Energy Levels of $_{68}Er^{166}$ and $_{69}Tm^{166}$ (7.7 h) Excited in the Decay of $_{67}Ho^{166}$ (26.7 h), Ho^{166m} (1.2×10^3 yr), and $_{70}Yb^{166}$ (57 h)

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The γ-ray spectra accompanying the decay of $_{67}Ho^{166}$ (26.7 h), $_{67}Ho^{166m}$ (1.2×10^3 yr), $_{70}Yb^{166}$ (57 h), and $_{69}Tm^{166}$ (7.7 h) have been examined with Ge(Li) detectors. Chemically purified sources of Yb^{166} revealed only the known 82.3-keV transition in Tm^{166}. Nine transitions observed in the 26.7-h Ho^{166} activity fit known excited levels in Er^{166}: 80.57 (2^+), 786.4 (2^+), the 1460.9-keV (0^+) β-vibrational state, and two higher levels at 1663.0 (1^+), and 1830.5 keV (1^-). Forty-two of the 63 transitions observed in the spectrum of 1.2×10^3-yr $_{67}Ho^{166m}$ are assigned among 14 excited states in Er^{166}; these states are at 80.57 (2^+), 265.0 (4^+), 545.4 (6^+), 911.2 (8^+), 859.9 (3^+), 956.4 (4^+), 1075.4 (5^+), 1216.3 (6^+), 1376.1 (7^+), 1556.1 (8^+), 1666.5 (5^-), 1693.0 (5^-), 1787.3 (6), and 1828.1 keV (5,6). The first four levels are members of the $K=0$ ground-state rotational band. The next six states are members of the $K=2$ γ-vibrational band based on the 786.4-keV band head. Approximately 90 γ rays are resolved in the Ge(Li) spectrum of Tm^{166}. These, together with a summary of the results of internal-conversion measurements made previously by other investigators, are listed in a table containing 110 transitions believed to ocur in the Tm^{166} decay. We have placed approximately 80 of these γ rays into 23 excited states in Er^{166}. The energies (keV) of these states are 80.57 (2^+), 265.0 (4^+), 545.4 (6^+), 786.4 (2^+), 859.9 (3^+), 956.4 (4^+), 1075.4 (5^+), 1375 (2^+), 1458.9 (3^-), 1514.5 (3^-), 1530.1 (2^+ or 3^+), 1572.4 (4^-), 1704 (3^+ or 4^+), 1918.6 (3^-), 1940, 2134.4 (3^+), 2161.2 (3^+), 2174.4 (3^+), 2243, 2274, 2292, 2679, and 2728. The 1530- and 1704-keV states may be the 2^+ and the 4^+ levels of the β-vibrational band based on the 1460.9-keV (0^+) band head. A study of the γ-ray spectrum in coincidence with annihilation radiation (in triple coincidence) indicates that the two reported positron branches of 1932 keV (1% per disintegration) and 1210 keV (0.3% per disintegration) decay to the 80.57- and to the 786.4-keV levels, respectively. Comparison of the relative γ-transition intensities between members of the γ-vibrational band and various members of the ground-state rotational band yield a value of the mixing parameter $z=0.045\pm0.003$. The rotational $E2$ transition rates relative to the vibrational transition rates are calculated, yielding a mean value of 45.5 ± 3 for the ratio. The energy values of the members of the ground-state and γ-vibrational bands are compared with the usual expansion in $I(I+1)$. The third-order term $CI^3(I+1)^3$ is believed necessary to describe both bands.

I. INTRODUCTION

THE excited states of the highly deformed nucleus $_{68}Er^{166}$ are evidenced in the decay of three neighboring radioactive species: $_{67}Tm^{166}$ (7.7 h) and the two isomers of $_{67}Ho^{166}$, the 26.7-h ground state and the 1.2×10^3-yr isomeric state. The initial configurations of these three parent nuclides differ markedly in their properties from each other and in all three cases a considerable amount of decay energy is available so that the population of a wide variety of relatively high-lying states in the daughter nucleus is possible. The system therefore provides a fertile source of information about the Er^{166} nucleus. The main emphasis of the study reported here has been placed upon detailed examinations of the γ-ray spectra associated with each of the three β decays to Er^{166}. These high-resolution spectra were obtained with lithium-drifted germanium-diode detectors and, for the most part, the level assignments are supported by the energy and intensity balances resulting from analysis of these data. Extensive work has been carried out by many investigators on the two isomers of Ho^{166} as well as on the decay of Tm^{166}. No attempt is made here to review exhaustively this previous work and, except where specific comparisons with earlier reports are made, reliance is placed upon the thorough synopsis contained in the Nuclear Data Sheets.[1] For the most part, our results are consistent with other recent work.

The principal contribution of this study lies in the suggestion of several high-energy states not previously reported and in the determination of γ-ray intensities, which has not been extensive in sodium-iodide studies because of the extreme complexity of the spectra.

In contrast with the relatively simple spectrum associated with the decay of the 0^- state in Ho^{166}, the spectrum accompanying the decay of the 7^- isomeric state exhibits in excess of 60 transitions and more than 100 transitions are present in the Tm^{166} decay.

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[1] *Nuclear Data Sheets*, compiles by K. Way *et al.*, (U. S. Government Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1964), Vol. 6, Set 4, p. 36.

Several examinations of the internal-conversion spectra accompanying the Tm^{166} decay have been reported and we have relied upon these data in assigning the multipole character to several of the transitions. In addition, a number of the very close doublets resolved in these β-spectrometer measurements could not be differentiated by our apparatus. We have included much of these data in our tables.

Conversely, few internal-conversion data are available on either of the Ho^{166} activities. In the case of the 26.7-h decay, the branching to the high-lying states is extremely weak, so that the β-ray continuum renders conversion-spectrum studies difficult, while in the case of the long-lived Ho^{166} isomer, such measurements are handicapped by the problem of obtaining sources of sufficiently high specific activity.

By studying the decay of 57-h Yb^{166}, an effort was also made to extend knowledge of the states in the odd-odd nucleus Tm^{166} and to establish the parity of its ground state. These experiments yielded no new results.

The conclusions reached from a simultaneous consideration of the results of all of the experiments are presented in the discussion and—whenever possible—the characteristics of the high-energy states are deduced.

II. SOURCE PRODUCTION

A. Yb^{166} and Tm^{166}

The 4–6-mg samples of thulium oxide were irradiated with 52-MeV protons from the I.K.O. synchrocyclotron for periods of approximately 1 h. The desired Yb^{166} activity was produced by the reactions $Tm^{169}(p,4n)$-Yb^{166}. After 5–10 h of "cooling" time, the samples were purified chemically. It was found desirable to make two successive ion-exchange-column separations to produce pure carrier-free sources of Yb^{166}. For the first separation, a column 1-cm diam and approximately 40 cm high was used. This served to separate the carrier-free Yb^{166} from the bulk-target material as well as from any impurities that would not follow the Yb fraction. This first separation was carried out rather slowly, usually taking several hours, and without concern for the excellence of separation of the Yb^{166} from its daughter product Tm^{166}. The second separation was made with a column 1 cm in diam and about 20 cm high and usually required approximately 40 min. The height of the 184-keV γ-ray peak relative to the 80-keV complex was used of a criterion for the goodness of the separation.

The search for previously unreported transitions in Tm^{166} was made with these freshly separated samples of Yb^{166} and the studies of the spectra associated with the decay of the Tm^{166} were made with equilibrium sources.

B. Ho^{166} (26.7 h)

The 26.7-h sources of Ho^{166} were produced by thermal-neutron irradiation of samples of holmium oxide in the high-flux reactor at Reactor Centrum Nederland at Petten. After several hours of cooling, the samples were chemically purified by a procedure similar to that used for the Yb^{166} sources.

C. Ho^{166m} (1.2×10^3 yr)

The samples of Ho^{166m} were obtained from the Radioactive Center, Amersham, England.

III. γ-RAY SPECTRA

A. Apparatus

The γ rays were detected with one of two Li-drifted germanium crystals, RCA types SJGG/2/30 and SJGG/5/40. Both detectors exhibit an energy resolution width of 3.4 at 122 keV. The diodes were calibrated for efficiency in a standard way using the sources Na^{22}, Na^{24}, Cr^{51}, Co^{57}, Y^{88}, Nb^{95}, Hf^{180m}, Au^{198}, Hg^{203}, Bi^{207}, and Am^{241}. The energy calibration of the detectors was performed with standard activities of well-known γ energies in such a way that several peaks were measured for each energy region, thus correcting for possible non-linearities of the system. Most of the pulse-height analysis and data storage was accomplished with a 1024-channel Nuclear Data N.D. 181-FMR instrument.

Some of the spectra are presented for demonstration and in an effort to convey a measure of the confidence level of the authors with regard to questionable interpretations. All of the analysis was done manually and the need for development of computer techniques is clearly evident. Figures 1–3 show the spectrum of Yb^{166} in equilibrium with the Tm^{166} daughter. The region below 200 keV does not exhibit the complexity apparent at higher energies and is therefore not shown. All of the quantitative results were derived from expanded linear plots of these data. Many of the significant characteristics indicated in the figures are not readily interpretable from examination of the semilogarithmic plot. The scale compression present in the logarithmic plot is accentuated by the very high Compton background caused by γ rays of higher energy. This effect is illustrated in Fig. 2, where a small region of the spectrum has been plotted on both linear and logarithmic scales. The contrast that is gained by this method is clearly evident. Figure 3 shows the spectrum between 1.6 and 2.7 MeV. Notice that the high-energy peaks are much more discernible against the background even though the experimental uncertainties in the data points are relatively larger; here the spectral background is at a considerably lower level.

From linear plots of the data, such as that shown in Fig. 2, the channel position of the centroids of the peaks and thus the energies of the radiations were determined. The relative intensities were also determined from these plots by measuring the areas of the peaks and correcting them appropriately for the detection efficiency.

B. Tm^{166} Spectrum

Our current knowledge of the spectrum of γ rays accompanying the decay of Tm^{166} is summarized in

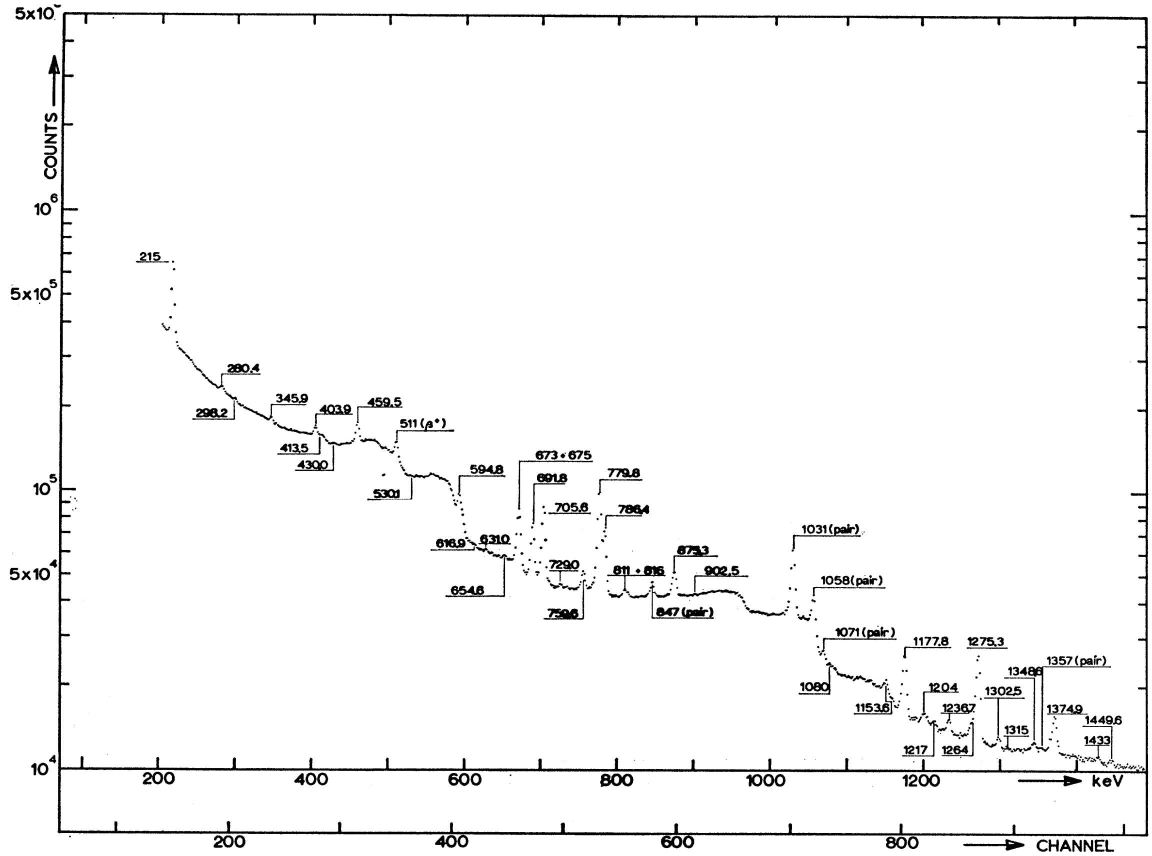

FIG. 1. γ-ray spectrum of Tm^{166} obtained with a Ge(Li) detector 0.2 cm thick by 2.8 cm^2. Of the 68 transitions listed in Table I, there are 15 (reported from conversion measurements) which are either unobserved or obscured by other peaks. In addition to the 40 peaks marked, 13 more γ rays were found in the linear plots of runs with lower uncertainties.

Table I. The spectra shown in Figs. 1–3 are but representative of a large number of runs, made with different amplifier gains and different sources. In column 1 the transitions are numbered for convenience of identification. The table is not restricted to γ rays observed in this study, but incorporates most of the transitions reported by other investigators.

In column 2, the energies of the transitions are listed along with estimated experimental uncertainties. Where no uncertainty is listed, the energy value has been assumed from previously reported measurements believed to have higher accuracy than those of the present study. This is the case for all of the transitions below 500 keV. In this section of the table, the energy values are averages derived from certain data.[2,3] From consideration of the spread observed in the various measurements of the same transition,[2–4] it is believed that within this group, most of the uncertainties are probably less than 0.3 keV. Our values for the more intense high-energy transitions were compared with those in the other reports and the best correspondence was found to exist between our energies and those of Grigoriev. Therefore, where it was felt that our data did not permit energy assignments as reliable as had been previously made, we assumed the values found in Ref. 2.

The entries in column 3 identify one or more of the references to earlier studies in which the transition was reported. (These references are not intended to be exhaustive and include only internal-conversion-electron measurements.)

The relative intensities of the γ rays together with estimated uncertainties are listed in column 4. If no number appears, the transition was not sufficiently well distinguished in the spectra to permit an intensity assignment from our own data. In these cases, one of three letters is entered in an effort to classify explanations for the missing intensity values. The letter "w"

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[2] E. P. Grigoriev, K. Ya. Gromov, B. S. Dzhelepov, Zh. T. Zhelev, V. Zvol'ska, and I. Zvol'skii, Izv. Akad. Nauk SSSR, Ser. Fiz. **25**, 1217 (1961) [English transl.: Columbia Techn. Transl. **25**, 1227 (1962)].

[3] A. A. Abdumalikov *et al.*, in *Program and Abstracts of the Fourteenth Annual Meeting on Nuclear Spectroscopy, Tbilisi* (Nauka, Leningrad, 1964), p. 61.

[4] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **123**, 1758 (1961).

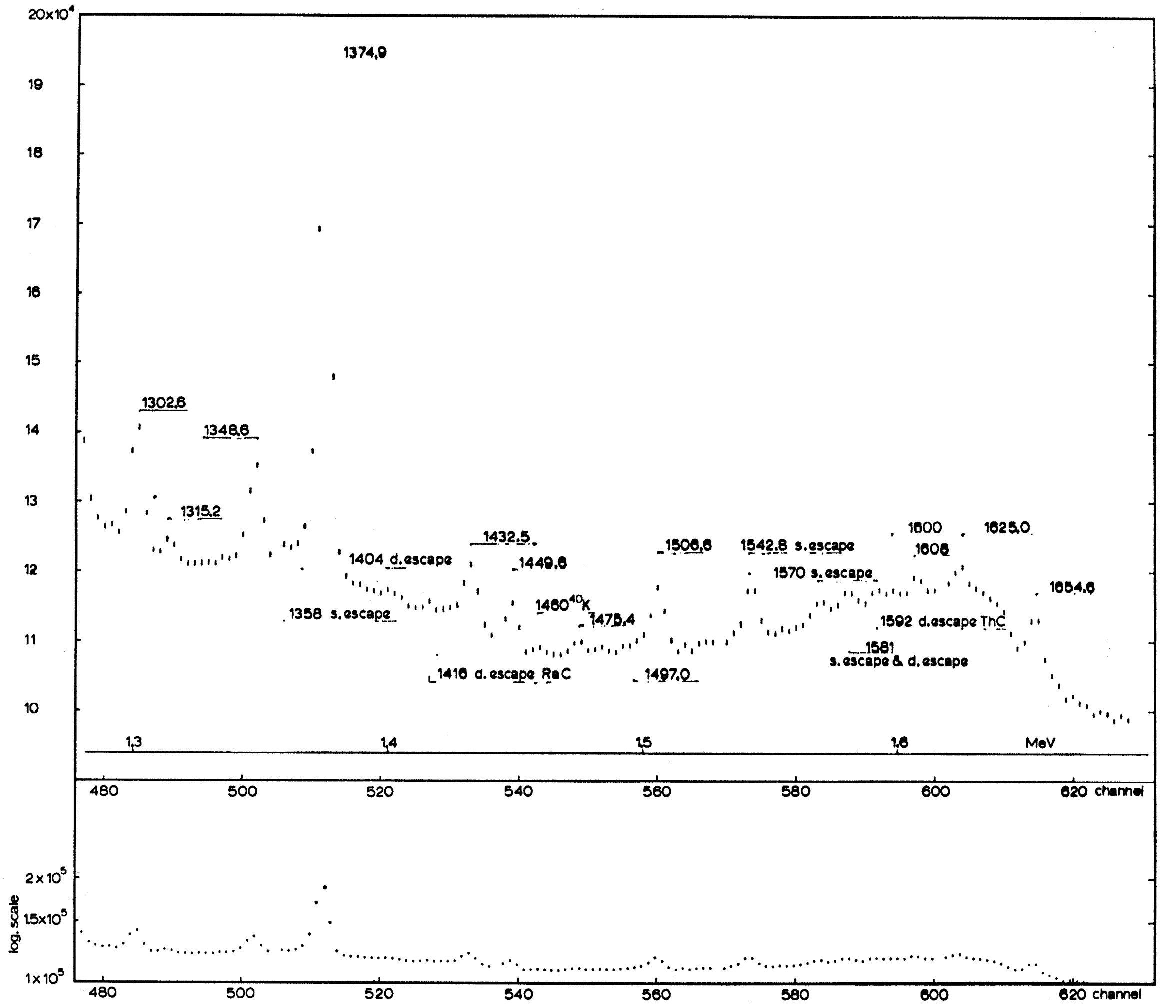

FIG. 2. γ-ray spectrum of Tm^{166} obtained with a Ge(Li) detector 0.5 cm thick by 3.8 cm^2. Escape peaks representing pair production of h igher-energy γ rays are indicated as well as some features attributable to background. The upper graph is a linear plot of the data that are plotted logarithmically below.

(weak) indicates that the transition was definitely observed but with too weak an intensity to justify an attempt to evaluate the area under the peak. The letter "u" (unobserved) indicates that the transition was unobserved in our data even though the region of the spectrum where it should have been seen was free of other interfering features. In some cases, reported transitions fall in spectral regions that are obscured by other prominent features—such as pair peaks of high-energy γ rays or sharp Compton edges. In these cases, the letter "h" (hidden) is entered. For this latter group, one should draw no conclusions from the data either regarding the existence or intensity of the transition. In several cases where close-lying doublets are reported in the internal-conversion data, the two transitions are bracketed and the total intensity of the combined unresolved peak is entered.

In column 5, the K-shell internal-conversion coefficients are listed. These values are deduced from our own γ-ray intensity measurements used in conjunction with the relative electron-intensity data found in Refs. 2 and 3. Normalization was accomplished by assuming the 184.4-keV transition to have pure $E2$ character. We have not attempted to tabulate estimated uncertainties for the conversion coefficients in column 5, since it is impossible for us to evaluate the experimental accuracy of the relative electron-intensity data taken from the other studies.

The probable character of each transition, based upon the calculated conversion coefficients, is listed in column 6. Where it was felt that the data were not adequate to permit even a doubtful assignment, no entry is made. The $E2$ character is also assumed for all of the transitions between the collective states of the two lower rotational bands.

The relative transition intensities are entered in column 7. These are derived from the experimental γ-ray intensities in column 4, and are corrected for internal

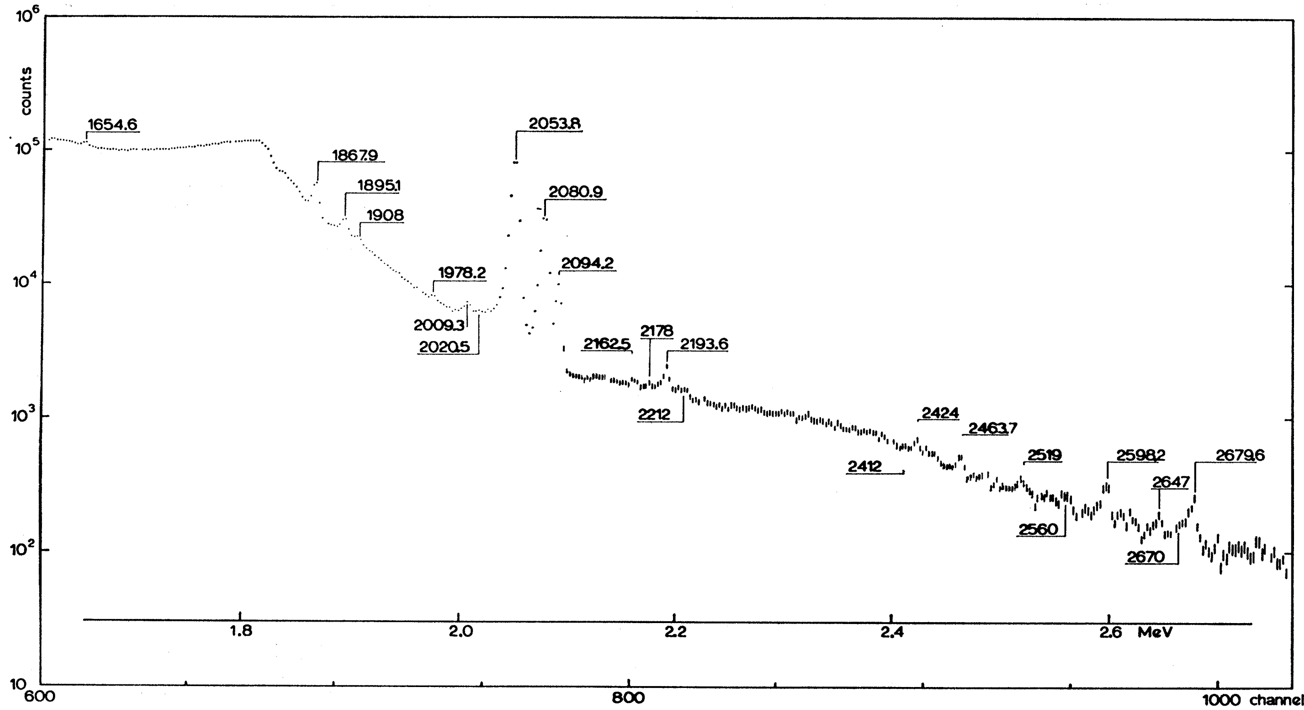

FIG. 3. γ-ray spectrum of Tm^{166} obtained with a Ge(Li) detector 0.5 cm thick by 3.8 cm^2. Of the 24 transitions listed in Table I for this energy region, 18 have not been observed in conversion measurements. Of these 18 "new" γ rays, four are identified as transitions previously reported by Bedrosyan, Brzal, Luptak, Molnar, Morozow, and Ubanetz in Ref. 3, p. 61.

conversion in those cases for which the multipole character was known, as indicated in column 6. For the total conversion coefficient of the 80.57-keV transition, we adopted the value 6.93 as deduced by Daniel and Kaschl[5] from a measured $L/(M+N+\cdots)$ conversion ratio and the theoretical K and L conversion coefficients as given by Sliv and Band. Where the character is unknown, no entry is made. In all cases above 450 keV, it is assumed that the correction for internal conversion is not significant and the transition intensity is assigned the same value as the γ-ray intensity.

The pair of letters in column 8 refers to the two levels in Er^{166} between which the transition is beleived to occur. All Er^{166} states that are believed to exist have been assigned identification letters in an effort to reduce the burden of rewriting the energy value of the states where the latter is not of particular intrinsic significance. In places where no entry has been made, no assignment of the transition has been made by the authors, although an assignment may have been made by other investigators. In the places where double assignments are made, the one appearing first is preferred although the degree of preference is not specified and none may in fact exist.

Table II provides a summary of the intensity balance for each state as well as direct reference to the detailed γ-transition information in Table I. The assignments of the transitions found in the Tm^{166} decay are rearranged with particular reference to their positions in the decay scheme. It is possible, by examination of this table, to determine at a glance which of the higher states decay to any particular level and, in turn, the lower states to which this level decays. The table is necessarily twofold-redundant in order to facilitate its use. The left-hand column lists the energy, spin, and parity of each state together with its identification letter. Each diagonal element of the table identifies one particular state. The transitions feeding or depopulating any state are then found by noting the entries above and below the diagonal element. The surplus of total decay over total populations is listed in γ-ray intensity units at the top of each column. From these numbers the β-branching may be inferred.

C. Ho^{166} (26.7 h) Spectrum

The recent value of 26.74±0.05 h measured by Daniel and Kaschl[5] for the half-life of Ho^{166} is adopted. The recorded γ-ray spectrum is shown in Fig. 4; full-energy peaks of nine transitions are visible. The spectrum reveals no γ rays not previously reported. The relative γ-ray intensities were compared with those reported by Cline *et al.*,[6] Hansen *et al.*,[7] and the earlier measurements of Sunyar,[8] and were found to be in agreement

[5] H. Daniel and G. Th. Kaschl, Nucl. Phys. **76**, 97 (1966).

[6] J. E. Cline, E. C. Yates, and E. H. Turk, Nucl. Phys. **30**, 154 (1962).

[7] P. G. Hansen, D. J. Horen, and Lung-Wen Chiao, Nucl. Phys. **24**, 519 (1961).

[8] A. W. Sunyar, Phys. Rev. **93**, 1345 (1954).

TABLE I. Transitions observed in the decay of Tm^{166} (7.7 h). In column 2, the energy assignments given to all transitions below 500 keV are average values taken from internal-conversion data found in Refs. 2 and 3. For these transitions no experimental uncertainties are specified; but from an examination of the spread in the values found in Refs. 2–4, it is believed that the uncertainties are less than 0.3 keV. For the transitions above 500 keV, experimental uncertainties are entered only for those observed in this study. In column 3, the letters "H," "G," and "A" refer to the internal-conversion data of Harmatz *et al.* (Ref. 4), Grigor'ev *et al.* (Ref. 2), and Abdumalikov *et al.* (Ref. 3), respectively. Where no letters are entered, the transition has not been seen in internal-conversion measurements. In column 4 the relative γ-ray intensities are listed in arbitrary units. All numerical entries are derived from the present study. Where no intensity assignment is made, the letter "u" indicates that the transition was unobserved, the letter "w" (weak) indicates that the transition was definitely observed but that it was too weak to permit an intensity assignment, and the letter "h" (hidden) indicates that the presence of the transition could not be observed because of the presence of other features of the spectrum. In column 5 rough values for the K-conversion coefficients are listed, deduced from the present values of the γ intensities and the K-conversion data from Refs. 2–4. The values are normalized to the theoretical value 0.20 for the 184.4-keV $E2$ transition. The character of the transitions in column 6 is obtained from the measured α_K or from the assignment in the decay scheme. The values for the transition intensities in column 7 are the γ intensities from column 4 corrected for the effect of internal conversion. Below 450 keV, no entry is made where the character of the transition is unknown. The pairs of letters in column 8 refer to the two levels (Fig. 8) between which the transition is believed to occur. Where no entry is made the transition has not been placed in the decay scheme.

Transition number	E (keV)	Ref.	γ-ray intensity	$1000\alpha_K$	Character	Transition intensity	Assignment
1	73.50	AH	0.6±0.2		$E2$	7±2.5	$\beta\alpha$
2	80.57	GHA	}	1800	$E2$	3050±400	BA
3	82.3		805±100		$M1$		Tm^{166}
4	84.15	HA	}				JH
5	90.7	H	w			w	
6	96.7	HA	w			w	$\gamma\beta$
7	112.8	A	w			w	
8	131.0	HA	27±3			60	RN,XT
9	147.3	GHA	14±2				
10	154.5	GHA	9.5±1.0				
11	170.2	GHA	2.0±0.3		$E2$	2.7±0.4	$\gamma\alpha$
12	184.4	GHA	715±40	(200)	$E2$	970±55	CB
13	194.8	GHA	36±4		$M1$	55±5	SQ
14	215.2	GHA		~40	$E1$	225	SP
15	215.8	A	240±15		$E2$	15	$\delta\beta$
16	228.1	A	u			u	
17	238.5	A	u			u	
18	280.4	GHA	12.7±2.5	70	$E2$	13.9±3.0	DC
19	293.1	A	u			u	
20	298.2	GA	16±3				
21	319.8	HA	u			u	
22	345.9	GHA	15.5±1.5	120	$M1$	16.5±1.5	PN
23	385.5	A	w			w	
24	389.4	GA	} 2.7±1.3			} 2.8±1.3	PM
25	390.3	A	}			}	
26	403.9	GHA	37±3.5	50	$M1$	38±4	PL
27	410.7	GA	w			w	γD
28	413.1	GA					
29	430.0	GHA	9.8±2.7			10±2.7	SR
30	459.6	GHA	124±10	40	$M1$	130±10	PJ
31	472.5	GA	4±2	40	$M1$	4±2	UR
32	496.9	A	11.4±2.0	10	$E1$	11.4±2.0	$N\delta$
33	501.0±1.5		w			w	$J\gamma$
34	521.2±1.0	GHA	w			w	αC
35	530.4±1.0	GA	w			w	δD
36	544	A	u			u	PH
37	557.7±1.0		11±2	<5	$E1$	11±2	$L\gamma$
38	563.2±1.0		9.5±2.0	<6	$E1$	9.5±2.0	SN
39	594.8±0.8	GHA	} 150±20		$E2$	~90	βC
40	599.0±0.8	GHA	}			~60	$J\beta$
41	604.5±1.0	GA	w			w	SM
42	616.9±1.0		3.8±1.0			3.8±1.0	$N\gamma$
43	631.0±1.0		8.0±2.0			8.0±2.0	
44	654.6±0.6		11±1			11±1	$L\beta$
45	673.1	GHA	} 390±40	} ~2.9	$E1$	270	$J\alpha$
46	675.5	GHA	}	}	($E1$)	120	SJ
47	691.8±0.5	GHA	305±30	8	$E2$	305±30	γC
48	702.7	A	} 490±50		$E1$	90	TJ
49	705.6	GHA	}	~9	$E2(M1)$	400	αB
50	712.4±0.5	HA	w			w	$N\beta$
51	729.0±1.0	HA	11.5±3.0			11.5±3.0	$L\alpha$
52	759.3±0.6	GHA	90±10	13	$M1$	90±10	SH
53	779.8±0.6	GHA	880±90	5	$E2(M1)$	880±90	βB
54	786.4±0.6	GHA	435±44	5.4	$E2(M1)$	435±44	αA
55	811.5±0.6	GHA	47±5	5.1	$E2(M1)$	47±5	δC
56	815.5±1.5		1.6±1.0			1.6±1.0	WJ
57	875.3±0.6	GHA	165±17	5.1	$E2$	165±17	γB

TABLE I (*continued*).

Transition number	E (keV)	Ref.	γ-ray intensity	$1000\alpha_K$	Character	Transition intensity	Assignment
58	902.5±1.5		6.5±3.0			6.5±3.0	
59	1058.2	HA	h			h	$P\beta$
60	1072.0	H	h			h	
61	1080.0±1.0	GHA	6.5±3.0			6.5±3.0	$Q\beta$
62	1085.0±1.5	A	w			w	
63	1121.1±1.0		6.5±2.0			6.5±2.0	
64	1132.0±1.5		w			w	$P\alpha$
65	1153.6±1.5	GHA	55±6	6.4	$M1$	55±6	$Q\alpha$
66	1162.0±2.0		w			w	
67	1177.8±0.6	GHA	390±40	4.8	$M1$	390±40	$S\gamma$
68	1193	H	u			u	JC
69	1204.4±1.0	GHA	52±5	3	$M1$	52±5	$T\gamma$
70	1217.4±1.0		26±3			26±3	$U\gamma$
71	1236.7±0.6	HA	75±8			75±8	
72	1250.3±1.5		5±2			5±2	LC
73	1265.3±1.0	HA	30±10			30±10	MC
74	1275.3±0.6	GHA	610±60	3.7	$M1$	610±60	$S\beta$
75	1302.5±1.0	GHA	} 52±5			} 52±5	$T\beta$
76	1306.4±1.5	H					NC
77	1315.2±1.5		13±4			13±4	$U\beta$
78	1348.6±0.8	GHA	32±3	3.6	$M1$	32±3	$S\alpha$
79	1374.9±0.8	GHA	200±20	3.6	$M1$	200±20	$T\alpha,(HA)$
80	1432.5±1.0	GH	30±5	3.8	$M1$	30±5	$X\beta$
81	1449.6±1.0	GH	24±5	3.6	$M1$	24±5	MB
82	1475.4±2.0		5±2			5±2	
83	1497 ±2	H	w			w	
84	1506.6±1.0		35±4	3.3	$M1$	35±4	$X\alpha$
85	1600 ±2	H	w			w	
86	1608.2±1.5		3.0±1.5			3.0±1.5	
87	1625.0±1.0	G	10±3			10±3	RB
88	1654.6±1.5		20±6			20±6	PC
89	1838.0±2.0		w			w	PB
90	1867.9±1.0	GH	145±15	1.0	$E2M1$	145±15	SC
91	1895.1±1.0	GH	42±5	1.2	$E2M1$	42±5	TC
92	1908.1±2.0		13±4			13±4	UC
93	1978.2±1.5		2.0±0.8			2.0±0.8	VC
94	2009.3±1.5		3.5±1.0			3.5±1.0	WC
95	2020.5±2.0		w			w	
96	2053.7±1.0	GH	770±80	0.9	$E2M1$	770±80	SB
97	2080.9±1.0	GH	270±27	0.8	$E2M1$	270±27	TB
98	2094.2±1.0	H	65±7			65±7	UB
99	2162.5±2.0		1.8±0.5		$M1(E1)$	1.8±0.5	VB
100	2178 ±2		1.0±0.5		$M1(E2)$	1.0±0.5	
101	2193.6±1.5		7.5±2.0			7.5±2.0	WB
102	2212 ±2.0		1.5±0.6			1.5±0.6	XB
103	2412.5±2.0		w			w	YC
104	2424.5±2.0		1.0±0.4			1.0±0.4	
105	2463.7±1.5		1.8±0.5			1.8±0.5	ZC
106	2519.3±2.0		1.1±0.4			1.1±0.4	
107	2560 ±2.0		1.0±0.5			1.0±0.5	
108	2598.2±1.5		2.4±0.6			2.4±0.6	YB
109	2647.0±2.0		0.8±0.3			0.8±0.3	ZB
110	2670 ±2.0		w			w	
111	2679.6±1.5		3.0±0.7			3.0±0.7	YA

with the scintillation measurements. In Table III the results are summarized in a manner similar to that in Table I. The dearth of internal-conversion data precludes the possibility of entering such information. Table IV presents the intensity balance derived from the information contained in Table III.

D. Ho^{166m} (1.2×10^3 yr) Spectrum

The sources of Ho^{166m} were obtained from the Radioactive Center, Amersham, England, several months before these experiments were undertaken. After the spectra had been taken and analyzed, the sources were passed through the same ion-exchange column described earlier and the spectra again observed. No other radioactive fractions were found during the separation and no differences were detectable in the spectra taken before and after the purification.

The γ-ray spectrum of the long-lived Ho^{166m} activity is shown in Fig. 5. It manifests a complexity comparable to that of the Tm^{166} data shown in Figs. 1–3. Of the 62 transitions detected, only 40 are indicated in the figure; 22 others, discernible only on the expanded linear plots, are included in the list. The data are summarized in Table V in the same manner as for the Tm^{166} results in

TABLE II. Intensity diagram for the decay of Tm^{166} (7.7 h). The diagram shows energy values (rounded off) and intensities (in parentheses) of the transitions feeding and depopulating the states in Er^{166}. The left-hand column lists the energy, spin, and parity of each state together with its identification letter. Each diagonal element (boldface) identifies one particular state (its energy in keV). The transitions feeding or depopulating any state are then found by noting the entries above and below the diagonal element. The surplus of total decay over total population is listed in transition intensity units at the top of each column. An entry in parentheses indicates that the value is believed to be practically zero. The negative entry above the 80.57-keV state lies within the experimental uncertainties.

States in Er^{166}		(−550)	200	(0)	200	200	(−10)	50		(−10)	(0)	50	(−19)		(−17)	65	2460	700	120	3.8	12.6	66.5	5.5	2.6
Z 2728		2647.0 (0.8)	2463.7 (1.8)																					**2728**
Y 2679 (2⁺)	2679.6 (3.0)	2598.2 (2.4)	2412.5 (w)																				**2679**	
X 2292		2212 (1.5)			1506.6 (35)	1432.5 (30)																**2292**		
W 2274		2193.6 (7.5)	2009.3 (3.5)							815.5 (1.6)											**2274**			
V 2243		2162.5 (1.8)	1978.2 (2.0)																	**2243**				
U 2174.4(3⁺)		2094.2 (65)	1908.1 (13)			1315.2 (13)	1217.4 (26)							472.5 (4)					**2174**					
T 2161.2(3⁺)		2080.9 (270)	1895.1 (42)		1374.9 (200)	1302.5 (<52)	1204.4 (52)			702.7 (∼90)								**2161**						
S 2134.4(3⁺)		2053.7 (770)	1867.9 (145)		1348.6 (32)	1275.3 (610)	1177.8 (390)		759.3 (90)	675.5 (∼120)		604.5 (w)	563.2 (9.5)	430.0 (10)	215.2 (225)	194.8 (55)	**2134**							
Q 1940 (2⁺3⁺)					1153.6 (55)	1080.0 (6.5)										**1940**	194.8 (55)							
P 1918.6(3⁻)		1838.0 (w)	1654.6 (20)		1132.0 (w)	1058.2 (h)			544 (u)	459.6 (130)	403.9 (38)	389.4 (<2.8)	345.9 (16.5)		**1918**		215.2 (∼225)							
R 1704 (3⁺4⁺)		1625.0 (10)											131.0 (∼60)	**1704**			430.0 (10)		472.5 (4)					
N 1572.4 (4⁻)			1306.4 (<52)			712.4 (w)	616.9 (3.8)	496.9 (11.4)					**1572**	131.0 (∼60)	345.9 (16.5)		563.2 (9.5)							
M 1530.1(2⁺3⁺)		1449.6 (24)	1265.3 (30)									**1530**			389.4 (<2.8)		604.5 (w)							
L 1514.5(3⁻)			1250.3 (5)		729.0 (11.5)	654.6 (11)	557.7 (11)				**1514**				403.9 (38)									
J 1458.9(3⁻)			1193 (u)		673.1 (∼270)	599.0 (∼60)	501.0 (w)		84.2 (h)	**1458**					459.6 (130)		675.5 (∼120)	702.7 (∼90)			815.5 (1.6)			
H 1374.9(2⁺)									**1375**	84.2 (h)					544 (u)		759.3 (90)							
δ 1075.4(5⁺)			811.5 (47)	530.4 (w)		215.8 (∼15)		**1075**					496.9 (11.4)											
γ 956.4(4⁺)		875.3 (165)	691.8 (305)	410.7 (w)	170.2 (2.7)	96.7 (w)	**956**			501.0 (w)	557.7 (11)		616.9 (3.8)				1177.8 (390)	1204.4 (52)	1217.4 (26)					
β 859.9(3⁺)		779.8 (880)	594.8 (∼90)		73.5 (7)	**859**	96.7 (w)	215.8 (15)		599.0 (∼60)	654.6 (11)		712.4 (w)		1058.2 (h)	1080.0 (65)	1275.3 (610)	1302.5 (<52)	1315.2 (13)			1432.5 (30)		
α 786.4(2⁺)	786.4 (435)	705.6 (∼400)	521.2 (w)		**786**	73.5 (7)	170.2 (2.7)			673.1 (∼270)	729.0 (11.5)				1132.0 (w)	1153.6 (55)	1348.6 (32)	1374.9 (200)				1506.6 (35)		
D 545.4(6⁺)			280.4 (13.9)	**545**			410.7 (w)	530.4 (w)																
C 265.0(4⁺)		184.4 (970)	**265**	280.4 (13.9)	521.2 (w)	594.8 (∼90)	691.8 (305)	811.5 (47)		1193 (u)	1250.3 (5)	1265.3 (30)	1306.4 (<52)		1654.6 (20)		1867.9 (145)	1895.1 (42)	1908.1 (13)	1978.2 (2.0)	2009.3 (3.5)		2412.5 (w)	2463.7 (1.8)
B 80.57(2⁺)	80.6 (3050)	**80.6**	184.4 (970)		705.6 (∼400)	779.8 (880)	875.3 (165)					1449.6 (24)		1625.0 (10)	1838.0 (w)		2053.7 (770)	2080.9 (270)	2094.2 (65)	2162.5 (1.8)	2193.6 (7.5)	2212 (1.5)	2598.2 (2.4)	2647.0 (0.8)
A 0 (0⁺)	**0**	80.6 (3050)			786.4 (435)				1374.9														2679.6 (3.0)	

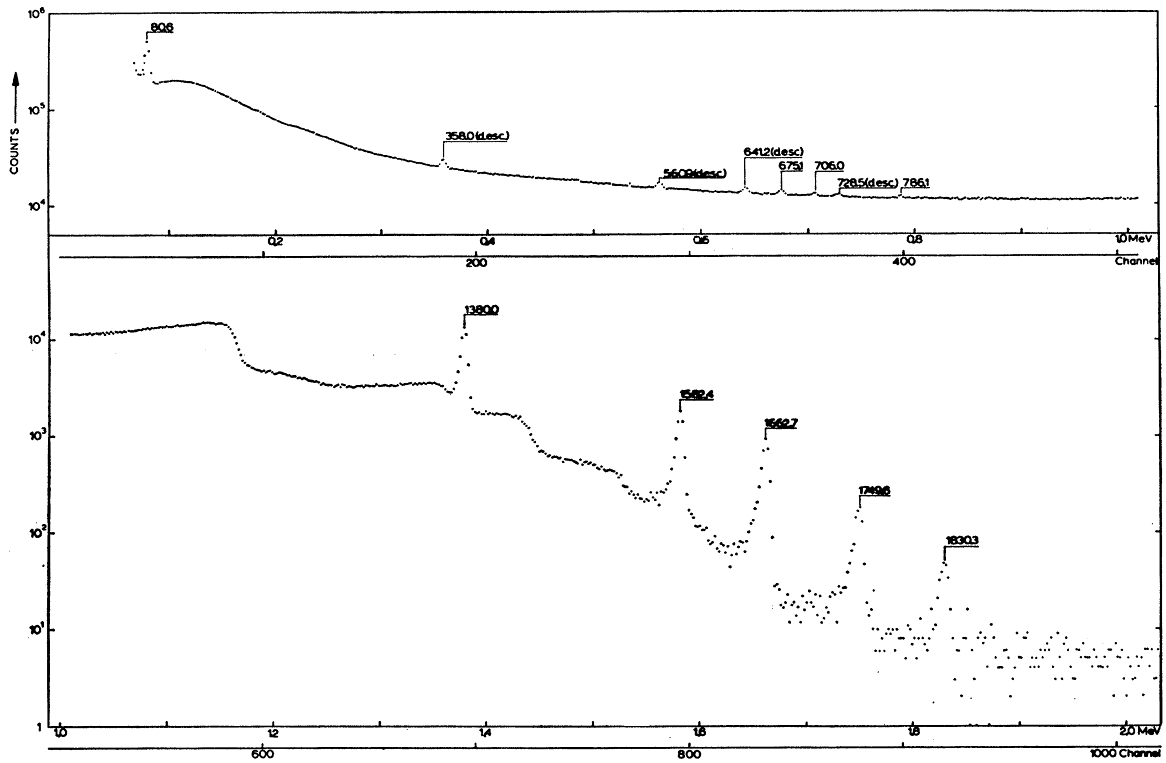

FIG. 4. γ-ray spectrum of Ho^{166} (26.7 h) obtained with a Ge(Li) detector 0.5 cm thick by 3.8 cm^2.

Table I. Few internal-conversion measurements have been made because of the difficulty of obtaining sources of sufficiently high-specific activity. Except for the 80.57-keV transition, the energies listed are those derived from our own data. The value for the 80.57-keV γ ray is again assumed from the crystal spectrometer measurements.[9–11] In column 3, the letters identify some authors who have also examined this decay either with β-ray spectrometers or with Ge(Li) detectors. This list does not include references to scintillation data. Where no entry is made, the transition has not been previously reported, so far as our present knowledge extends.

The entries in column 5 do not represent experimental determinations of the character but merely indicate those transitions for which the $E2$ character is evident by their placement in the decay scheme. The nature of the rotational-band structure seems sufficiently well established to justify these conclusions. For these

TABLE III. Transitions observed in the decay of Ho^{166} (26.7 h). A general description of the entries is given in Table I. The reference letters "M," "S," "H," and "N" in column 3 refer to crystal spectrometer data and β spectrometer data as reported by Marklund and Lindström (Ref. 9), Schult (Ref. 10), Hardell (Ref. 11), and by Marklund, van Nooyen, and Grabowski (Ref. 16), respectively. The relative transition intensities in column 6 are given in percent per disintegration. This normalization is based on the value 0.93% per disintegration for the 1380-keV transition as measured by Cline *et al.* (Ref. 6). The states belonging to the identification letters in column 7 are given in Table IV and in Fig. 8.

Transition number	E (keV)	Ref.	γ-ray intensity	Character	Transition intensity	Assignment
201	8057	MSH	6.2 ±0.4	$E2$	49 ±3	BA
202	675.1±0.5		0.030 ±0.002		0.030 ±0.002	$K\alpha$
203	706.0±0.7		0.019 ±0.003		0.019 ±0.003	αB
204	786.1±0.7		0.015 ±0.003	$E2$	0.015 ±0.003	αA
205	1380.0±0.5	N	0.93(norm)	$E2$	0.93(norm)	KB
206	1582.4±0.4	N	0.192 ±0.009		0.192 ±0.009	λB
207	1663.0±0.5	N	0.120 ±0.006		0.120 ±0.006	λA
208	1750.0±0.6		0.031 ±0.001		0.031 ±0.001	τB
209	1830.3±1.0		0.0093±0.0007		0.0093±0.0007	τA

[9] I. Marklund and B. Lindström, Nucl. Phys. **40**, 329 (1963).
[10] O. Schult, Ref. 1; also private communication.
[11] R. Hardell and S. Nilsson, Nucl. Phys. **39**, 286 (1962).

TABLE IV. Intensity diagram for the decay of Ho^{166} (26.7 h). A description of the features of this table is given in Table II. The values for the transition intensities (in parentheses) are given in this table as percent per disintegration.

States in Er^{166}		47.7	0.004	0.96	0.31	0.040
τ 1830.5 (1^-)	1830.3 (0.0093)	1750.0 (0.0306)				**1830**
λ 1663.0 (1^+)	1663.0 (0.120)	1582.4 (0.192)			**1663**	
K 1460.9 (0^+)		1380.0 (0.93)	675.1 (0.0298)	**1460**		
α 786.4 (2^+)	786.1 (0.0153)	706.0 (0.0185)	**786**	675.1 (0.0298)		
B 80.57 (2^+)	80.57 (49)	**80.6**	706.0 (0.0185)	1380.0 (0.93)	1582.4 (0.192)	1750.0 (0.0306)
A 0 (0^+)	**0**	80.57 (49)	786.1 (0.0153)		1663.0 (0.120)	1830.3 (0.0093)

cases, the theoretical conversion coefficients have been used to compute the transition intensities in column 6 from the γ-ray intensity values in column 4. In a few cases an entry is also made based on other results.[12] Where it was felt that there was no sound basis for assuming the multipole characters, no entries are made in the intensity column for the transitions below 450 keV. Above that energy, the correction for conversion is assumed to be negligible and the transition is given the same intensity as that measured for the γ ray.

In column 7, where the transition assignments are indicated, those that are supported by coincidence

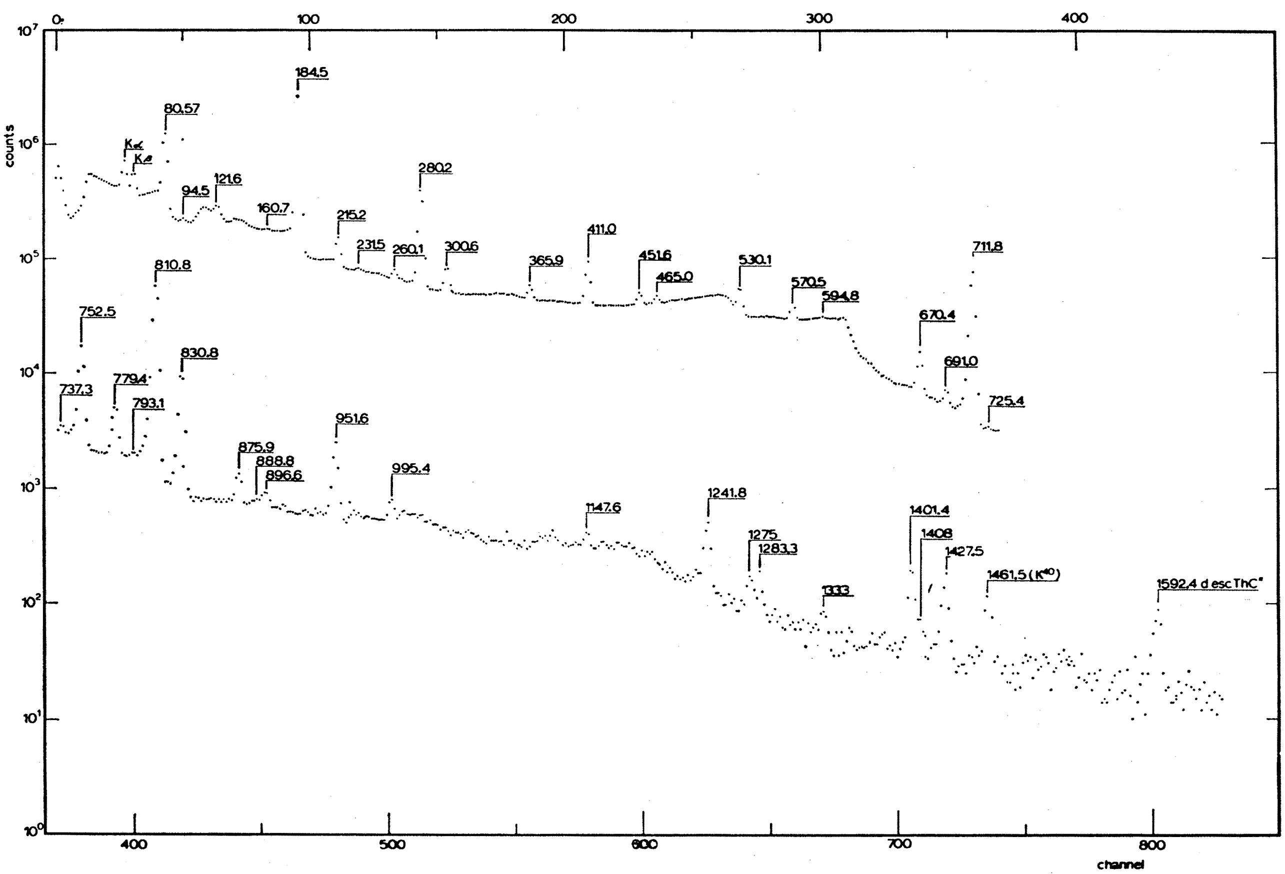

FIG. 5. γ-ray spectrum of Ho^{166m} (1.2×10^3 yr) obtained with Ge(Li) detector 0.5 cm thick by 3.8 cm^3. In addition to the 40 transitions indicated, 22 others were visible only on the expanded linear plots of the type shown in Fig. 2.

[12] G. W. Reich and J. E. Cline, Phys. Rev. **137**, B1424 (1965).

Table V. Transitions observed in the decay of Ho^{166m} (1.2×10^3 yr). A description of the general features of the table is given in Table I. The reference letters "G," "C," "P," "N," and "S" in column 3 refer to the data reported by J. S. Geiger, R. L. Graham, and G. T. Ewan [Nucl. Phys. **30**, 409 (1962)], by Reich and Cline (Ref. 12), by H. Postma [Reactor Centrum Nederland, Petten (private communication)], by Gallagher *et al.* (Ref. 17), and by D. A. Shirley and S. S. Rosenblum [Bull. Am. Phys. Soc. **9**, 498 (1964)]. The intensity values in column 4 are normalized to the value 1000 for the 184.4-keV transition. No conversion coefficients are listed because of the lack of conversion-intensity data. In column 7 the boldface assignments are supported by the coincidence measurements of Reich and Cline (Ref. 12). Where an entry is placed in parentheses, it is believed that the assignment has a lower level of confidence than an assignment belonging to an entry without parentheses.

Transition number	E (keV)	Ref.	γ-ray intensity	Character	Transition intensity	Assignment
301	80.57	GCP	145±29	$E2$	1150±230	BA
302	94.5±0.5	C	1.6±0.3	($M1$)	(6.7±1.3)	$\omega\nu$
303	111.8±1.0		⩽7			
304	121.6±0.7	C	7 ±5	($E2$)	(18±13)	$\omega\mu$
305	135.7±1.0	C	1±1	($M1$)	(2.2±2.2)	$\boldsymbol{\sigma\nu}$
306	160.7±0.7	C	3.5±1	($M1$)	(5.9±1.7)	$\boldsymbol{\sigma\mu}$, $(\eta\epsilon)$
307	184.5±0.6	GCP	1000	$E2$	1360	CB
308	215.2±0.6	GCP	38±4	$E2$	46±5	$\delta\beta$
309	231.5±1.0		3±2			$\omega\theta$
310	260.1±0.7	CP	18±5	$E2$	20±6	$\epsilon\gamma$
311	280.2±0.6	GCP	395±28	$E2$	427±30	DC
312	300.6±0.6	GCP	48±4			$\eta\delta$
313	340 ±2	N	}5±1			$\theta\epsilon$
314	345 ±2					
315	365.9±0.6	CP	29±3	$E2$	30±3	ED
316	411.0±0.6	GCP	}158±12		155	$\boldsymbol{\omega\eta}$
317	411.0±0.6	GCP			3	γD
318	451.6±0.7	CP	35±7		35±7	$\boldsymbol{\sigma\mathrm{n}}$, $(\mu\epsilon)$
319	465.0±0.8	C	20±4		20±4	ηE
320	476.7±1.5		4±2		4±2	$\nu\epsilon$
321	530.1±0.6	GCP	103±10		103±10	δD
322	570.5±0.6	CP	68±7		68±7	$\omega\epsilon$
323	594.8±1.0	MC	12±4		12±4	βC
324	611.1±1.5	MC	14±10		14±10	$\sigma\epsilon$
325	644.4±1.5	N	2.7±1.5		2.7±1.5	θE
326	670.4±0.6	CPS	70±7		70±7	ϵD
327	682.3±1.2		3±2		3±2	
328	691.0±0.8	CPS	19±4		19±4	γC
329	711.8±0.6	GCPS	725±60		725±60	$\boldsymbol{\omega\delta}$, $(\mu\gamma)$
330	725.4±1.0		1.9±1		1.9±1	
331	737.3±0.8	S	4.5±1.5		4.5±1.5	$\nu\gamma$
332	752.5±0.6	CPS	161±12		161±12	$\sigma\delta$
333	779.4±0.6	CPS	38±3		38±3	βB
334	793.1±1.5	P	1.7±1		1.7±1	
335	810.8±0.6	GCPS	760±80		760±80	δC
336	830.8±0.6	GCPS	125±10		125±10	$\boldsymbol{\eta\mathrm{D}}$, $(\omega\gamma)$
337	875.9±0.8	CPS	11.5±1.5		11.5±1.5	γB, (ωE)
338	888.8±1.5	P	}7.3		}7.3	
339	896.6±1.0	S				
340	951.6±0.6	CPS	36±6		36±6	$\boldsymbol{\varepsilon\mathrm{C}}$
341	996.8±1.0		7.3±2.4		7.3±2.4	$\sigma\beta$
342	976.1±1.5		1.2±0.6		1.2±0.6	
343	995.4±1.0		5±1.5		5±1.5	
344	1004.8±1.5		2±1		2±1	
345	1012.0±2	N	1±1		1±1	ΘD
346	1085.6±1.2		3±1		3±1	
347	1113.5±2.0	C	}7.5±2.5		~2.5	
348	1121.5±1.5	CS			~5.0	μD
349	1147.6±1.0	CPS	3.8±0.6		3.8±0.6	νD
350	1160.4±1.5		1±0.5		1±0.5	
351	1172 ±2		w		w	
352	1225 ±2		2±1		2±1	
353	1241.8±0.8	CPS	12.5±2.5		12.5±2.5	ωD
354	1275 ±1		}8±1.5		~4	
355	1283.3±1.0	CPS			~4	σD
356	1333 ±1.5	P	2±1		2±1	
357	1401.4±0.8	CPS	}9.3±0.9		8	$\boldsymbol{\mu}$ **c**
358	1408 ±2				1.3	
359	1427.5±0.7	CPS	6.9±0.7		6.9±0.7	$\boldsymbol{\nu}$ **c**
360	1493 ±3		}2±1		}2±1	
361	1510 ±2					
362	1522 ±2		2±1		2±1	ωC

measurements[12] are underscored. Particular attention is drawn to the 411.0-keV transition, which is believed to consist of two very close unresolved γ rays. This conclusion is reached primarily from consideration of the intensity data and is supported by the earlier coincidence measurement of Reich and Cline.[12] The intensity of the 692-keV transition is used to sample the population of the 956-keV state both in the Tm^{166} and in the Ho^{186} decays. This transition depopulates the 956-keV state to the 265-keV level. Relative to this reference line, the intensity of the 411.0-keV transition is found to be about 50 times greater in the Ho^{166m} than in the Tm^{166} case. Thus in the Ho^{166m} spectrum, only about 2% of the 411.0-keV transition can be attributed to decay from the 956-keV state, although this amount cannot reliably be assigned from this comparison of the two cases. In the coincidence work of Reich and Cline,[12] a strong peak at 411 keV is found to be in coincidence with the radiations bracketed by a channel from 790 to 850 keV. These results support their placement of this 411-keV transition between the 1787- and 1376-keV states. As a result of this interpretation, the 411-keV transition is concluded to be double and is given two assignments.

In the case where two entries appear, the assignment is ambiguous if the energy alone is considered. Where the coincidence data of Reich and Cline[12] support one of the two assignments, this choice is printed boldface and appears first. The second choice is then enclosed in parentheses. This indicates that such a transition, if it were present, would be obscured by the first one. If any other evidence apart from coincidence data indicates a strong preference, this choice appears first (but not in boldface) and the parentheses are also used with the second alternative assignment. Where no additional notation is present, the two possible alternative assignments are to be considered without preference.

As in Tables II and IV, Table VI summarizes the intensity balance for each state. The fact that the 411.0-keV γ-ray peak is interpreted as two distinct transitions is noted by an asterisk on both entries. We propose no new levels in Er^{166} as a result of the study. Of the 19 transitions believed to be not previously observed, we are able to assign only four. The remaining 15 unassigned transitions suggest other levels or the presence of very weak contaminants not removed by the chemical purifications of the sources.

E. Yb^{166} (57 h) Spectrum

Several attempts were made to detect new γ transitions in Tm^{166} following the Yb^{166} capture decay. Counting with the Ge(Li) detector was done for a series of 2-min intervals immediately after the Yb activity was collected from the column. The relative intensity of the 184-keV peak at the time of counting its equilibrium intensity showed that approximately 3% of the Tm^{166} activity had grown in prior to and during the first counting interval. This ratio indicated that the effective zero time for the separation was approximately 20 min before counting was commenced.

The equilibrium spectrum was normalized to the 184-keV peak and subtracted. The residual spectrum showed a small contamination of Yb^{167} formed by the (p,n) reaction and of course not separable from the activity of interest. The spectrum of Yb^{167} was then fitted to the data and a search was made for new lines. No evidence for any peak was found between about 86 and 250 keV. Peaks with an intensity greater than 3×10^{-3} times that of the 82.3-keV peak would have been observable.

The capsule thickness and walls of the cryostat made it impossible to examine the spectrum with the Ge(Li) detectors below about 40 keV, so a thin NaI detector (0.5 cm thick) equipped with a thin beryllium window was employed to examine the low-energy region of the spectrum. An upper limit of approximately 5% of the intensity of the 82.3-keV peak can be placed upon any possible γ-ray peak in the region between about 20 and 65 keV.

An analysis of the 81-keV composite peak in the equilibrium source was made from the source-growth data. Approximately 48% of the intensity in the peak is attributable to γ rays emitted at 80.57 keV in the Tm decay, and 52% to the 82-keV component accompanying the Yb^{166} decay. An examination of the electron structure of these two transitions with the I.K.O. iron-free double-focusing β-ray spectrometer yielded a ratio of about 0.25 for the intensity of the K line of the 80.57-keV transition to that of the 82.3-keV transition. These data confirm previous studies of these transitions and indicate that if the $E2$ and $M1$ characters for the 80.57- and 82.3-keV transitions are correct, then there must be very little branching to the ground state of Er^{166}, unless, of course, there were to be an equal amount of branching from the Yb^{166} state to the ground state of Tm^{166}. The latter coincidence is highly unlikely in view of the results reported by Jasinsky *et al.*,[13] who reported a maximum value of 4% per disintegration for the direct feeding of the ground state of Tm^{166}.

IV. THE DECAY SCHEMES

No scintillation or coincidence counting was performed in conjunction with the experiments on either holmium activity. All interpretations of such data are therefore based only on the energy and intensity balances derived from the γ-ray spectra. The coincidence measurements carried out on the Tm^{166} activity are discussed at the appropriate points in the following sections. The existence and spin-parity assignments of the states belonging to the rotational band based on the ground state are well established and accepted as pre-

[13] A. Jasinski, J. Kownacki, H. Lancman, and J. Ludziejewski, Nucl. Phys. 41, 303 (1963).

TABLE VI. Intensity diagram for the decay of Ho^{166m} (1.2×10^3 yr). A description of the general features of this diagram is given in Table II. The 411-keV transition is believed to consist of two separate parts; this is noted by an asterisk on the two entries for these transitions. The negative value for the total depopulation minus the total population of the 80.57-keV level is believed to be zero within the errors of the experiment.

States in Er^{166}				(−260)	90	70	(−3)	(7)	(9)	(25)	35	(3)	3	(−11)	10	990	230
σ	1828.1	(5,6)				1283.3 (4)	996.8 (7.5)			752.5 (161)	611.1 (14)	451.6 (35)		160.7 (6)	135.7 (2.0)		**1828**
ω	1787.3	(6±)			1522 (2)	1241.8 (12.5)				711.8 (725)	570.5 (68)	411.0* (155)	231.5 (3)	121.6 (18)	94.5 (6.7)	**1787**	
ν	1693.0	(5⁻)			1427.5 (6.9)	1147.6 (3.8)			737.3 (4.5)		476.7 (4)				**1693**	94.5 (6.7)	135.7 (2.2)
μ	1666.5	(5⁻)			1401.4 (8)	1121.5 (5)								**1666**		121.6 (18)	160.7 (6)
θ	1556.1	(8⁺)				1012 (1)		644.4 (2.7)			340 (2.5)		**1556**			231.5 (3)	
η	1376.1	(7⁺)				830.8 (125)		465.0 (20)		300.6 (48)		**1376**				411.0* (155)	451.6 (35)
ε	1216.3	(6⁺)			951.6 (36)	670.4 (70)			260.1 (20)		**1216**		340 (2.5)		476.7 (4)	570.5 (68)	611.1 (14)
δ	1075.4	(5⁺)			810.8 (760)	530.1 (103)	215.2 (46)			**1075**		300.6 (48)				711.8 (725)	752.5 (161)
γ	956.4	(4⁺)		875.9 (11.5)	691.0 (19)	411.0* (3)			**956**		260.1 (20)				737.3 (4.5)		
E	911.2	(8⁺)				365.9 (30)		**911**				465.0 (20)	644.4 (2.7)				
β	859.9	(3⁺)		779.4 (38)	594.8 (12)		**859**			215.2 (46)							966.8 (7.3)
D	545.4	(6⁺)			280.2 (427)	**545**		365.9 (30)	411.0* (3)	530.1 (103)	670.4 (70)	830.8 (125)	1012 (1)	1121.5 (5)	1147.6 (3.8)	1241.8 (12.5)	1283.3 (4)
C	265.0	(4⁺)		184.5 (1360)	**265**	280.2 (427)	594.8 (12)		691.0 (19)	810.8 (760)	951.6 (36)			1401.4 (8)	1427.5 (6.9)	1522 (2)	
B	80.57	(2⁺)	80.57 (1150)	**80.6**	184.5 (1360)		779.4 (38)		875.9 (11.5)								
A	0		**0**	80.57 (1150)													

viously described in the literature. The same also holds for the γ-vibrational band built on the 786.4-keV state. Only the values of the energies of these states as here presented are to be considered original to this paper. In some cases we have detected previously unobserved transitions in support of the assignment of these states.

Since the literature is replete with "possible" states in Er^{166}, no attempt is made to evaluate the previous work or to present historical accounts of each state. Approximately 50 out of 182 transitions still remain unassigned. This indicates that as yet the decay scheme (Fig. 8) remains incomplete, and further that probably some of the levels are incorrectly placed. The major part of the energy levels reported in the present study are derived from energy and intensity data only. It is possible to introduce other levels in the decay scheme which would have only a slightly worse degree of fitting. The levels discussed in this section should be seen only as representing the most probable explanation of the data available at the moment.

The following discussion of the experimental evidence supporting each state is presented in three groups corresponding to the three activities studied. The identification of the members of the two rotational bands is presumed in all cases and only their energies are evaluated.

A. Levels Populated in the Decay of Tm^{166}

The 2^+, 4^+, and 6^+ members of the ground-state rotational bands are excited. Beginning with the 786.4-keV 2^+ band head, the 3^+, 4^+, and 5^+ states are observed.

1. Branching of the Positron Decay to Er^{166}

In the decay of Tm^{166} to Er^{166}, two very weak positron components are present. For these branchings, Preibisz[14] reports endpoint values, one of 1932 and another of 1219 keV, with intensities of about 1 and 0.1% per decay. These branches are supposed to feed the 80.57-keV level and the 786.4-keV level (with possible feeding also to the 859.9-keV level). We have attempted to ascertain if these levels are in fact the ones that are being fed by positron decay.

The experimental setup is shown in Fig. 6. Annihi-

[14] Z. Preibsz and J. Zylicz, Phys. Letters 9, 258 (1964).

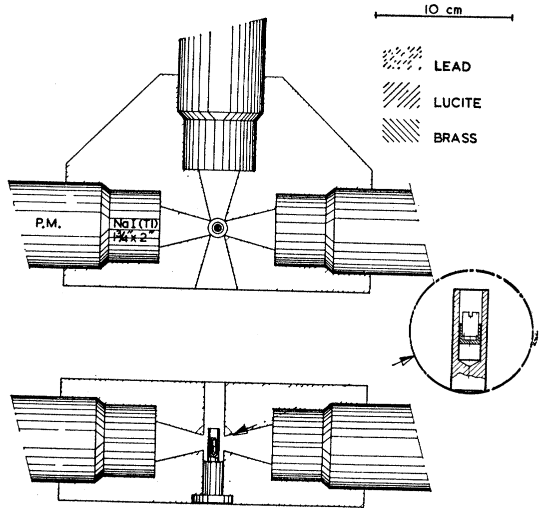

FIG. 6. Geometric arrangement of scintillation counters used for triple-coincidence measurements.

lation radiation from a Tm^{166} source is detected in two NaI crystals which are placed coaxially on either side of the source. The source is surrounded by a brass mantle 0.15 cm thick (sufficient to stop all positrons with energies less than 2.5 meV). On the outputs of two detectors, channels are set at 511 keV. The pulses from the third NaI detector shown in Fig. 6 are displayed on a multichannel analyzer gated by a conventional fast-slow coincidence system which gives a gating signal only when two pulses from the 511-keV detectors are coincident with a pulse from the third detector. In this coincidence system, we made use of three clipping cables corresponding to resolving times of $2\tau = 50$ nsec. Because of the extreme weakness of the positron branches, even in this system more than 10% of the coincident pulses from the two 511-keV detectors were caused by Compton pulses from coincident γ rays of higher energy. This effect could be seen when the output of one of these detectors was displayed in coincidence with the 511-keV pulse from the other. A correction for this contribution to the coincident spectrum was made by subtracting a spectrum obtained from a thin Tm^{166} source in the same way as described. The source backing in this case was so thin that annihilation occurred mainly in a region where the 511-keV pairs were not detected. Before subtraction, this spectrum was normalized in such a way that the total number of "false" gating pulses (those not caused by annihilation) was equal in both spectra.

The remaining spectrum showed peaks at 80.6, 184 and two peaks of equal intensity at about 700 and 780 keV. The 184-keV peak could be completely explained as being caused by pair production by the 1865-keV radiation which directly feeds the 265-keV level. The peaks at 700 and 780 keV we concluded to originate from decay of the 786-keV state. This would correspond to positron feeding of this level, the intensity being 0.3 $\pm 0.15\%$. The two peaks at 700 and 780 keV are of about equal intensity; direct feeding of the 860-keV level would result in enhancement of the 780-keV peak relative to the peak at 700 keV. This enhancement indicates that the 860-keV level is still more weakly populated. We find no evidence for positron decay to the 4^+ level at 265.0 keV as reported by Wilson and Pool.[15]

2. *1375-keV State*

The existence of the 1375-keV state is most strongly suggested by the consistency of the energy fit of the three feeding transitions from the 2134-, the 1918-, and the 1458-keV states. In opposition to this is the unfavorable circumstance that no depopulating transitions are observed except that a transition to the ground state can be completely masked by the relatively intense 1375-keV γ ray which is assigned between the 2161- and the 786.4-keV states. All three feeding states are believed to have spin 3, but the two lower levels at 1918 and 1458 keV are thought to have odd parity, so that the only acceptable assignment for the state is 2^+. Placement of this state should be considered to be tentative.

3. *1458.9-keV State*

The presence of this 1458.9-keV state is supported by the assignment of four feeding transitions and five depopulating γ rays. The feeding from the 2274-keV state is not taken into consideration, but the 3^+ character of the two levels at 2134 and 2161 keV (discussed subsequently) is assumed. Similarly, the odd parity of the 1918-keV level is assumed for the moment in assigning the character of the 1459-keV level. The state is thus fed from three levels with spin 3, two having even and one having odd parity. It decays to states with spin 2^+, 3^+, and 4^+. (As with the 2274-keV state, decay to the less reliable level at 1375 keV is not taken into consideration.) A sixth possible depopulating transition might feed the 80.6-keV state. However, such a transition would again be masked by the 1375-keV transition. The only assignment for the nature of the state and compatible with the foregoing is 3^-. This decision is also supported by the fact that both the 673.1- and 675.5-keV transitions are probably $E1$ in character.

An effort was also made to ascertain the existence of the 1458.9-keV state by a triple-coincidence measurement. The apparatus used was described above in Sec. IVA.1. The spectrum from the third detector was measured in coincidence with coincident pulses from two channels at about 700 keV. The 1458.9-keV level decays mainly through the 786.4-keV state with emission of γ rays of 673.1 keV and 705.6 or 786.4 keV. In a coincidence measurement with two channels at about 700 keV, one therefore expects that the γ rays feeding

[15] R. G. Wilson and M. L. Pool, Phys. Rev. **119**, 262 (1960).

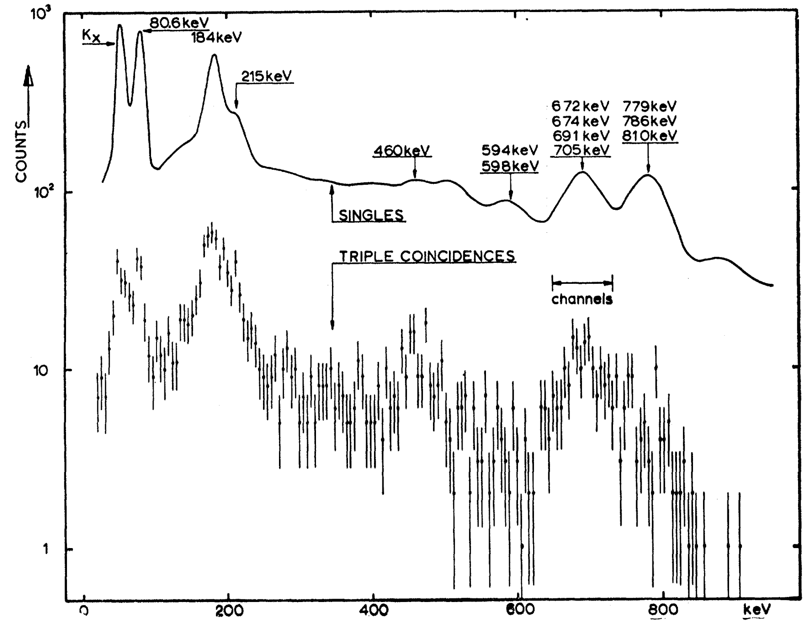

FIG. 7. γ-ray spectrum of Tm^{166} (7.7 h) measured in triple coincidence with pulses from two channels set on the peak at about 700 keV. These two channels will accept the full-energy peaks of the 672- and the 705-keV transitions. These transitions form a cascade which depopulates the 1458.9-keV state. Comparison of the coincidence spectrum and the singles spectrum shows that the 674- and the 460-keV transitions feeding the 1458.9-keV state, and also the 215.2-keV transition which feeds this level indirectly from the 2134-keV state via the 460-keV transition, are all accentuated in the coincidence spectrum.

the 1458.9-keV level will be accentuated when compared with a single measurement. From examination of Fig. 7, it is clear that the 460-keV transition, which is supposed to feed the 1458.9-keV state, stands out much more in the coincidence than in the singles spectrum. The composite peak at 700 and 800 keV is explained as resulting from the triple cascade 675, 673, and 705 or 786 keV, where the 675-keV transition is feeding the 1458.9-keV level from the 2134.3-keV state. The strong peak at 184 keV is probably caused by coincidences between Compton pulses of about 700 keV from the 1177-keV transition which is feeding the level at 956.4 keV and the 691-keV transition between this level and that at 265.0 keV. This cascade is strongly coincident with the 184-keV transition. In the coincidence spectrum it is also evident that the 184-keV peak is much wider than in the singles spectrum. One would expect this effect to be caused by the 215.2-keV transition which feeds the 1458.9-keV level indirectly via the 460-keV transition. Although the triple-coincidence spectrum shown in Fig. 8 represents the data collected during a 2.5-day run, the low counting rate does not allow a detailed analysis of this peak.

4. *1514.5-keV State*

Although only one transition seems to populate this 1514.5-keV state, four γ rays can be assigned to its depopulation—all very weak. The 403.8-keV transition which feeds the state from the 1918-keV level apparently has $M1$ character. The fact that the four depopulating transitions feed levels 2^+, 3^+, and 4^+ indicates that the state most probably has 3^- character.

5. *1530.1-keV State*

The 1530.1-keV level is populated by transitions from the 3^+ state at 2134.4 keV and the 3^- level at 1918.6 keV. Two depopulating transitions are observed decaying to the 80.6-keV and the 265.0-keV levels. The data are not decisive because of the low intensity of all of the transitions. However, the 1449.6-keV transitions seems to have $M1$ character, so that the assignment for the state is most likely 2^+ or 3^+. We are unable to make estimates of the conversion coefficients for either of the populating transitions.

6. *1572.4-keV State*

Three transitions are assigned to feeding the 1572.4-keV state and four to depopulating it. The transition from the 1704-keV state is ignored, because placement of that state is considered somewhat doubtful. The level is populated from the 2134.4-keV 3^+ state and the 1918.6-keV 3^- level. The state decays to the 3^+, 4^+, and 5^+ levels of the γ-vibrational band and perhaps to the 4^+ level of the ground-state band. The spin must be 2, 3, or 4 with even parity or 4 with odd parity. The latter choice is indicated tentatively as the preferred one, since there is some indication that the 496.6-keV transition has $E1$ character.

7. *1704-keV State*

Feeding to the 1704-keV state is indicated from the 2134.4-keV and the 2174.4-keV levels, but presence of the transition that might also be expected from the 2161.2-keV level cannot be excluded because it could not be observed under the intense 459.6-keV transition.

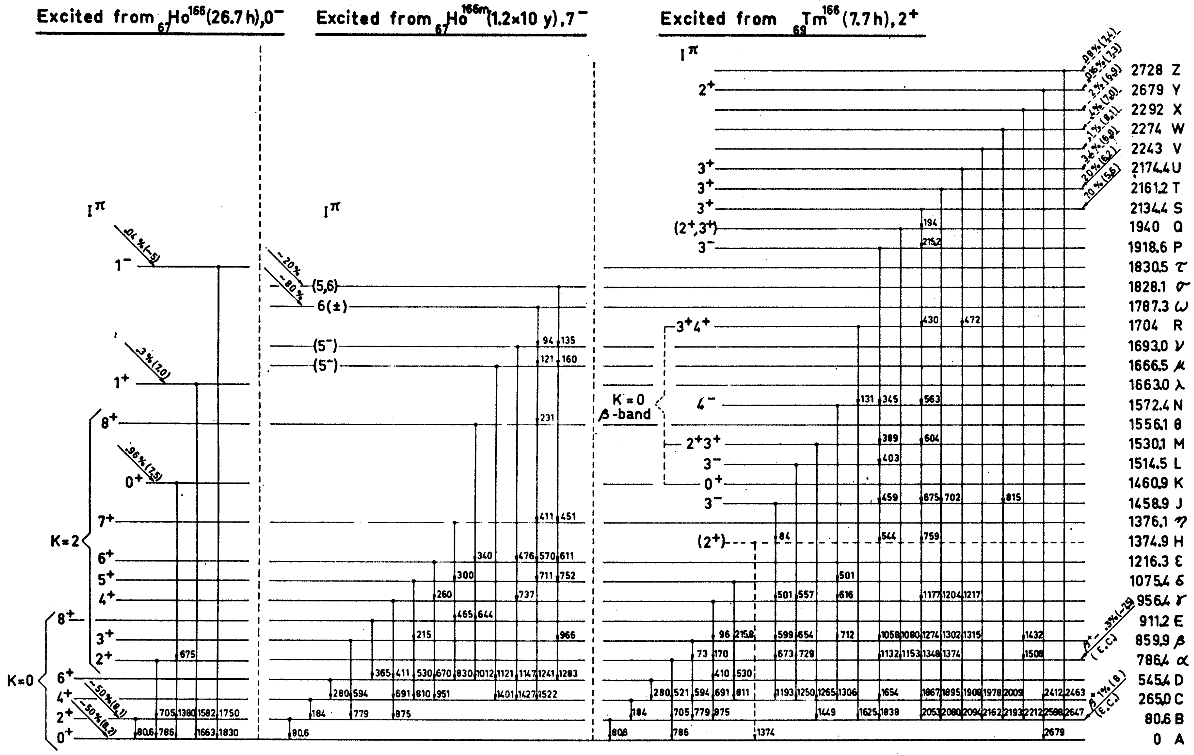

FIG. 8. Decay scheme of the levels in Er^{166} populated from Ho^{166} (26.7 h), Ho^{166m} (1.2×10^3 yr), and Tm^{166} (7.7 h). All 35 levels are spaced equally for reasons of clearness. The right-hand column gives the energies (keV) and the identification letters used in this report for each state. Spin and parity are listed at the left end of each line representing a particular state. The ground-state rotational band, the γ-vibrational band, and the possible β-vibrational band are indicated with brackets. The transitions leaving each level are indicated by arrows starting with a black dot. The entry at the end of each arrow is a rounded-off energy value for the transitions and is used for identification. The accurate energies and the intensities of the corresponding transitions can then be found in one of the tables. The slanting arrows indicating the β-ray feedings from Ho^{166} and from Tm^{166} are labeled with the branching ratios (%) and (in parentheses) the values of log*ft*. No log*ft* values are given for the feedings from Ho^{166m} because here the total energy is not known with sufficient accuracy.

Depopulation is observed only to the 80.6-keV state with the possible decay also to the 1375-keV level. Only tentative assignments of character can be made to the transitions, but over-all consideration of these available indications suggest either 3^+ or 4^+ assignment for the state.

8. 1918.6-keV State

Populated by the 215.2-keV transition from the 2134.4-keV state in about 6% of the total number of capture events, the 1918.6-keV level is depopulated by nine transitions to lower states. Consideration of the complete set of data leads to a spin and parity assignment of 3^- for the level.

The strongest arguments are the $E1$ character of the 215.2-keV transition and the $M1$ character of the 459.6-keV γ ray leading to the 3^- level at 1458.9 keV.

9. 1940-keV State

This 1940-keV level is populated from the 2134-keV state and is depopulated by the 1153.6- and the 1080-keV γ transitions to the first two members of the γ-vibrational band. As the 1153.6-keV γ ray is probably an $M1$ transition, the state will have 2^+ or 3^+ character.

10. 2134.4-keV State

The previously assigned 3^+ spin and parity for the 2134.4-keV state are confirmed.

11. 2161.2-keV State

The 3^+ spin and parity are indicated for the 2161.2-keV state as for the 2134.4-keV state.

12. 2174.4-keV State

The assignment 3^+ is made for the 2174.4-keV state because its behavior is observed to be quite similar to that of the other two nearby 3^+ levels. The relative intensity ratios with respect to the transitions decaying to the 2^+ and 4^+ members of the ground-state band relative to the corresponding transitions from these 3^+ states are very consistent. No transition is observed to the 786.4-keV level, but it does decay to the 860- and 956-keV levels.

13. 2243-, 2274-, 2292-, 2679-, and 2728-keV States

All of these levels are placed entirely on the basis of energy consideration of the very weak high-energy γ rays.

The three levels at 2243, 2274, and 2728 keV all decay to the 2^+ and 4^+ levels of the ground-state band. None of these levels decay to the ground state, so that 3^+ or 4^+ assignments for all three are preferred. The 2274-keV level also decays to the 3^- state at 1458.9 keV, but this fact does not alter the possible assignment of 3^+ or 4^+. Only the 2679-keV level decays to the ground state as well as to the first 2^+ and 4^+ levels. This suggests an assignment of 2^+. The level at 2292 keV decays to the 80.6-keV 2^+ state and to 2^+ and 3^+ states at 786 and 860 keV, again suggesting 3^+ as the most likely assignment.

B. Levels Populated in the Decay of Ho^{166} (26.7 h)

In agreement with the work of Cline *et al.*,[6] nine observed γ transitions are fitted into a system of five excited states in Er^{166}. Only our independent determination of the energy values of these levels is presented as original. Comments concerning the 80.6-keV 2^+, the 786.4-keV 2^+, and the 1460.9-keV 0^+ states are unnecessary. The directional-correlation measurements of Marklund[16] established the spin of the 1663.0-keV state to be 1, and the log *ft* of about 7 indicates a preference for even parity, as suggested in the Nuclear Data Sheets, and not odd parity, as indicated in several of the previous reports. The assignment of 1 for the spin of the 1830.5-keV state seems to be the only choice allowed by the log *ft* of 5.

C. Levels Populated in the Decay of Ho^{166m} (1.2×10^3 yr)

Of the 62 transitions listed in Table III, 42 are assigned among 14 of the excited states found in the decay scheme. Thirteen of these levels are identified with those reported by Reich and Cline[12] and the 1556-keV level is also reported by Gallagher *et al.*[17] There are, however, several new transitions observed between various of these levels. As in the other two studies, the energy values differ slightly from previous values.

In addition to the lower 2^+, 4^+, and 6^+ levels excited in the Tm^{166} decay, the 8^+ level at 911.2 keV is populated. The 2^+ 786.4-keV base of the γ-vibrational band is populated so weakly that transitions from it are not detectable. Estimates made from the measured intensity ratios in the Tm^{166} study show this result to be not inconsistent. In addition to the 3^+, 4^+, and 5^+ members of the γ band populated in the Tm^{166} decay, states at 1216.3, 1376, and 1556.1 keV are identified as 6^+, 7^+, and 8^+ members of the band. With regard to the last mentioned level, in addition to the three depopulating γ rays mentioned by Gallagher *et al.*,[17] we observe a feeding transition from the 1787-keV state.

1. 1666.5- and 1693.0-keV States

From the depopulating transitions to 4^+ and 6^+ states, both the 1666.5- and the 1693.0-keV levels must be limited to possible spin values of 4, 5, or 6. Preference is given to the value 5 for both states as earlier indicated. If the 7^- spin for the parent is accepted, the failure to observe β feeding to these states suggests odd parity.

2. 1787.3-keV State

If the very weak 231-keV transition is correctly placed between the 1787- and 1556-keV states, then the parity of the 1787-keV level should be even rather than odd; but the transition is so weak that this possibility should only be considered.

3. 1828.1-keV State

The 966.8-keV transition placed from the 1828-keV level to the 3^+ state at 860 keV, if properly assigned, suggests an assignment of 5^+ for the level—in contradiction with the 6^- assignment made by Reich and Cline.[12,18]

V. DISCUSSION

When considered together, the three parent nuclides Tm^{166}, Ho^{166}, and Ho^{166m} populate 4 excited states of the ground-state rotational band and 7 levels constituting the γ-vibrational band in Er^{166} (Fig. 8). The basic rules describing the expected intensity ratio between two γ transitions depopulating one level of the $K=2$ band to two different members of the $K=0$ band have been presented by Alaga.[19] The intensity ratios are expected to be altered if mixing of the two bands occurs and the phenomenon has been considered by a number of authors.[17,20,21] Of the 17 possible transitions which might occur between the two bands, 16 are seen in one or another of the three activities, although some are too weak to permit a determination of their intensity. The spins of the pairs of states between which the ratios of the corresponding γ transition intensities might be examined are indicated in column 1 of Table VII. In column 2, the theoretical ratios of the reduced transition probabilities (ratio of the squares of the appropriate Clebsch-Gordan coefficients) are listed. The form of the correction factor F, in terms of the

[16] I. Marklund, B. van Nooyen, and Z. Grabowski, Nucl. Phys. **15**, 533 (1960).

[17] C. J. Gallagher, Jr., O. B. Nielsen, and A. W. Sunyar, Phys. Letters **16**, 298 (1965).

[18] J. E. Cline and C. W. Reich, Phys. Rev. **129**, 2152 (1963).

[19] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 9 (1955).

[20] O. B. Nielsen, in *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Birks (Heywood and Company, Ltd., London, 1961), p. 317.

[21] P. Gregers Hansen, O. B. Nielsen, and R. K. Sheline, Nucl. Phys. **12**, 389 (1959).

TABLE VII. Determination of the mixing parameter z for the $K=0$ and $K=2$ rotational bands in Er^{166}. For each pair of transitions proceeding from one level of the γ-vibrational band J_i to two different members of the ground-state band J_{f1} and J_{f2}, the energy-corrected experimental intensity ratios (column 5) are used in conjunction with the geometric and mixing factors (columns 2 and 3) to calculate the values of the mixing parameter z. A weighted average of the results in column 6 yields a value $\bar{z}=0.045\pm0.003$.

$\frac{J_i\to J_{f1}}{J_i\to J_{f2}}$	$\frac{C^2(J_i\to J_{f1})}{C^2(J_i\to J_{f2})}$	$\frac{F_i}{F_2}$	$\frac{\Delta E_1}{\Delta E_2}$	$\frac{I(\gamma_1)}{I(\gamma_2)}\times\frac{E^5(\gamma_2)}{E^5(\gamma_1)}$ Tm^{166}	Ho^{166m}	Ho^{166}	Mixing parameter z Tm^{166}	Ho^{166m}	Ho^{166}
$\frac{2\to0}{2\to2}$	0.7000	$\frac{(1-z)^2}{(1+2z)^2}$	$\frac{786.4}{705.8}$	0.633±0.10		0.46±0.11	$0.017_{-0.017}^{+0.030}$		$0.072_{-0.038}^{+0.049}$
$\frac{2\to4}{2\to2}$	0.05002	$\frac{(1+9z)^2}{(1+2z)^2}$	$\frac{521.4}{705.8}$	?					
$\frac{2\to0}{2\to4}$	14.00	$\frac{(1-z)^2}{(1+9z)^2}$	$\frac{786.4}{521.4}$	?					
$\frac{3\to4}{3\to2}$	0.4000	$\frac{(1+6z)^2}{(1-z)^2}$	$\frac{594.9}{779.3}$	?	1.22 ±0.4			$0.096_{-0.039}^{+0.030}$	
$\frac{4\to2}{4\to4}$	0.3395	$\frac{(1-5z)^2}{(1+2z)^2}$	$\frac{875.8}{691.4}$	0.166±0.024	0.185 ±0.05		$0.047_{-0.008}^{+0.009}$	$0.040_{-0.015}^{+0.018}$	
$\frac{4\to6}{4\to4}$	0.08641	$\frac{(1+13z)^2}{(1+2z)^2}$	$\frac{411.1}{691.4}$	?	?				
$\frac{4\to2}{4\to6}$	3.929	$\frac{(1-5z)^2}{(1+13z)^2}$	$\frac{875.8}{411.1}$	?	?				
$\frac{5\to4}{5\to6}$	1.750	$\frac{(1-3z)^2}{(1+8z)^2}$	$\frac{810.4}{530.1}$	?	0.884 ±0.13			$0.033_{-0.007}^{+0.008}$	
$\frac{6\to4}{6\to6}$	0.2692	$\frac{(1-9z)^2}{(1+2z)^2}$	$\frac{951.3}{671.0}$		0.0898±0.017			$0.042_{-0.006}^{+0.006}$	
$\frac{6\to8}{6\to6}$	0.1058	$\frac{(1+17z)^2}{(1+2z)^2}$	$\frac{305.1}{671.0}$						
$\frac{6\to4}{6\to8}$	2.546	$\frac{(1-9z)^2}{(1+17z)^2}$	$\frac{951.3}{305.1}$						
$\frac{7\to8}{7\to6}$	0.6667	$\frac{(1+10z)^2}{(1-5z)^2}$	$\frac{464.9}{830.8}$		2.92 ±0.63			$0.053_{-0.009}^{+0.007}$	
$\frac{8\to6}{8\to8}$	0.2395	$\frac{(1-13z)^2}{(1+2z)^2}$	$\frac{1010.8}{644.9}$		?				

mixing parameter z, is shown for each case in column 3. In column 4, the energies of the γ transitions are tabulated (the values entered are differences in energies assigned to the various levels rather than measured γ-ray energies). The experimental intensity ratios, corrected for energy dependence, are listed for each activity in column 5; these data are taken from Tables II, IV, and VI. Where the spaces are left blank, one or the other of the needed γ transitions was not observed. In the spaces where question marks appear, both γ rays were observed but it was believed that the intensities were too uncertain to justify making the calculation. In column 6, the calculated values of the mixing parameter z are shown. From the eight independent values listed, a weighted average $\bar{z}=0.045\pm0.003$ is obtained, where the uncertainties were treated as statistical. This result is in agreement with the value of 0.047 determined by Reich and Cline[12] and that of 0.050 determined in the study by Gallagher *et al.*[17]

The rotational $E2$ transition rates relative to the vibrational transition rates have been calculated for eight cases and the results summarized in Table VIII.

TABLE VIII. Determination of intraband rotational $E2$ transition rates in the γ-vibrational band relative to transitions to levels in the $K=0$ ground-state band. The weighted average value of the entries in column 6 is

$$B(E2)\text{-Rot}/B(E2)\text{-Vibr}=45.5\pm3.$$

Intraband / Interband: J_iK_i—Rot → J_fK_f / J_iK_i—Vibr → J_fK_f	γ energy: E_γ(Rot) / E_γ(Vibr)	Intensity ratio: $\frac{I_{\gamma r}}{I_{\gamma v}}\times\frac{E_{\gamma v}^5}{E_{\gamma r}^5}$	Geometric factor: C^2(Vibr) / C^2(Rot)	Mixing factor $F(z=0.045)$	$B(E2)$ ratio: Rotational / Vibrational
4,2 → 2,2 / 4,2 → 2,0	170.2 / 875.3	59.4 ±10	Tm^{166} / 1.000	$(1-5z)^2=0.601$	36± 6
4,2 → 2,2 / 4,2 → 4,0	170.2 / 691.8	9.85± 1.7	Ho^{166m} / 2.945	$(1+2z)^2=1.19$	34± 6
5,2 → 3,2 / 5,2 → 4,0	215.2 / 810.8	45.5 ± 7.3	1.666	$(1-3z)^2=0.748$	57± 9
5,2 → 3,2 / 5,2 → 6,0	215.2 / 530.1	40.2 ± 6	0.9524	$(1+8z)^2=1.85$	71±11
6,2 → 4,2 / 6,2 → 4,0	260.1 / 951.6	364 ±110	0.4167	$(1-9z)^2=0.354$	54±18
6,2 → 4,2 / 6,2 → 6,0	260.1 / 670.4	32.7 ±11	1.548	$(1+2z)^2=1.19$	60±20
7,2 → 5,2 / 7,2 → 6,0	300.6 / 830.8	66.5 ± 8.6	1.138	$(1-5z)^2=0.601$	45± 6
7,2 → 5,2 / 7,2 → 8,0	300.6 / 465.0	22.8 ± 5	0.7583	$(1+10z)^2=2.10$	36± 8

The intraband and interband transitions for which the ratio of intensities is examined are specified by the spins of the states between which they occur in column 1. In columns 2 and 3 the energies and corrected intensity ratios are listed. The geometric factors are tabulated in column 4, and in column 5 the factors used to correct the vibrational transitions for band mixing are shown. The value $z=0.045$ used for the mixing parameter is that determined in this study. The results are shown in column 6 and a weighted average of the eight numbers yields a mean value of 45.5±3 for the ratio of the rotational $E2$ transition probability within the γ band relative to the vibrational transitions to the $K=0$ ground-state band. This result concurs with that of Gallagher *et al.*, who find a value of 43±5.

The excited states of the ground-state band as well as the seven members of the γ-vibrational band are compared with the relation

$$E_I-E_0=AI(I+1)+BI^2(I+1)^2+CI^3(I+1)^3.$$

In both cases ($K=0$ and $K=2$), the function containing either two or three parameters was fitted to the data. The results of these calculations are presented in Table IX. The errors associated with the parameters

TABLE IX. Comparison of the relative magnitudes of the second- and third-order correction terms in $I(I+1)$ needed to describe the rotational states in the ground-state and γ-vibrational bands. The tabulated values of A, B, and C are the results of making least-squares fits of the indicated function (containing either two or three parameters) to the experimentally determined energies of the states in each band. Function fitted: $E_I-E_0=AI(I+1)+BI^2(I+1)^2+CI^3(I+1)^3$.

K	Number of parameters	A (keV)	B (eV)	C (eV)	B/A	C/A
0	2	13.479±0.010	−11.523±0.212		0.855×10^{-3}	
	3	13.506±0.018	−13.229±0.936	0.0195±0.010	0.979×10^{-3}	1.44×10^{-6}
2	2	12.378±0.030	− 9.251±0.447		0.747×10^{-3}	
	3	12.432±0.078	−11.268±2.737	0.0191±0.026	0.906×10^{-3}	1.54×10^{-6}

should be considered somewhat qualitative in nature, since there is obviously some difficulty in assigning statistically meaningful uncertainties to the energies of the states. The ratios of B/A and C/A are shown in the last two columns of the table in order to compare the relative significance of the correction terms. It is of particular interest to note that the relative magnitude of the third-order term C, as well as that of B, is very nearly the same for both bands, albeit C is very small in both cases. A plot (not shown) of

$$(E_I-E_K)/[I(I+1)-K(K+1)]$$

as a function of $I(I+1)+K(K+1)$ was made for the $K=0$ and $K=2$ bands. Both sets of data manifest a comparable departure from linearity with a very slight convexity toward the $I(I+1)$ axis. The consistently similar behavior of the two sets of states suggest that we must arrive at the same decision for both bands, although, within the uncertainties of the measurements, one might conclude that the coefficient C is zero in either case. In our opinion that the third-order correction term is needed in the ground-state band as well as in the γ vibrational band, although the evidence in support of this conclusion is not strong. This interpretation differs somewhat from that reached by Gallagher *et al.*,[17] who stated that the third-order correction was "clearly needed" for the γ-vibrational band but probably not for the ground-state band. The more positive conclusion by those authors can probably be explained by the fact that there is a systematic deviation in the energy values assigned in the two studies. In the earlier paper,[17] the energies of the $K=0$ band are uniformly slightly lower than our own, while the first few states of the γ band lie somewhat higher. This latter trend tapers off for the higher spin states, which again have energies lower than those assigned in this study.

The two levels at 1530.1 and 1704 keV populated in the decay of Tm^{166} may possibly be the 2^+ and 4^+ members of a β-vibrational band based upon the 0^+ band head at 1460.9 keV. (The latter state is not populated in the Tm decay, but has been well established in the studies on the 26.7-h Ho^{166}.) Both levels decay only to members of the ground-state band while no transitions to the γ-vibrational band are seen.

The six states assigned at 1374.9, 1458.9, 1514.5, 1572.4, 1918.6, and 1940 keV were examined but seem to manifest no clear evidence of band structure. We find six weakly populated levels above the two well-known states at 2134 and 2161 keV. Only the one at 2292 keV de-excites mainly to the first members of the γ-vibrational band; the other five decay primarily to the ground-state band. So far as our present knowledge extends, the levels at 1375, 1704, 2174, 2243, 2274, 2679, and 2728 keV have not been reported earlier. (Note last paragraph of this section.)

The present determination of the K-conversion coefficients of the transitions depopulating the 2134- and the 2161-keV levels once more indicate the positive parity of these states. Thus, it seems that the ground state of Tm^{166} has indeed a 2^+ character (the spin 2 is measured in an atomic-beam experiment[22]). The high $\log ft$ value (≈ 8) of the β transition to the 80.57-keV level may result from K forbiddenness. The high $\log ft$ value (≈ 8) of the transition to the 786.4-keV level remains unexplained.

Most of the energy levels found in this study are deduced from energy and intensity fits, without corroborative coincidence data. Several other possible levels are not discussed here nor mentioned in the decay scheme. These levels, obtained in the same way, are only omitted because of a slightly less favorable energy or intensity fitting. The energies of these possible states would be 1014, 2002, and 2022 keV.

In the decay of the two holmium activities, no new energy levels are found in the present investigation. It seems probable that the 1663.0-keV level excited from the Ho^{166} (26.7 h) activity has 1^+ character. The spin of 1 is established from directional-correlation measurements[9] and, although the state has been assigned odd parity in several earlier publications, we believe the value[5] $\log ft=7.1$ clearly favors assignment of even parity to the state.

The spin of 6 assigned to the state at 1787.3 keV in Ho^{166m} (1.2×10^3 yr) is the only choice compatible with the depopulating γ transitions and concurs with the directional-correlation measurements.[12] In the work of Cline and Reich,[18] odd parity is assgined to the state on the basis of the probable $E1$ character of some of the transitions. In the present study, we find two additional γ transitions present: the 1522-keV to the 4^+ state at 265 keV and the weak 231.5-keV transition to the 8^+ state at 1556 keV. If the odd parity is correct, these transitions must have $M2$ character, which, though not impossible, is highly improbable. In addition, the $\log ft$ value of approximately 8 for the β-decay branch to the 1787-keV level is more consistent with even rather than odd parity for this level. We therefore submit that at this time the parity of the 1787-keV state remains in doubt. A tentative spin of 5^+ is proposed for the state at 1828.1 keV because of the 966.8-keV transition which populates the 3^+ state at 859.9 keV. Because of the very low energy (approximately 27 keV) of the β transition to the 1828.1-keV state, there is insufficient knowledge of the limits on the $\log ft$ value to permit consideration of that datum in evaluating the properties of this state.

No new transitions are found in Tm^{166} from the decay of Yb^{166} (57 h).

During the final phase of the preparation of this paper, Zylicz *et al.*[23] published an extensive study on the decay of Tm^{166}. Their work and our own concur in

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placement of the levels at 1458.9, 1514.5, 1530.1, 1572.4, 1918.6, 1940, and 2292 keV.

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$K/(L+M+\cdots)$ Ratio of the 355-keV Transition in ^{133}Cs

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The $K/(L+M+\cdots)$ internal-conversion ratio for the 355-keV transition in ^{133}Cs has been measured as 4.27 ± 0.13. Interference of K-shell electrons from the 382-keV transition was eliminated by standard fast-slow coincidence techniques using pulses from a Si(Li) detector at 77°K and NaI(Tl) scintillator. The experimental result indicates the multipolarity of the 355-keV transition to be (97.5% $E2$, 2.5% Max $M3$) when compared with existing tabulations of internal-conversion coefficients (ICC) compared with predictions made using Coulomb-screened ICC calculations, a predominantly $M3$ multipolarity is implied. In either case no $M1$ contribution is evidenced and the spin of the 436-keV level is verified as $\frac{1}{2}^+$, allowing this level to be interpreted in terms of the shell model, as a single-particle excitation to an $s_{1/2}$ state.

I. INTRODUCTION

THE nuclide ^{133}Ba decays by orbital electron capture to ^{133}Cs which in turn de-excites by emission of γ rays having energies at or near 54, 79, 81, 160, 276, 302, 355, 382, and 436 keV.[1] Excited levels have been found in the ^{133}Cs nucleus at 81, 160, 382, and 436 keV. (See Fig. 1) The ^{133}Cs nucleus has a particular interest because these low-lying levels, with one exception, may be interpreted as single-particle excitations in terms of the shell model. This paper is concerned with the 355-keV transition which connects the levels at 436 and 81 keV. On the basis of the shell model these levels are interpreted as $s_{1/2}$ and $d_{5/2}$, respectively.[2] Most previous measurements of the spins and parities of these levels agree with these predictions.[3] However, the spin assignment of $\frac{1}{2}^+$ to the 436-keV level has been questioned by Subba Rao[4] on the basis of a measurement of the directional correlation between the 355-keV γ ray and the conversion electron from the 81-keV transition. He concludes that the spin of the 436-keV level is $\frac{3}{2}^+$ and that the multipolarity of the 355-keV transition is 0.7 $M1$+0.3 $E2$. The conversion electron from the 81-keV transition is now thought to be seriously influenced by nuclear-penetration effects.[5] Also, the l-forbidden character of this transition evidenced by the 6.3-nsec lifetime of the 81-keV level, suggests that measurements involving conversion electrons from this transition should not be used in the assignment of spins, multipolarities, and mixing ratios because the theoretical calculations of conversion coefficients and directional correlation particle parameters are ambiguous when nuclear-structure effects are important.

Recently the directional correlation between the conversion electron from the 355-keV transition and

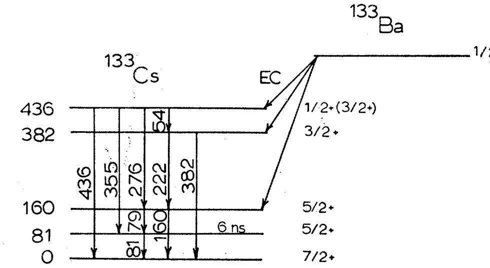

FIG. 1. Decay scheme of ^{133}Ba.

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