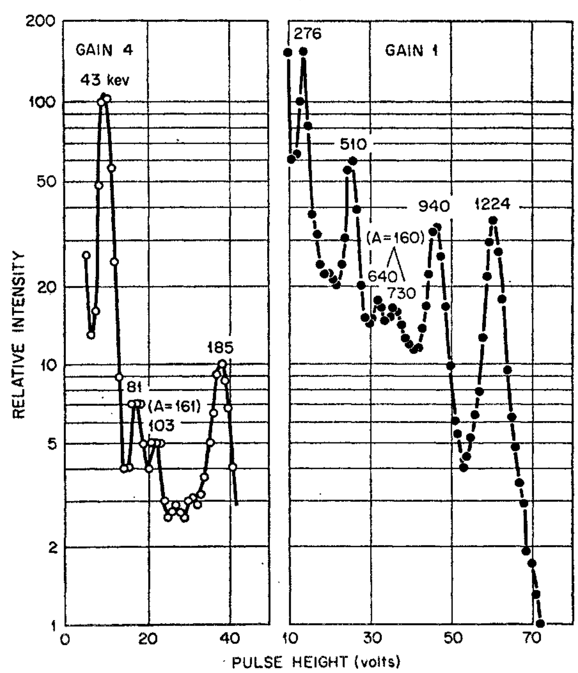

FIG. 6. Scintillation counter spectrum of gamma rays in the Ho^{162} decay to Dy^{162} taken with a 3×3-in. NaI(Tl) crystal.

TABLE XV. Gamma-ray intensities and multipolarities for transitions in Dy^{162}.

Transition energy (kev)	Assigned multipolarity[a]	Relative photon intensities Calculated[b]	Experimental[c]
80.7	$E2$	625	575
185.2	$E2$	1700	1700
283.2	$E2$	860	840
940.4	($E1$)	1165	1170
1223.8	($E1$)	1945	1820

[a] $E2$ multipole assignments are made on the basis of K/L ratio, L-subshell ratio, and internal conversion coefficients.
[b] Deduced photon intensities are obtained from conversion electron data and theoretical conversion coefficients (reference 17).
[c] Experimental photon intensities are normalized relative to the 185-kev $E2$ transition.

An $M3$ transition of 59 kev ($6- \rightarrow 3-$) was also observed in Lu. In Ho, the 38.3- and 57.8-kev radiation are likewise of $M1$ character. By placing the two transitions in sequence above the 1+ state, the energy spacing appears rotational ($I=1$, 2, and 3). The energy constants for the rotational sequence: $3\hbar^2/\mathscr{I}$ and B, are 59 and -0.0058 kev, respectively. The corresponding values obtained for Lu^{174} are 67 and -0.0013 kev. The level scheme of Ho^{162} may be made self-consistent if one postulates a low-energy (<10 kev) $E3$ transition depopulating the 67-min 6− state. Although the partial half-life against gamma-ray decay is enormous, the experimental half-life could be reduced to the observed value since the internal conversion coefficient for an $E3$ transition of very low energy should be quite large.

The intensities of the observed K x-ray peak and of the 80.7-kev transition ($2+ \rightarrow 0+$) are sufficiently large to indicate some electron capture to the 0+ and 2+ levels of the ground-state band. The logft is in the allowed range. A sizable β^+ branch is indicated by the 510-kev annihilation peak, but a portion of this may be attributed to impurities (the decay rate is somewhat more rapid than for the other peaks).

It should be noted that the Ho decay spectrum is very complex, and only the most intense transitions can be placed in the decay scheme. There is possibly an excited state in Dy^{162} at 1115 kev which proceeds to the 0+ and 2+ levels of the ground-state band. This level is in the region of the expected $I=K=2+$ state although such an assignment is at best speculative.

Jørgensen, Nielsen, and Skilbreid[39] reported recently on this activity. Their interpretations of results are in accord with ours. As they point out, the rather small log(ft) values for the β decay (or electron capture) are indicative of allowed unhindered transitions where the protons and neutrons involved in the decay have the same asymptotic quantum number, and thus reduce the degree of uncertainty as to which odd particle orbitals for the two unpaired nucleons are relevant.

We have made a systematic search among other odd-odd rare earths for additional low-energy transitions which may occur between isomeric states. Activities of Eu^{152}, Eu^{150}, Tb^{154}, Re^{182}, and Re^{184} failed to disclose such radiation. There is evidence for assignment of two transitions (61 and 76 kev) to Pm^{148m}, decaying to levels in Pm^{148} with a half-life of about 46 days. The differences in energy of the L and M subshell conversion lines of the 61.5-kev transition are those of Pm. This transition is interpreted as probably $E3$ from the conversion line ratio $K/L_{II}/L_{III}=w/100/100$. A second transition of 75.7 kev is assigned to Pm on the basis of the K and L_I energy difference. This radiation is probably magnetic dipole since $K/L_I \approx 6$ and L_{III} was unobserved. The conversion line intensity ratio of $61-L_{II}/75-L_I$ is 3.6; thus the total intensities of the proposed $E3$ and $M1$ transitions are very similar. Probably, the two radiations are in cascade proceeding from Pm^{148} (46 day) to Pm^{148} (5 day).

F. Tb^{156} (5.6 day) → Gd^{156}

The low-energy transitions of the decay chain $Tb^{156m} \rightarrow Tb^{156} \rightarrow Gd^{156}$ were reported on previously,[31] and a rotational series at 89 kev (2+), 288 kev (4+), and 585 kev (6+) based on the ground state of Gd^{156} was proposed. A number of subsequent studies have extended the level scheme of Gd^{156}. Both Ofer[40] and Hansen *et al.*[41] have made extensive gamma-ray and conversion coefficient measurements and performed coincidence experiments. In addition, Ofer performed gamma-gamma angular correlations. The well-established features of their scheme include a gamma-vibrational band based at 1156.9 kev (2+), a possible band based at 1513.6 kev (4+), and states at 1938.3 kev (3−), and 2048.4 kev (4−). Level energies quoted here are those determined in the present internal-conversion electron study. Table XVI lists the internal conversion data (2.3-Mev maximum energy). Seventeen of these transitions were not previously observed, for reasons of either intensity or resolution. Close agreement is obtained between the conversion line intensities of Table XVI and those obtained with a beta-ray spectrometer by Hansen *et al.*[41] wherever comparison may be made.

Our more complete data indicate the possible existence of a 1358.4-kev (4+) rotational state in the gamma-vibrational band ($K=2$). This state may be fed by transitions of 155.6 kev ($M1$) and 266.9 kev ($M1$) from the 1513.6-kev (4+) and 1625.6-kev (5+) levels. The decay mode is mainly between two 4+ levels via a 1070.4-kev ($E2$) transition to the 288-kev state. The excitation and de-excitation intensity about the 1358.4-kev state are then essentially equal. The energies of the states in the $K=2$ band have been fitted to the rotational energy formula. The value obtained for $3\hbar^2/\mathscr{I}$ is 99.5 kev and for B is -0.16 kev. For the

[39] M. Jørgensen, O. B. Nielsen, and O. Skilbreid, Nuclear Phys. **24**, 443 (1961). We are indebted to Dr. Nielsen for a preprint of their paper.

[40] S. Ofer, Phys. Rev. **115**, 412 (1959).
[41] P. G. Hansen, O. B. Nielsen, and R. K. Sheline, Nuclear Phys. **12**, 389 (1959).

TABLE XVI. Conversion electron data for decay of Tb^{156} (5.6 day) → Gd^{156}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	N	Remarks[a]
89.0[b]	>1000	[c]	870[c]	910	430	120	$E2$
111.95[b]	110	18	~2	[d]	[d]		$M1$
115.65	4.0	~0.5					
155.2[b]	45	7.5[c]					
170.8	[d]	0.5					
199.3[b]	360	[c]	70[c]	35	30	8	$E2$
262.5[b]	26	[c]	4.6[c]	1.8	1.4	0.5	$E2$
266.9	0.7						
296.3[b]	13	[c]	2.4[c]	1.0			$E2$
356.4[b]	21	[c]	3.8[c]	1.2	1.2		$E2$

Energy (kev)	K	L	Energy (kev)	K	L	Energy (kev)	K	L
374.0	w		962.6[b]	0.33		1424.7[b]	0.68	0.11
381.4[b]	0.9	[d]	1012.1	w		1649.4[b]	0.085	
422.4[b]	2.9	0.4	1040.4[b]	0.22		1848.6[b]	0.078	
535.2[b]	13	1.8	1042.8[b]	0.42	0.06	1950.7	w	
687.5	w		1067.9[b]	1.3	0.15	2014.0	0.023	
781.8[b]	0.24		1070.4	~0.26		2090.0	w	
843.8[b]	~0.09		1156.9[b]	0.92	0.12	2105.0	w	
867.5[b]	<0.15		1162.0[b]	0.66	0.11	2140.6	w	
927.5[b]	0.55	w	1225.3[b]	2.6	0.4	2268.6	w	
943.4	~0.1		1337.6[b]	0.17		2281.3	w	
951.2	0.14					2310.2	w	

[a] Multipole assignments are based on K/L and L-subshell ratios. Intensity data are internally consistent. "w" indicates weak line.
[b] Transition reported previously in references 40 and 41.
[c] Conversion line is partially resolved.
[d] Conversion line is a composite of two different lines.

ground-state band, $3\hbar^2/\mathcal{I}=90$ and $B=-0.03$ kev. There is possibly some perturbation of the $K=2+$ band due to interaction with the nearby states.

Our transition data indicates a tentative assignment of 3+ for a level at 1131.9 kev and a possible odd-parity level at 2302.2 kev. The dominant electron capture consists of an 80% branch to the level at 2048.4-kev (4−), and an 11% branch to the 1938.3-kev (3−) state, in addition to other weak branches. Both high-energy states are probably fed by allowed electron-capture transitions which are consistent with a 3− or 4− assignment for Tb^{156}. The $\log(ft)$ values are 5.9 and 7.0, respectively, for branching to the 2048 and 1938-kev states, using a decay energy of 2.5 Mev for Tb^{156}. It would appear that branching to the former level is preferred on the basis of K selection rules. The branching ratio of transitions from the 1938-kev (3−) to the ground-state band yields

$$B(E1:3\rightarrow 2)/B(E1:3\rightarrow 4)=0.79,$$

to be compared with the theoretical value 0.75 for $K_i=0$ and 1.3 for $K_i=1$. The branching ratio of the transitions from the 2048-kev (4−) level to the 1513-kev (4+) and 1625-kev (5+) states gives

$$B(E1:4\rightarrow 4)/B(E1:4\rightarrow 5)=3.8.$$

The theoretical ratio is 1.9, where $K_i=K_f=4$.

Experiments have been carried out on the disintegration scheme of Eu^{156} by Ewan *et al.*[42] They have proposed levels at 89.0 (2+), 288.2 (4+), 1154.0 (2+), 1168.5 (1, 2), 1242.2 (1−), 1319.8 (2−), 1366.1 (1−), 1966.0 (1, 2+), 2026.0 (1, 2+), and 2186.7 (1, 2+) kev. Only the 89, 288, and 1154-kev states appear in common with the electron-capture decay of Tb^{156}. (Our energy measurements are slightly higher than the more precise ones of Ewan *et al.*) This lack of common levels in the two modes of decay is to be expected since Eu^{156} should possess a low spin (0, 1), while Tb^{156} should be in a high spin state (3, 4).

G. Tb^{154m} and Tb^{154} → Gd^{154}

Our previous experiments[31] with Tb^{154} produced by the $Gd^{155}(p,2n)Tb^{154}$ reaction indicated a complex decay from two isomeric states of half-lives of 8 hr and 22 hr. Conversion electron (ce) measurements suggested three $E2$ transitions of 123, 248, and 347-kev energy. The postulated rotational levels of 123 kev (2+) and 371 kev (4+) were verified by the coincidence studies of Henry *et al.*[43] The absence of coincidences between the 347-kev gamma ray and the ground-state rotational transitions ruled out a possible 6+ level at 718 kev. The ground-state band ($K=0$) is also populated by β^- decay of Eu^{154} which was investigated by Juliano and Stephens.[44]

Using more intense sources, transitions up to 2.5-Mev energy have been measured and an attempt made to classify the data according to the decay rate of the

[42] G. T. Ewan, R. L. Graham, and J. S. Geiger, Bull. Am. Phys. Soc. **5**, 21 (1960).

[43] R. W. Henry, L. T. Dillman, N. B. Gove, and R. A. Becker, Phys. Rev. **113**, 1090 (1959).

[44] J. O. Juliano and F. S. Stephens, Phys. Rev. **108**, 341 (1957).

transitions (see Table XVII). It was observed that some of the levels were populated by either the 8-hr or the 22-hr activity but some are common to both activities. The two half-lives were not sufficiently different to permit a complete analysis of the activities by aging the source. Both 5.6-day Tb^{155} and Tb^{156} were present as impurities. No differentiation as to the half-lives of the weaker transitions, which however do belong to this activity, could be made. In constructing the decay scheme (see Fig. 7). use was made of the fact that transitions originating at the same level in Gd^{154} should exhibit an intensity ratio independent of elapsed time irregardless of the mode of population of the level. The fact that the two isomeric states of Tb^{154} would be expected to have considerably different spins was also of aid in constructing the decay scheme.

Studies with Eu^{154} activity[44] indicated levels in Gd^{154} at 998 kev (2+) and 1129 kev (3+) which could be described as a gamma-vibrational band ($K=2$). Identical states are populated in the Tb^{154} decay, in addition to a probable 4+ rotational level at 1265.3 kev. Rotational constants associated with the $K=2+$ bands, $3\hbar^2/\mathcal{J}$ and B are, respectively, 143 kev and -0.34 kev as compared with 128 kev and -0.14 kev for the ground-state band. The branching ratio of the 997.3-kev (2+) level to the ground-state band yields

$$B(E2:2,\,2\rightarrow 0,\,0)/B(E2:2,\,2\rightarrow 0,\,2)=0.44,$$

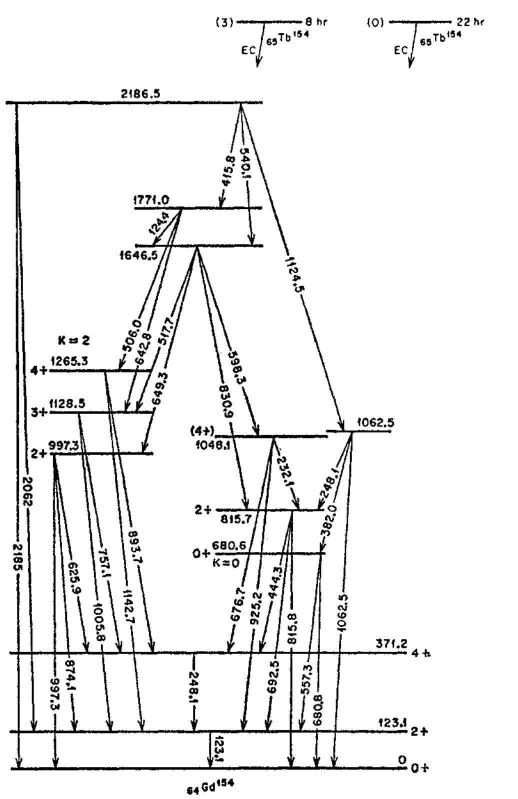

FIG. 7. Partial decay scheme for Tb^{154} (8 hr and 22 hr).

TABLE XVII. Conversion electron data for decay of Tb^{154m} and Tb^{154} to Gd^{154}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a]
Tb^{154} (8 hr) → Gd^{154}						
123.1[b]	5000	~420	1610	1510	760	E2
124.4	~75					
232.1	21	c	5.5	1.5	2	E2
248.1[b]	450	c	90	40	35	E2
255.6	2.4					
Energy (kev)	K	L	Energy (kev)	K	L	
329.7	4					
382.0	12.5	2.1	692.5[b]	40	5.6	
415.8	4.7	0.87	757.3[b]	4	w	
444.3	5.6	0.95	815.8	1.5	w	
461.0	2.5		830.9	~1		
506.0	3.1	w	874.1[b]	10	1.5	
517.7	23	3.6	893.7	3.5	w	
540.1	23	3.6	925.2	~1.2		
598.3	6		997.3[b]	5.8	0.8	
625.9	w		1005.7[b]	7.0	1.2	
642.8	~1.2		1142.7	~0.6	w	
649.3	23	d	1276.5[b]	~0.5		
676.7	57	8.6	1292.5	~0.2		
Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a]
Tb^{154} (22 hr) → Gd^{154}						
123.1[b]	7700	~640[c]	2490	2330	1170	E2
124.4	~115	d				
141.4	190	32				
226.0	30	w				
248.1[b]	570	c	110[c]	48	45	E2
265.9	12					
346.9	100	c	18[c]	4	5	E2
Energy (kev)	K	L	Energy (kev)	K	L	
426.9	13.6	w	1124.5	7		
444.3	10.5	1.8	1276.5[b]	3		
557.3	25	d	1292.5	~2		
602.6	5		1460.0	~2		
680.8	55	13	1994	2.4		
692.5[b]	75	10	2062	2.4		
815.8	2.7	w	2116	1.7		
874.1[b]	8	w	2185	2.7		
997.3[b]	4.6	0.65				
Energy (kev)[e]	Energy (kev)[e]	Energy (kev)[e]	Energy (kev)[e]			
337.7	1129.7	1759.4	2304			
534.3	1190.3	1905.4	2339			
830.9	1243.4	1930.5	2427			
850.9	1259.8	2004	2461			
1062.5	1575.5	2017	2480			
1086.0	1735.4	2277				

[a] Electron intensity data are internally consistent for lines of the same activity. "w" indicates a weak line. Multipole assignments are based on K/L and L-subshell ratios.
[b] Conversion lines are observed also in decay of Eu^{154} (16 yr) → Gd^{154}.
[c] Conversion line is partially resolved.
[d] Conversion line is a composite of two different lines.
[e] Associated with 8- and/or 22-hr decay.

assuming pure $E2$ radiation where $K_i=2$ and $K_f=0$. The theoretical ratio is 0.7. The $E2$ branching ratio of the 1128.5-kev (3+) level to the 123-kev (2+) and 371-kev (4+) states gives 0.8, to be compared with the theoretical value of 2.5. Branching from the postulated 1265-kev (4+) level yields

$$B(E2:2,\,4\rightarrow 0,\,2)/B(E2:2,\,4\rightarrow 0,\,4)=0.09.$$

The calculated ratio is 0.34. Experimental branching ratio data above are consistently smaller than the calculated values but are consistent with experimental results for other nuclei as shown in Table II.

The fact that the 8-hr state feeds the 1265-kev (4+) state and that both the 8-hr and the 22-hr states populate the 997-kev (2+) level are consistent with assignment of high spin for short-lived Tb^{154} and low spin for long-lived Tb^{154}. The assignments of Nilsson orbitals[22] are not very definitive for Tb^{154} which is in the region of sharp change in nuclear deformation. If the proton and neutron orbitals are taken as 3/2+ [411] and 3/2+ [651], respectively, then the coupling rules[21] would predict spins of 3 and 0 for Tb^{154} isomers. The data are not yet good enough to exclude a weak population of the 1128.5-kev (3+) state by the 22-hr activity.

The level scheme indicates a rotational band based at 680.6 kev. These states which may be interpreted as members of a beta-vibrational band ($K=0$) are at 680.6 kev (0+), 815.7 kev (2+), and 1048.1 kev (4+). In the few cases where energies of beta- and gamma-vibrational states are known, the beta bands are consistently of lower energy than the gamma bands. For this rotational excitation, the parameters are $3\hbar^2/\mathcal{I}=146$ kev and $B=-0.30$ kev. Similar values are obtained for the $K=2+$ band. An alternate value of -0.29 kev for B for the ground-state sequence predicted by substituting the energies of the beta- and gamma-vibrational excitations in the expression

$$B=-\tfrac{1}{2}(\hbar^2/\mathcal{I})^3[3/E_\beta^2+1/E_\gamma^2].$$

The postulated 680.6-kev (0+) state is excited by the electron-capture decay of Tb^{154} (22 hr) which has a possible spin assignment of 0. Both low- and high-spin states of Tb^{154} may feed the 815.7-kev (2+) level while the 1048.1-kev (4+) level is excited only by 8-hr Tb^{154} decay. Reduced transition probabilities for transitions (assumed pure $E2$) between bands $K_i=K_f=0+$ and $I_f=0$, 2, 4 states are compared as follows: experimental 0.023/1/0.42; theoretical 0.7/1/1.8 for the 815-kev (2+) state; and experimental 0.008/1; theoretical 1.1/1 for the 1048-kev (4+) state. This lack of agreement may be due to the presence of $E0$ admixture to the $E2$ ($\Delta I=0$) transitions. The ce_K/γ branching ratio for transitions from the 680-kev (0+) level to $I=0$ and 2+ ($K=0$) states is 0.016 as compared with 0.013 for the 685-kev (0+) state in Sm^{152}. The 680.8-kev radiation (0+→0+) is expected to be pure $E0$.

Tb^{154} (8 hr) populates a pair of states at 1646.5 and 1771.0 kev which suggest a spin sequence of 2, 3, or perhaps 3, 4. The different decay rate for transitions originating at the tentative 2186-kev level suggest that perhaps there are two close-lying levels at about this energy.

H. Tb^{152} (18 hr) → Gd^{152}

Excited states of Gd^{152} have been studied using sources of Eu^{152} (9 hr) and Eu^{152} (13 yr). Marklund *et al.*[45] discussed the prominent levels in Gd^{152} fed by Eu^{152} (9 hr), and presented data relevant to the 1315-kev (1−) level and the 0+, 2+, 0+ sequence of levels at 0, 344, and 615 kev. Eu^{152} (13 yr)[13] populates high-spin states in Gd^{152} at 755 kev (2 or 4+) and 1122 kev (3−) as well as possible higher levels. The level scheme published by Toth *et al.*[46] indicates that all of the above levels, both low and high spin, are excited in Tb^{152} decay. In the course of that work, other levels at 1047-kev (0+) and 929-kev (1 or 2+) were observed.

TABLE XVIII. Conversion electron data for decay of Tb^{152} (18 hr) → Gd^{152}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a,b]
117.3	3					
271.0[d]	69	[c]	16[c]	6	5	$E2$
344.3[d]	197	[c]	40[c]	10	11	$E2$
351.4	~0.4					
410.9[d]	8.5	1.8[c]	[c]			$E2$
432.1[d]	46	7			1.5	
496.5	0.7					
526.6	1.8					
586.3[d]	20	3				
615.3[d]	100	15.5			4	
622.7	~0.8					
703.1	1.0					
765.3	1.5					
772.7	w					
779.4	~0.7					
974.3	1.2					
1048.4[d]	1.6					

[a] Multipole assignments are based on K/L and L-subshell ratios.
[b] Intensity data are internally consistent. "w" indicates weak line.
[c] Conversion line is partially resolved.
[d] Internal conversion transitions reported previously (references 46 and 47).

In this study of Tb^{152}, enriched Gd^{152} was irradiated with 12-Mev protons. Analysis of the conversion electron spectrum of the Tb^{152} fraction indicated a number of weaker transitions which were not previously recorded by Basina[47] and Toth *et al.*[46] Table XVIII presents the conversion line energy and intensity data, which are in good agreement with the latter measurements where comparison may be made.

Our conversion electron investigations of Tb^{152} confirm the above level structure and indicate a possible additional level at 966.7 kev.

I. Eu^{150} and Eu^{150m} → Sm^{150}

Some data have been available regarding the levels of Sm^{150} which are populated by the β^- decay of Pm^{150} (2.7 hr)[48] the decay of Eu^{150} (14 hr),[14] and the capture gamma rays[49] following the formation of the compound

[45] I. Marklund, O. Nathan, and O. B. Nielsen, Nuclear Phys. **15**, 199 (1960).
[46] K. S. Toth, O. B. Nielsen, and O. Skilbreid, Nuclear Phys. **19**, 389 (1960).
[47] A. C. Basina, Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **24**, 813 (1960).
[48] V. K. Fischer and E. A. Remler, Bull. Am. Phys. Soc. **3**, 63 (1958).
[49] L. Rosler and C. A. Fenstermacher, Bull. Am. Phys. Soc. **2**, 268 (1957).

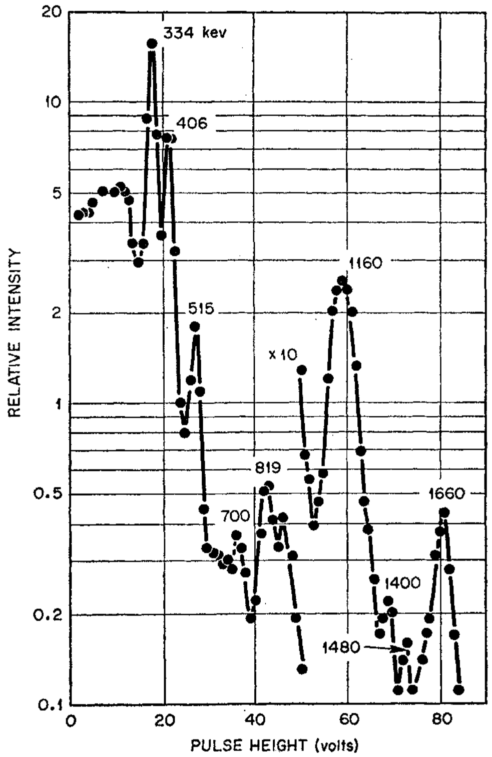

FIG. 8. Scintillation counter spectrum of gamma rays in the Eu^{150} (14 hr) decay to Sm^{150}.

nucleus Sm^{150*} resulting from neutron capture of Sm^{149}. No consistent level scheme, however, could be constructed.[14] Sm^{150} has 88 neutrons and would be expected to exhibit the properties of a spherical nucleus in contrast to Sm^{152} which has 90 neutrons and has the distinct properties of a deformed nucleus.

The decay of Eu^{150} (14 hr) which was produced by the (p,n) reaction on enriched Sm^{150} was studied. Eu^{152m} (9-hr) was present as an impurity to the extent of 2%. Due to the intense β^- background blackening the films, the obtaining of any conversion electron data was difficult. The internal-conversion electron data and the photon intensities as obtained with a scintillation spectrometer (see Fig. 8) are listed in Table XIX. These sets of data were normalized to the 334.1-kev transition which is of $E2$ character as indicated by K/L ratio[50] and conversion coefficient data.[51] The energies and intensities of the transitions are consistent with levels at 334.1, 740.7, and possibly at 1153.1, and 1256.1 kev, as shown in Fig. 9. A relatively intense K-conversion line for a transition of 741.3 kev is seen; an upper limit for the unobserved photon peak is consistent with the conclusion that either the 741.3-kev transition is of very high multipole order or else is an $E0$ transition. The latter choice seems more realistic, and accordingly the

[50] C. T. Hibdon and C. O. Muehlhause, Phys. Rev. 88, 943 (1952).
[51] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. 28, 432 (1956).

TABLE XIX. Experimental data for decay of Eu^{150m} and Eu^{150} to Sm^{150} (Fig. 9).

Transition energy (kev)	Relative intensity K-electron[a]	Photon[b]	Assigned multipole
Eu^{150m} (14 hr) $\rightarrow Sm^{150}$			
334.1[c]	100	3120	$E2$
406.3[c]	46	2300	$E2$
515.3	~21	<530[d]	
700	...	140	
741.0[c]	~40	<100	$E0$
819.0	w	315	
922.3	w	240	
1160	...	250	
1660	...	60	
Eu^{150} (>5 yr) $\rightarrow Sm^{150}$			
334.1	100	3120	$E2$
439.2	40	2440	$E2$
590	...	1530	
740	...	340	

[a] Electron intensity data are internally consistent for lines of the same activity. "w" indicates weak and dashes indicate unobserved lines.
[b] Gamma-ray intensities are normalized to the 334-kev $E2$ radiation for which $\alpha^K = 0.032$ (reference 17).
[c] Conversion lines are observed also in decay of Pm^{150} (2.7 hr) $\rightarrow Sm^{150}$.
[d] May be partly due to annihilation radiation.

741-kev level has been designated as 0+. It follows that the Eu^{150} (14 hr) has a low spin (perhaps 0− in analogy with 9-hr Eu^{152m}). It is interesting to note that the β^- decay of Pm^{150} also feeds the 740.7-kev level, implying that Pm^{150} has a small spin. The higher energy spectrum appears similar for both modes of decay to Sm^{150}. Tentative states are shown at 1153 and 1256 kev based on energy differences of two gamma rays in each case. The partial decay scheme of Fig. 9 shows that 14-hr Eu^{150} decay proceeds to states at 1256, 1153, and 740 kev with approximate $\log(ft)$ values of between 6.2 and 6.5, using a disintegration energy of 2.6 Mev.[14]

A study of aged Eu sources (produced by protons on Sm^{150}) indicated a composite decay curve for the 334-kev transition. This is due to the fact that there exists a long-lived Eu^{150} activity with a half-life of not less than 5 years, as determined by a comparison of decay rates of transitions due to Eu^{149} (120 day). Two internally converted transitions of 334.1 and 439.2 kev were observed (see Table XIX). Gamma-ray spectra of Eu^{150} (>5 years) taken with a NaI spectrometer showed additional photopeaks at 590 and 740 kev. No appreciable annihilation radiation was observed. Only the 334-kev radiation is common to both short- and long-decay activities. The 334- and 439-kev transitions are the two most intense ones observed in the capture gamma-ray spectrum of Sm^{150}, and coincidence studies[49] indicate that these two transitions are in cascade, originating at a level of 773 kev. It is logical that the spin of this level is fairly large, perhaps 4. The long-lived Eu^{150} may possess a large spin (13-yr Eu^{152g} is in a 3− state, for example). It is worth noting that the observed 590 and 740-kev gamma rays are also present in the capture gamma-ray spectrum.

Figure 9 shows only a partial decay scheme of long-lived Eu^{150}. The two close-lying ($I=0+$, $4+$) states

at about 750-kev excitation may be the expected two-phonon vibration of this spherical nucleus. The ce_K/γ branching ratio for the 741-kev (0+) level to the ground state and first excited 2+ state is 0.017 in Sm^{150} as compared with 0.013 for the analogous ratio for the 685-kev (0+) state in Sm^{152}.[45]

Note added in proof. Experiments now in progress at Notre Dame by Guttman *et al.* have established the presence of beta-decay to Gd^{150}. Therefore the log *ft* values in Fig. 9 are lower limits. Furthermore, the postulated spins of the 740.7- and 773.3-kev levels have been confirmed by directional correlation measurements, as has the spin (0) of the 1256.1-kev level.

J. Eu^{149} (120 day) → Sm^{149}

In the previous section, the decay of the two isomers of Eu^{150} was discussed. Since the analysis of a composite source containing a considerable amount of Eu^{149} was required, we present here the data on this activity.

The radiations of Eu^{149} (120 days) observed in conversion electron and gamma-ray spectra were analyzed. The experimental information is summarized in Tables XX and XXI. Radiations which belong to long-lived Eu^{150} (e.g., 334 and 439 kev) were also present in the spectra. It was possible to normalize gamma-ray intensities to the internal-conversion electron intensities in Table XXI by using the theoretical $E2$ conversion coefficient of the 439-kev transition. These data are consistent with the level scheme shown in Fig. 10 in which upper states of negative parity are depopulated mainly by $M1$ radiation to the 22-kev and ground states. One may note that the levels of Sm^{149} as populated in electron capture appear to be arranged in doublets with small energy spacings.

The spin of Sm^{149} is measured as 7/2; the parity is probably odd since an $f_{7/2}$ orbit is predicted by the shell model. The most intense electron-capture branches proceed to the levels at 22.5, 277.2, and 350.2 kev. Considerably weaker branches terminate at the levels of 528.6 and 558.3 kev. No data are available as to any ground state decay. Assuming a disintegration energy[14] of ~800 kev for Eu^{149}, one may obtain log(*ft*) values for the various branches which range from 7.6 to 7.9. Eu^{149} is in a $d5/2$ state according to the shell model, and the electron-capture decay is probably first-forbidden in most cases.

An interesting comparison may be made with the

TABLE XX. Internal conversion electron data for decay of Eu^{149} (120 days) → Sm^{149}.

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M	Remarks[a,b]
22.5		1350	580	640	840	$M1/E2=90$
72.95	>10	2.2	[c]	w	0.6	$M1+E2$
178.4	2	0.3				$M1$
207.9	0.3					
254.7	22	3.7				
277.2	100	13			3	
327.7	70	9.7			3	
350.2	3.4	0.7			0.2	
506.1	2.2	0.3				
528.7	1.6	0.3				
536.0	0.2					
558.3	0.24					

[a] Multipole assignments are based on K/L and L-subshell ratios.
[b] Intensity data are normalized to 1350 units for the most prominent line. "w" indicates weak line.
[c] Conversion line is partially resolved.

TABLE XXI. Intensity and multipolarity assigned to transitions depopulating levels shown in decay scheme of Eu^{149} (120 day) → Sm^{149} (Fig. 10).

Proposed excited states (kev)	De-exciting transitions (kev)	Multipole[a] assignment	Photon intensities Calculated[b]	Experimental[c]
22.5	22.5	$M1/E2=90$	150	
277.2	254.7	($M1$)	210	
	277.2	$M1$	1190	1145
350.2	72.95	$M1+E2$	4	
	327.7	$M1$	1296	1135
	350.2	$M1$	74	<90
528.6	178.4	$M1$	7	<30
	506.1	($M1$)	122	
	528.7	($M1$)	98	

[a] Multipolarities are consistent with conversion-electron ratios and available conversion coefficients. Assignments in parentheses are uncertain.
[b] Estimates of photon intensity are based on conversion-electron data and theoretical conversion coefficients.
[c] Relative gamma-ray intensity data are normalized to agree with the $E2$ conversion coefficient of the 439-kev gamma ray belonging to Eu^{150}.

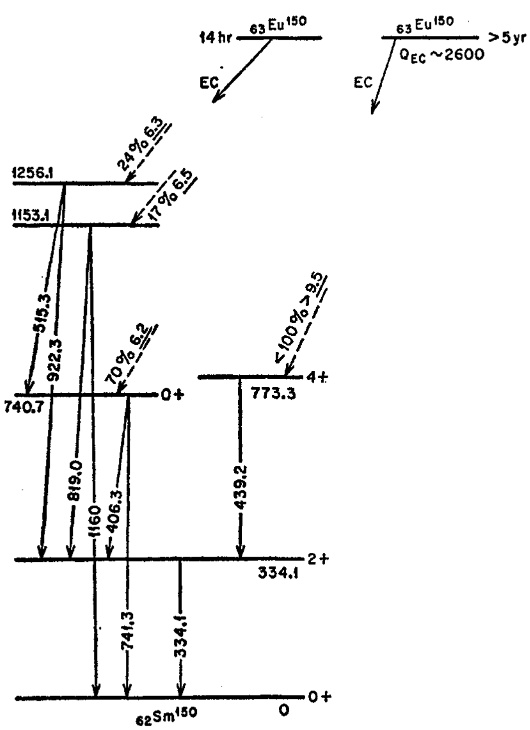

FIG. 9. A fragmentary decay scheme for Eu^{150} (14 hr and >5 yr). Electron-capture branches for the two isomers are shown independently. *Note added in proof.* The branching ratios are approximate and are meant to serve only as a guide. The branching to the 740.7-kev state should be 60%. The decay of the long-lived Eu^{150} proceeds to higher lying states also.

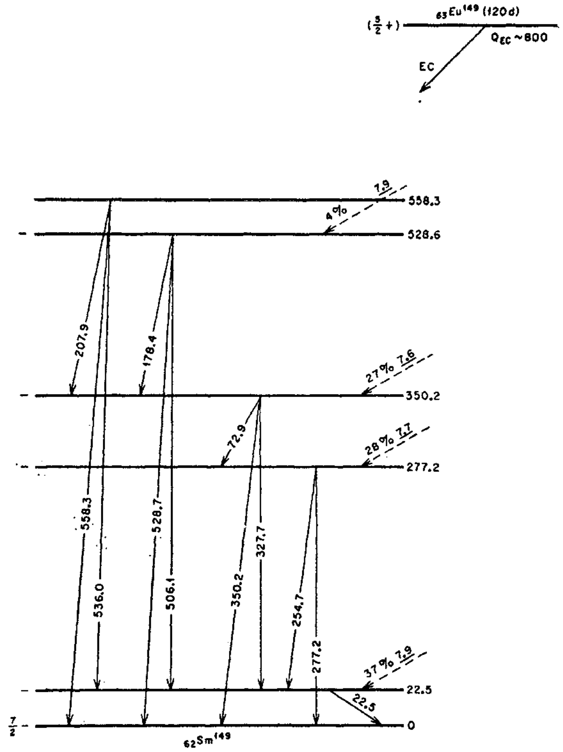

FIG. 10. Levels in Sm^{149} populated by electron-capture decay of Eu^{149} (120 day). *All* observed transitions are placed in the scheme. The branching ratios are approximate; no data as to the existence of an electron capture branch to the ground state was obtained.

results of Schmid and Burson[52] who studied the β^- decay of Pm^{149} which also proceeds to levels in Sm^{149}. Apparently there are no levels common to both decays. Recent nuclear alignment experiments by Chapman *et al.*[53] indicate that the spin of the 285-kev state in Sm^{149} (observed only in the β^- decay) is either 5/2− or 9/2−. The recently reported results of Lindgren *et al.*[54] indicate that the Pm^{149} in the ground state has a spin of 7/2. It is clear that the β^- decay of Pm^{149} populates states of fairly high spin; therefore the levels in Sm^{149} which are populated by the electron capture of Eu^{149} must be of relatively low spin ($I \leq 7/2$) unless some very unexpected beta-decay selection rules are operating.

III. SUMMARY AND DISCUSSION

New and more precise data are presented in this survey of 14 activities. The precision of the energy and intensity determinations has been discussed previously. It is these data which were used, in the main, in the construction of the level schemes, incorporating as well any other measurements available in the literature.

Many level assignments are not unique, and certainly further experiments are needed to confirm the decay schemes and to extend their meaning. An assumption is made that pure multipole transitions proceed between different possible bands. In the absence of hindrance factors, dipole radiation which is allowed under angular momentum selection rules should be dominant. On the other hand, there is mounting evidence that in the case of transitions between the gamma ($K=2+$) bands and the ground-state ($K=0+$) bands, $M1$ radiation is quite weak.

Analyses of the decay schemes are based to some extent on the level structure predicted by the unified model.[1] The experimental data indicate levels which are describable by that model. It would be interesting to see what the improved asymmetric rotor model can do as far as describing the higher-lying states which are being established.

In summary, the trends in the *positions* of nuclear levels may be examined; first, the 0+ level energies are compared. In one of the two near-spherical nuclei discussed here, Sm^{150} ($N=88$), evidence for two of the three expected states of the two-phonon triplet (0+, 2+, 4+) was obtained. The energy of the 0+ state is 741 kev. There is also a well-established 0+ state in Gd^{152} ($N=88$) at 615 kev. The deformed nucleus Sm^{152} [45] ($N=90$) has a 0+ level at 685 kev which is possibly a beta-vibrational excitation with a rotational state at 811 kev (2+). In the case of Gd^{154} ($N=90$), there is a possible beta vibration based at 680 kev (0+) with two indicated rotational excitations. No other 0+ states in the rare-earth region have been reported, except the level at 1460 kev in Er^{166} (see Table XXII). As noted previously, this level and its associated band are not seen in the decay of Tm^{166} ($I=2-$). A previous $I=0+$ assignment[38,55] to a 1321-kev state in Yb^{174} has been found to be incorrect.[56] There is evidence for a beta-vibrational band in W^{182}, where the position of the band base ($I=0+$) is somewhat uncertain due to perturbations of the level positions, but on the basis of the data is predicted to be at 1180 kev.

Very recent work by Gallagher *et al.*[57] on the decay of Ta^{178} (9.3 min) indicated the possible existence of a beta-vibrational band at 1197 kev (0+) in Hf^{178}. The 2+ rotational state is given as 80 kev above the 0+ state, as compared with 93.7 kev for the 2+ level of the ground-state band. These new data on the possible existence of the beta bands help to confirm the speculations made previously[7] as to the relative "softness" of the nuclei in this region to various types of vibrational excitation.

Some new data on the proposed beta- and gamma-vibrational bands are presented in Table XXII. Many

[52] L. C. Schmid and S. B. Burson, Phys. Rev. **120**, 161 (1960).
[53] C. J. S. Chapman, M. A. Grace, J. M. Gregory, and C. V. Sowter, Proc. Phys. Soc. (London) **A259**, 377 (1960).
[54] I. Lindgren, A. Cabezas, R. Marrus, and M. Rubenstein, Bull. Am. Phys. Soc. **5**, 504 (1960).
[55] W. G. Wilson and M. L. Pool, Phys. Rev. **117**, 517 (1960).
[56] H. J. Prask, E. G. Funk, and J. W. Mihelich (to be published).
[57] C. J. Gallagher, H. L. Nielsen, and O. B. Nielsen, Phys. Rev. **122**, 1590 (1961). We are indebted to the authors for a preprint.

TABLE XXII. Empirical constants for quadrupole vibrational bands in even-even nuclei in the rare earth region.

		Gamma vibrational band (kev)			Beta vibrational band (kev)			
N	Nucleus	E_0	$3\hbar^2/\mathcal{I}$	B	E_0	$3\hbar^2/\mathcal{I}$	B	Reference
90	Sm^{152}	1086	147		685.0	126		45
	Gd^{154}	997.3	143.4	−0.340	680.6	146	−0.30	This work
92	Gd^{156}	1156.9	99.5	−0.157				This work
94	Gd^{158}	1182	75					58
	Dy^{160}	965.8	84.1	−0.031				14
98	Er^{166}	787.0	74.0	−0.013	1460.3			This work, 6
100	Er^{168}	822.4	74.8	−0.004				20
	Yb^{170}	1231.6	77.0					38
102	Yb^{172}	1467.5	83.2	−0.007				This work
106	Hf^{178}				1197	80		57
108	W^{182}	1221.8	109.8		1180[a]	77	+0.029	This work, 26
110	W^{184}	904.4	105.1	−0.077				This work

[a] The unobserved (0, 0+) state is predicted from energy constants.

of these bands have been reported previously by Marklund *et al.*[6]; however, the improved energy data made it possible to check more carefully the positions of these bands, as well as the empirical constants in the rotational energy formula.

Knowles *et al.*[58] recently proposed a gamma-vibrational state at 1182 kev (2+) in Gd^{158}, based on studies of the neutron-capture gamma-ray spectra. A level at 984 kev in Yb^{168} has been proposed by Wilson and Pool,[59] based on energy sums of transitions to the 0+ and 2+ states of the ground-state band. It is possible, on the basis of systematics of energy levels in this region and experimental branching ratios, that the 984-kev state may be the 2+ state of the $K=2+$ band. Such an assignment, however, is quite speculative.

It is evident that the position of the 2+ level of the proposed gamma-vibrational bands is rising sharply from $Er^{166,168}$ ($Z=68$) to $Yb^{170,172}$ ($Z=70$). (This was predicted by Sheline[7] on the basis of the observed values of "B" for these nuclei.) It should be pointed out that the gamma-vibrational assignment[38] in Yb^{170} is not certain, although the branching ratios de-exciting the postulated band are consistent with the vibrational interpretation. The next heavier nuclei for which the data are very reliable are $W^{182,184}$ ($Z=74$), where the energy of the band base decreases. For these nuclei where energies of both beta- and gamma-vibrational states are listed, the beta-bands are of lower energy than the gamma-bands except for the case of Er^{166}.

It is clear that in this region of the periodic table, a considerable number of levels may be grouped together into rotational structures, some of which are the now familiar quadrupole vibrational excitations. A number of other positive-parity bands do not seem to fall into this quadrupole category; examples of such excitations are those postulated in Gd^{156}: 1513 kev (4+), Dy^{160}: 1696 kev (4+), and Yb^{172}: 1174 (3+), 1702 (3+), 1664 (3+), and 2075 kev (4+).

Numerous negative-parity bands have been reported, and it is likely that at least part of these are due to octupole vibrations. $K=2-$ bands have been assigned in Dy^{160} at 1264 kev, and in W^{182} at 1289 kev. Negative-parity bands which may be characterized by $I_0=K=3$ have been proposed in Er^{166} (2164 kev), Er^{168} (1543 kev), and possibly W^{182} (1437 kev). Other possible $I=3-$ excitations, not clearly defined as to K number but apparently of $K \ll 3$, have been mentioned in Gd^{156} (1938 kev), Er^{166} (2137 kev), and Er^{168} (1095 kev). Other possible negative parity excitations are those in Dy^{162} at 1489 kev (5−) as well as several in W^{182}. With regard to possible octupole vibrations, $I=1-$ and $K=0$, levels at 963 kev in Sm^{152},[45] 1663 kev in Er^{166},[6] and 1590 kev in Yb^{172},[34] have been assigned as such.

In the tables of data, multipolarities are indicated which are based on experimental results (L or K/L ratios, or internal conversion coefficients). Some of the other multipolarities are deduced, consistent with the decay scheme and selection rules. Tabulated ratios of reduced gamma-ray transition probabilities were based on relative K-conversion line intensities and the appropriate internal conversion coefficients; pure multipolarity is assumed in the absence of a statement on mixing ratios. The possibility of multipole mixing, as well as the likelihood of mixing of K quantum numbers, would have considerable effect on these ratios. Nevertheless, the branching ratios, both intraband and interband, are evaluated in the manner specified. To observe the effect of K selection rules, reduced gamma ray intensities for transitions which proceed between states of the same spin and parity were compared. Any consistency in the various ratios may point out systematics which would not be obvious otherwise. Many experiments are needed to obtain accurate internal conversion coefficients and angular correlation functions.

For a number of low-energy transitions, the indicated $M1/E2$ mixing ratios were obtained from the measured L ratios. In some cases, the existence of an appreciable

[58] J. W. Knowles, G. Manning, G. A. Bartholomew, and P. J. Campion, *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 576.

[59] R. G. Wilson and M. L. Pool, Phys. Rev. 118, 227 (1960).

amount of $E2$ admixture to $M1$ radiation is related to the collective excitations described by the unified model. Rotational ($\Delta I=1$) transitions in cascade appear to have similar $M1/E2$ mixing ratios, as have been observed in odd-A nuclei.[38] In other cases, admixtures of $E2$ were interpreted as evidence of K-forbiddenness for $M1$ radiation.

Several examples of the mutual repulsion of two levels of the same spin and parity were noted in the region of the higher excitation of these nuclei, and were mentioned in the text.

To summarize, then, additional data were presented for the decay of $Eu^{150,150m}$, $Tb^{152,154,154m,156}$, $Ho^{162,162m}$, Tm^{166}, Lu^{172}, $Re^{182,182m,184}$, and as a corollary, data on Eu^{149} and Pm^{148m}. These new data help to extend some of the decay schemes. The assignments are not certain in all the nuclei, but are consistent with energy fits and intensities, as well as with feeding and decay branching ratios. Furthermore, certain regularities appear in the properties of the rotational spectra of the even-even nuclei. For example, the inertial parameters, $3\hbar^2/\mathfrak{J}$, for the various postulated bonds in Yb^{172} and W^{182} are 71 ± 5 and 80 ± 5 kev, respectively, except for the $K=0+$ and $2+$ bands where the value is appreciably larger. In fact, the inertial parameters for the neighboring odd-neutron nuclei are of the same magnitude as for the bands for which $K\neq0+$ or $2+$.

ACKNOWLEDGMENTS

We should like to extend our thanks to R. S. Livingston for his continued interest in this work. The ORNL Isotopes Division supplied the enriched samples. We are also indebted to the operating crew of the ORNL 86-inch cyclotron for a large number of successful irradiations, and to the Y-12 Analytical Chemical Development Group for use of their Leeds and Northrup Microphotometer.