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Levels in ^{165}Tm Excited by Decay of 10-min ^{165}Yb and by the ^{158}Gd(^{11}B, 4$n\gamma$) Reactions*

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The levels of the deformed nucleus ^{165}Tm were studied both by β decay and by heavy-ion in-beam γ-ray spectroscopy. In addition to confirming the four lowest bands $\frac{1}{2}+[411]$, $\frac{7}{2}+[404]$, $\frac{7}{2}-[523]$, and $\frac{1}{2}-[541]$, evidence is obtained for the $\frac{5}{2}+[402]$ and $\frac{3}{2}+[411]$ bands, and many other higher levels. Several higher members of the ground band are shifted in energy from earlier proposals. Comparison is made with theory both with regard to rotational spacing parameters and to band-head energies.

[RADIOACTIVITY ^{165}Yb; measured E_γ, I_γ, $\gamma\gamma$ coin. ^{165}Tm deduced levels, J, π, K, logft.
NUCLEAR REACTIONS ^{158}Gd(^{11}B, 4n), E=47.5–88 MeV; measured E_γ, $I_\gamma(\theta)$, $\gamma\gamma$ coin. ^{165}Tm deduced levels, J, π, K.]

I. INTRODUCTION

The odd-mass thulium isotopes form a most interesting series from the standpoint of nuclear theory. Three Nilsson bands have been identified and traced[1-3] across the series from mass 165 through 171. These are the ground band $\frac{1}{2}+[411]$ and excited bands $\frac{7}{2}+[404]$ and $\frac{7}{2}-[523]$. (Bands are designated by the usual Nilsson asymptotic quantum numbers $\Omega\pi[N, n_z, \Lambda]$.) The energy separations of these bands shift in ways not readily explainable in terms of simple deformation shifts in the Nilsson model. The ground-band properties[4] have been extensively studied, especially for stable ^{169}Tm, where Mössbauer scattering and Coulomb excitation are available tools.

We initiated twofold studies of ^{165}Tm via radioactivity and heavy-ion in-beam γ spectroscopy at the Yale Heavy Ion Accelerator Laboratory at a time when the information on this nucleus was limited. There had been a few decay-scheme studies[5-8] of the radioactivity of parent ^{165}Yb, made difficult by its inconveniently short half-life of 10 min. We reported preliminary results of our studies earlier.[9] Before completion of our work, the independent in-beam γ studies of the Grenoble group of Gizon *et al.*[10] were published, nicely establishing four rotational band sequences up to high spin. Our in-beam studies confirm their assignments except for some changes above the $\frac{7}{2}$ spin in the ground band, and our γ angular distributions confirm multipolarity assignments. The complex radioactive decay populates many additional levels not observed by the in-beam work, thus providing a nice complementarity. After completion of our work a new independent study of the radioactive decay was reported by Adam *et al.*[11] This report shows only the decay to the lower levels, in complete agreement with our work, but it supplements our work in that conversion electron and positron spectroscopy were performed, offering direct assignments of multipolarities and a needed redetermination of the positron end point. In Ref. 11 the ground-state energy is about 2 keV lower than we propose. There is insufficient detail in the very brief Ref. 11 to resolve this discrepancy, for no electron or γ spectra or tables are presented.

II. EXPERIMENTAL METHODS OF RADIOACTIVITY STUDY

The ^{165}Yb sources were produced by the ^{159}Tb (^{11}B, 5n) reaction with ^{11}B ions accelerated in the Yale heavy-ion accelerator (HIA). The thickness of the metallic terbium target was ~5–7 mg/cm^2 and the beam energy of ^{11}B ions was degraded from 116 to 60 MeV with aluminum and terbium absorbers to enhance the (^{11}B, 5n) reaction over the 4n and 6n reactions.

Both in the γ-ray singles and coincidence measurements, 40-cm^3 Ge(Li) detectors in conjunction with pulse pileup rejection amplifier chains were employed. The over-all system energy resolution was 1.5 keV full width at half maximum at 100 keV. A conventional fast-slow coincidence setup with 40-ns time resolution was used, the fast signals being used to trigger a time-to-height converter. The three signals for each coincidence event, namely, the energy of the first γ ray, the energy of the second one, and the time elapsed between the γ rays, were digitized and recorded serially on magnetic tape by a PDP 8/I computer system. The various coincidence relationships were unraveled by sorting through the tape after the experiments.

Complementary to the ^{159}Tb(^{11}B, 5n) reaction, the ^{169}Tm (p, 5n) reaction was utilized to observe the γ rays in the ^{165}Yb decay with an appreciable reduction of ^{164}Tm impurity. The 50-MeV proton beam was accelerated in the synchrocyclotron at the Institute for Nuclear Study, University of Tokyo.

For the energy and intensity calibrations, ^{177}Lu^m and the International Atomic Energy Agency standard sources were employed in the Yale experiments, while ^{110}Ag^m, ^{133}Ba, ^{152}Eu, ^{168}Tm, and ^{170}Tm were used at the Institute for Nuclear Study.

Following the experiments, the γ-ray spectra were analyzed for peak positions, area, and γ-ray energies using the computer programs SAMPO[12] on the Yale Computer Center's 7040-7094 DCS system and BOB[13] on the FACOM 230/60 system.

III. EXPERIMENTAL METHODS OF IN-BEAM γ SPECTROSCOPY

The experimental techniques employed in this investigation are similar to those described previously.[14] Usually three separate experiments are performed: excitation function measurements, γ-γ coincidences, and γ angular distributions. For all of these experiments, an 8.6-mg/cm^2 metallic ^{158}Gd (97.6% enriched) target obtained from the Oak Ridge National Laboratory was irradiated with a ^{11}B beam from the Yale HIA. For the excitation function measurements, ^{11}B beam energies of 47.5, 52, 60, 64.5, 70, and 88 MeV were used, the γ-ray spectra being observed at 55° with respect to the incident beam by a 40-cm^3 Ge(Li) detector.

For the γ-γ coincidence experiment, two 40-cm^3 Ge(Li) detectors were placed at 90° relative to the incident beam, each approximately 2 cm from the target, thus subtending a substantial solid angle, though open to spurious coincidences from Compton scattering events.

The angular distribution of γ rays was measured by placing the target in a thin-walled (0.5-mm aluminum) cylindrical chamber 5 cm in diameter. The beam and any particles recoiling from the target were stopped by a 150-mg/cm^2 lead foil, curved to a radius of 0.5 cm, and placed 0.5 cm behind the target. γ measurements were made at angles of 0, 30, 45, 60, and 90° with respect to the beam, at a distance of 3.75 cm from the target. The target Gd K x-ray intensities were used for normalization of the spectra.

Calibrations of detectors and analyses of γ-ray spectra were performed as described in Sec. II.

IV. RADIOACTIVITY RESULTS

By repeated bombardments and decay curve counting it was possible to assign nearly a hundred γ lines to the decay of ^{165}Yb. Principal interfering activities are the decay of 30.1-h ^{165}Tm itself and the activities in the adjacent mass chains 76-min ^{164}Yb and its daughter, 1.9-min ^{164}Tm, and 57.5-h ^{166}Yb and its daughter, 7.7-h ^{166}Tm, and 18-min ^{167}Yb and its daughter 9.6-day ^{167}Tm. Figures 1(a)–1(c) show the singles γ-ray spectra of ^{165}Yb.

The first column of Table I lists the γ rays assigned from singles spectra to the decay of ^{165}Yb, (Table II is a supplementary γ-ray list of transitions inferred later from coincidence results or decay-scheme considerations.) The energies are listed as determined and not readjusted in light of the proposed level scheme. The γ energies listed on the proposed level schemes are those determined by exact subtraction of proposed level energies. Thus, a comparison of the energy consistency of the level scheme is readily made. Where a dual assignment of a γ ray has been made, asterisks are placed in the level scheme.

Column 2 lists the γ-ray intensities relative to the 80.1-keV γ ray, taken as 100. Both energies and intensities were obtained from least-squares fitting of the peaks by the Berkeley routine SAMPO[12] and by BOB.[13]

Column 3 lists assignments of initial and final states in the level scheme with the notation giving the spin, the K (angular momentum projection) value, and parity of the initial and final states, separated by the solidus. In cases where complete quantum number assignments could not be made, the energy of the level serves to specify the assignment. Multiple assignments of presumably unresolved lines are bracketed.

With the large number of γ rays of ^{165}Yb it was crucial to have extensive coincidence measurements. Using the three-dimensional (γ-γ-time) event-by-event tape recording of coincidences on the Yale HIA computer and using many source preparations, it was possible to accumulate sufficient events to be statistically significant for all the stronger transitions. It is not practical here to present all the data, for even a tabular summary would be lengthy and possibly misleading in cases of low statistics. Three representative coincidence sorts are shown in Figs. 2(a)-2(c). Contribution from the Compton pedestal backgrounds have been subtracted out by gating on flat portions of the spectra near the gate lines. Other coincidence results can be read from the level-scheme diagram, where solid dots indicate the coincidence relationships.

We have not carried out new measurements of conversion electrons or positrons but would note here the essential results from earlier work published by Paris,[7] by Tamura,[8] and by Adam *et al.*[11]

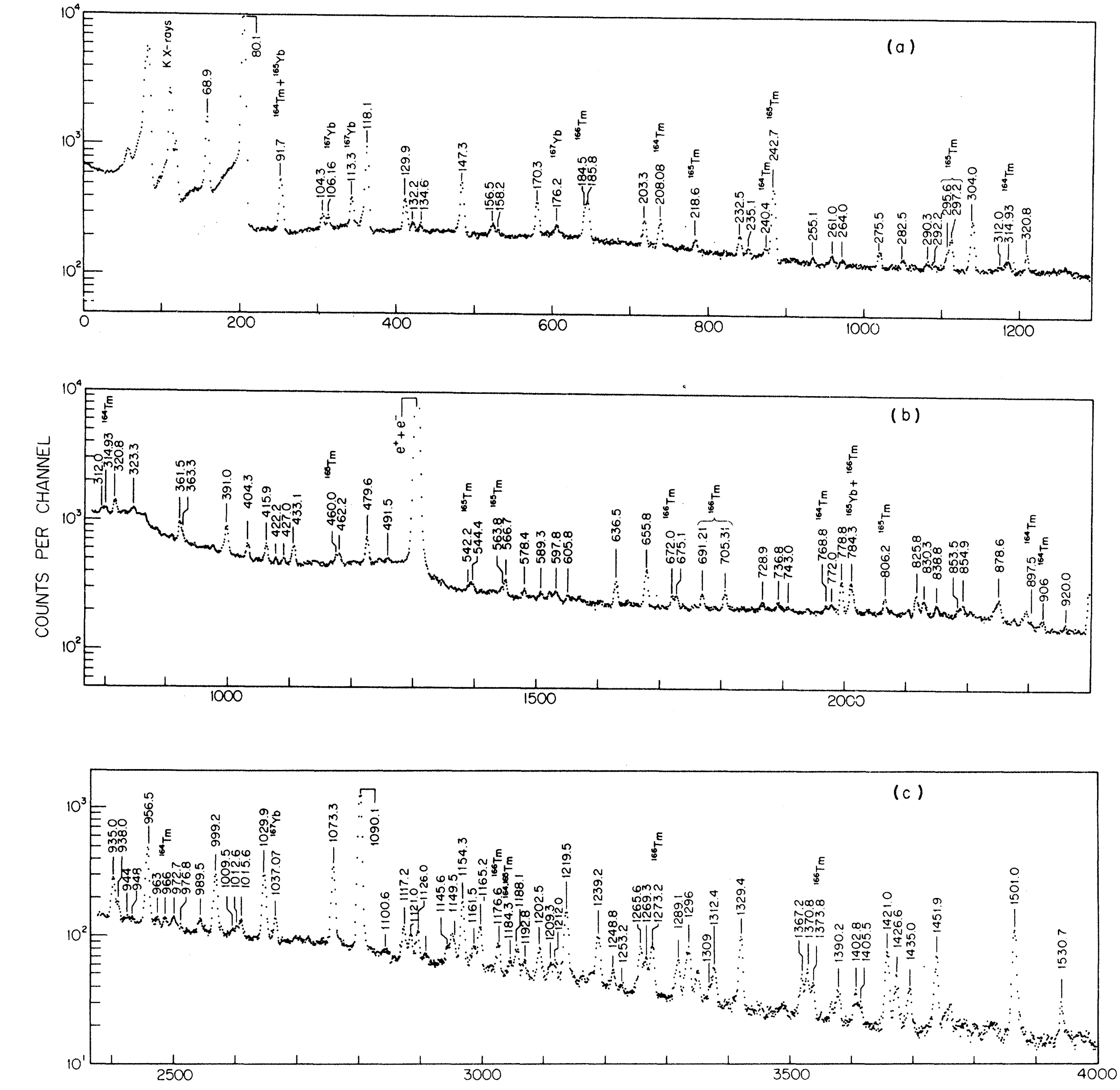

FIG. 1. (a)–(c) Singles γ-ray spectrum of radioactive decay of 10-min ^{165}Yb. Shown is the sum of spectra from three separate irradiations. Each of the three was observed over the time interval 5 to 25 min after the end of 10-min bombardments of Tb targets with ^{11}B ions; (a), (b), and (c) are the corresponding spectra for the low-, medium-, and high-energy parts for the sources produced by the ^{169}Tm(p, $5n$) reaction. The figure labels the ^{165}Yb lines by energy (keV) only and the peaks of contaminants by energy and isotopic label. Decay curves were followed to establish isotopic assignment of the lines.

TABLE I. γ rays in ^{165}Yb decay studies.

E_γ	I_γ	Assignment Initial/final state $IK\pi$ or E (keV)
30.8 ± 0.1	W	$(\frac{7}{2}\frac{7}{2}-/\frac{5}{2}\frac{1}{2}+)$ [a]
68.9 ± 0.1	17	$\frac{7}{2}\frac{7}{2}+/\frac{3}{2}\frac{1}{2}+$
80.1 ± 0.1	100	$\frac{7}{2}\frac{7}{2}-/\frac{7}{2}\frac{7}{2}+$
91.7 ± 0.1	1.2	$\frac{9}{2}\frac{7}{2}-/\frac{7}{2}\frac{7}{2}-$ [b]
104.3 ± 0.1	0.40	$\frac{7}{2}\frac{5}{2}+/\frac{5}{2}\frac{5}{2}+$
118.1 ± 0.1	4.8	$\frac{5}{2}\frac{1}{2}+/\frac{3}{2}\frac{1}{2}+$
129.9 ± 0.1	1.1	$\frac{5}{2}\frac{1}{2}+/\frac{1}{2}\frac{1}{2}+$ $\frac{9}{2}\frac{7}{2}+/\frac{7}{2}\frac{7}{2}+$
132.2 ± 0.1	0.20	$\frac{9}{2}\frac{5}{2}+/\frac{7}{2}\frac{5}{2}+$
134.6 ± 0.1	0.18	$\frac{9}{2}\frac{1}{2}-/\frac{7}{2}\frac{1}{2}+$
147.3 ± 0.1	1.8	$\frac{7}{2}\frac{1}{2}+/\frac{3}{2}\frac{1}{2}+$
156.5 ± 0.1	0.29	$\frac{5}{2}\frac{5}{2}+/\frac{7}{2}\frac{1}{2}+$
158.2 ± 0.1	0.13	
170.3 ± 0.1	1.1	$\frac{5}{2}\frac{1}{2}-/\frac{3}{2}\frac{1}{2}+$
185.8 ± 0.3	0.64	$\frac{5}{2}\frac{5}{2}+/\frac{5}{2}\frac{1}{2}+$
203.3 ± 0.1	0.55	$\frac{9}{2}\frac{1}{2}+/\frac{7}{2}\frac{1}{2}+$
208.0 ± 1.0	Masked	$\frac{11}{2}\frac{7}{2}-/\frac{7}{2}\frac{7}{2}-$ [c]
232.5 ± 0.2	0.37	$\frac{9}{2}\frac{1}{2}+/\frac{5}{2}\frac{1}{2}+$
235.1 ± 0.2	0.13	$\frac{5}{2}\frac{5}{2}+/\frac{7}{2}\frac{7}{2}+$
255.1 ± 0.2	0.10	$\frac{11}{2}\frac{1}{2}+/\frac{7}{2}\frac{1}{2}+$ (1582.0/1326.5)
261.0 ± 0.2	0.13	$\frac{7}{2}\frac{5}{2}+/\frac{7}{2}\frac{1}{2}+$
264.0 ± 0.5	VW	$(\frac{3}{2}\frac{1}{2}-/\frac{3}{2}\frac{3}{2}+)$
275.5 ± 0.2	0.30	$\frac{3}{2}\frac{1}{2}-/\frac{1}{2}\frac{1}{2}+$
282.5 ± 0.5	W	
290.3 ± 0.5	0.10	$\frac{7}{2}\frac{5}{2}+/\frac{5}{2}\frac{1}{2}+$
292.2 ± 0.5	0.04	
304.0 ± 0.1	1.60	$\frac{5}{2}\frac{5}{2}+/\frac{3}{2}\frac{1}{2}+$
312.0 ± 1.0	0.15	
320.8 ± 1.0	0.36	$\frac{7}{2}\frac{1}{2}-/\frac{5}{2}\frac{1}{2}+$
332.3 ± 0.5	W	$491.2/\frac{7}{2}\frac{1}{2}+$
361.5 ± 0.3	0.34	$491.2/\frac{5}{2}\frac{1}{2}+$
363.3 ± 0.5	0.14	$725.1/\frac{9}{2}\frac{1}{2}+$
391.0 ± 0.2	0.53	
404.3 ± 0.2	0.26	1014.2/609.5
415.9 ± 0.2	0.27	
422.2 ± 0.3	0.05	
427.0 ± 0.5	0.06	
433.1 ± 0.1	0.31	$592.2/\frac{7}{2}\frac{1}{2}+$
462.2 ± 0.2	0.12	$592.2/\frac{5}{2}\frac{1}{2}+$
479.6 ± 0.2	0.50	$491.2/\frac{3}{2}\frac{1}{2}+$ $609.5/\frac{5}{2}\frac{1}{2}+$
491.5	W	$491.2/\frac{1}{2}\frac{1}{2}+$
544.4 ± 0.3	0.07	
566.7 ± 0.5	0.16	$725.8/\frac{7}{2}\frac{1}{2}+$
578.4 ± 0.5	0.10	
589.3 ± 0.7	W	1315.0/725.1
597.8 ± 0.5	0.04	$609.5/\frac{3}{2}\frac{1}{2}+$
605.8 ± 0.2	0.05	
636.5 ± 0.3	0.33	$1188.8/\frac{9}{2}\frac{5}{2}+$
655.8 ± 0.3	0.58	$950.0/\frac{5}{2}\frac{1}{2}-$
675.1 ± 0.1	0.13	
728.9 ± 0.5	0.07	
736.8 ± 0.5	0.09	
743.0 ± 0.5	0.03	
772.0 ± 0.5	0.09	
784.3 ± 0.5	0.52	$1100.5/\frac{5}{2}\frac{5}{2}+$
825.8 ± 0.5	0.35	$1037.8/\frac{9}{2}\frac{7}{2}+$
830.3 ± 0.5	0.29	$1013.1/\frac{5}{2}\frac{1}{2}-$
838.8 ± 0.5	0.11	
853.5 ± 1.0	0.06	
854.9 ± 1.0	0.05	$1014.2/\frac{7}{2}\frac{1}{2}+$
878.6 ± 1.0	0.39	1370.4/491.2 $1037.8/\frac{7}{2}\frac{7}{2}-$
920.0 ± 1.0	0.04	
935.0 ± 0.3	0.69	$1251.0/\frac{5}{2}\frac{5}{2}+$
938.0 ± 0.5	0.21	
944.0 ± 1.0	0.06	
948.0 ± 1.0	0.05	
956.5 ± 0.2	1.71	$1037.8/\frac{7}{2}\frac{7}{2}+$ $1326.5/\frac{11}{2}\frac{7}{2}-$
963 ± 1.0	0.05	
972.7 ± 0.5	0.07	
976.8 ± 1.0	0.04	
989 ± 1.0	0.09	

TABLE I (*Continued*)

E_γ	I_γ	Assignment Initial/final state $IK\pi$ or E (keV)
999.2 ± 0.1	1.10	1315.0/$\frac{5}{2}\,\frac{5}{2}+$ 1129.1/$\frac{5}{2}\,\frac{1}{2}+$
1002.5 ± 0.5	0.04	
1009.5 ± 1.0	0.06	
1012.6 ± 0.5	0.10	
1015.6 ± 0.2	0.17	
1029.9 ± 0.1	1.22	1582.0/$\frac{9}{2}\,\frac{5}{2}+$ 1188.8/$\frac{7}{2}\,\frac{1}{2}+$
1073.3 ± 0.1	1.44	1326.5/$\frac{9}{2}\,\frac{7}{2}-$
1090.1 ± 0.1	7.00	1251.0/$\frac{7}{2}\,\frac{7}{2}-$ 1100.5/$\frac{3}{2}\,\frac{1}{2}+$
1100.6 ± 1.0	0.1	1100.5/$\frac{1}{2}\,\frac{1}{2}+$ 1283.4/$\frac{5}{2}\,\frac{1}{2}-$
1117.2 ± 0.2	0.36	1129.1/$\frac{3}{2}\,\frac{1}{2}+$
1121.6 ± 0.2	0.24	1251.0/$\frac{5}{2}\,\frac{1}{2}+$
1126.0 ± 0.2	0.16	1308.7/$\frac{5}{2}\,\frac{1}{2}-$ 1283.4/$\frac{7}{2}\,\frac{1}{2}+$
1145.6 ± 0.5	0.013	
1149.5 ± 0.5	0.013	1308.7/$\frac{7}{2}\,\frac{7}{2}-$ 1308.7/$\frac{7}{2}\,\frac{1}{2}+$
1154.3 ± 0.3	0.68	
1161.5 ± 0.5	0.19	1582.0/$\frac{7}{2}\,\frac{5}{2}+$
1165.2 ± 0.2	0.37	1326.5/$\frac{7}{2}\,\frac{7}{2}-$
1188.1 ± 0.2	0.22	1370.4/$\frac{5}{2}\,\frac{1}{2}-$
1192.8 ± 0.2	0.12	1352.6/$\frac{7}{2}\,\frac{7}{2}-$
1202.5 ± 0.2	0.23	1283.4/$\frac{7}{2}\,\frac{7}{2}+$ 1565.0/$\frac{9}{2}\,\frac{1}{2}+$
1209.3 ± 0.3	0.11	
1212.0 ± 0.3	0.11	1370.4/$\frac{7}{2}\,\frac{1}{2}+$
1219.5 ± 0.5	0.83	1582.0/$\frac{9}{2}\,\frac{1}{2}+$
1239.2 ± 0.5	0.44	1251.0/$\frac{3}{2}\,\frac{1}{2}+$
1248.8 ± 0.2	0.07	1565.0/$\frac{5}{2}\,\frac{5}{2}+$
1253.2 ± 1.0	0.01	
1265.6 ± 0.3	0.30	1424.8/$\frac{7}{2}\,\frac{1}{2}+$ 1582.0/$\frac{5}{2}\,\frac{5}{2}+$
1269.3 ± 0.3	0.23	
1289.1 ± 0.2	0.27	1582.0/$\frac{9}{2}\,\frac{1}{2}-$
1296 ± 1.0	0.48	1424.8/$\frac{5}{2}\,\frac{1}{2}+$ [d]
1306 ± 1.0	0.04	
1309 ± 1.0	0.07	
1312.4 ± 0.3	0.17	
1329.0 ± 0.1	0.49	1582.0/$\frac{9}{2}\,\frac{7}{2}-$
1341.5 ± 0.5	0.04	
1353.5 ± 0.5	0.03	
1367.2 ± 0.2	0.15	
1370.8 ± 0.2	0.23	1582.0/$\frac{9}{2}\,\frac{7}{2}+$
1390.2 ± 0.3	0.13	
1399.5 ± 1.0		
1402.8 ± 0.5	0.10	
1405.5 ± 0.5	0.07	1565.0/$\frac{7}{2}\,\frac{1}{2}+$
1421.0 ± 0.1	0.45	1582.0/$\frac{7}{2}\,\frac{7}{2}-$ 1582.0/$\frac{7}{2}\,\frac{1}{2}+$
1426.6 ± 0.3	0.22	
1435.0 ± 0.3	0.14	1565.0/$\frac{5}{2}\,\frac{1}{2}+$
1451.9 ± 0.2	0.33	1582.0/$\frac{5}{2}\,\frac{1}{2}+$
1501.0 ± 0.2	0.85	1582.0/$\frac{7}{2}\,\frac{7}{2}+$
1530.7 ± 0.5	0.091	

[a] Not shown on decay scheme.
[b] With ^{164}Tm fraction subtracted.
[c] Mainly ^{164}Tm.
[d] Doublet with ^{164}Tm.

In Ref. 7 the positron end-point energy was determined as 1580 keV, and we use this value, which is near the average of all three determinations. Our subsequent analysis from the level scheme shows predominant decay to the 161.2-keV level. Hence, the total decay energy is $Q_{\beta^+} = 1.74$ MeV and $Q_{EC} = 2.76$ MeV.

We defer review of the conversion coefficient data and multipolarity assignments to the discussion section, except for the microsecond isomeric transitions. In Refs. 7, 8, and 11 $E1$ multipolarity assignments were made to the 80.1-keV transition. However, in Refs. 7 and 8, where the measured K and L conversion coefficients were given, their values were about twice the Hager-Seltzer theoretical were about twice the Hager-Seltzer theoretical values[15] for $E1$. Furthermore, the assumption of pure $E1$ multipolarity for the 80.1-keV transition would lead to serious difficulties in populating the 80.7-keV level. We believe that the conversion coefficients of the 80.1-keV transition are really higher than pure $E1$ and probably signify $M2$ admixture in the $E1$ transition. Taking Paris's value[7] of 0.05 ($E1$) and 49 ($M2$) we get $\delta^2(M2/E1)=0.008$. From the Moszkowski single-particle lifetime formula[16] for the $M2$ transition we get a retardation factor of 40, a reasonable value. From the Moszkowski formula we recalculate the $E1$ retardation factor of 6×10^7 for the 80.1 keV and an $E2$ retardation factor of 4×10^2 for the 68.9-keV transitions. It should be recognized that with $E1$ retardation so high for a K-allowed $E1$ transition, the penetration terms could give rise to anomalies[17] in the $E1$ conversion coefficient hence to uncertainties in the above estimate of $M2$ admixture. However, Gopinathan, Jain, and Baba[18] found no conversion anomaly in the analogous 63-keV transition in ^{169}Tm. Funke *et al.*[19] found the K-conversion coefficient about 25% higher than theoretical for pure $E1$ in the analogous 113-keV transition in ^{167}Tm.

TABLE II. Supplementary γ rays.

List for ^{165}Yb decay

E_γ (keV)	Assignment	Remarks
29.2	$\frac{7}{2}\frac{1}{2}+/\frac{5}{2}\frac{1}{2}+$	Needed for intensity balance Presumably too highly converted to observe photon
40.5	$\frac{9}{2}\frac{1}{2}-/\frac{9}{2}\frac{7}{2}-$	Seen by Grenoble group (Ref. 10) in beam
93.3	$\frac{9}{2}\frac{1}{2}-/\frac{5}{2}\frac{1}{2}-$	Seen in beam, both studies
116.6	$\frac{11}{2}\frac{7}{2}-/\frac{9}{2}\frac{7}{2}-$	Coincidence only; singles masked
120.4	$\frac{11}{2}\frac{1}{2}+/\frac{9}{2}\frac{1}{2}-$	Seen in beam (Ref. 10)
176.1	$\frac{7}{2}\frac{1}{2}-/\frac{3}{2}\frac{1}{2}-$	Line possible but obscured by ^{167}Yb activity
189.8	$552/\frac{9}{2}\frac{1}{2}+$	Coincidence only; no singles
269.4	$\frac{7}{2}\frac{1}{2}-/\frac{5}{2}\frac{1}{2}-$	Tentative coincidence evidence; no singles
431.0	$592.2/\frac{7}{2}\frac{7}{2}-$	Unresolved, broadening of 433.1 line
563.1	$1014.2/\frac{7}{2}\frac{1}{2}-$	Possible, but ^{165}Tm decay masks
595.2	$725.1/\frac{5}{2}\frac{1}{2}+$	Tentative coincidence; possible unresolved singles component
894.9	$1315.0/\frac{7}{2}\frac{5}{2}+$	Part of unresolved triplet also involving another isotope
895.7	$1188.8/\frac{9}{2}\frac{1}{2}-$	
996.5	$1308.7/\frac{5}{2}\frac{5}{2}+$	Coincidence only; no singles
1222.7	$1352.6/\frac{5}{2}\frac{1}{2}+$	Coincidence only; singles masked

Both these analogous cases involve less retarded $E1$ transitions than in ^{165}Tm, so our assumption of $M2$ admixture seems reasonable. Whether the excess conversion electrons are due to $M2$ admixture or $E1$ penetration terms does not affect the level-scheme intensity balance; that is the experimentally high conversion coefficient of the 80.1-keV transition gives it a total transition intensity nearly equal to the 68.9-keV transition; hence, the cascade of these transitions does not require direct β-decay feed to the intermediate state.

V. IN-BEAM RESULTS

Table III summarizes the results of our ^{158}Gd-(^{11}B, $4n\gamma$) reaction studies. Column 1 lists the γ-ray energies with energy determinations having probable errors of about ±0.05%. Columns 2 and 3 list for two bombarding energies the γ-ray intensities relative to the 147.2-keV line as 100. In general, the higher the spin of the parent level, the greater the rise in relative intensity of the γ rays with increasing beam energy. These coefficients are corrected for finite solid angle of the detectors. Substantial positive values of A_2/A_0 are indicators of stretched ($I\rightarrow I-2$) quadrupole character.

Figure 3 shows the angular distribution curves of 14 γ lines, taken at the optimum energy of 52 MeV.

Neither the singles nor coincidence spectra from in-beam work are presented here, as they confirm but do not essentially add to the published spectra of Gizon *et al.*[10] from ^{165}Ho(α, $4n\gamma$)^{165}Tm. Our spectra all have lower statistics, a consequence of the 2% duty cycle of the Yale HIA. Our spectra differ in replacement of the inelastic scattering γ lines of the ^{165}Ho target by the lines of the ^{158}Gd target and in somewhat greater suppression of the radioactivity background. Our in-beam γ measurements are gated on only during the 2-ms beam pulse, hence are unusually free of interference from radioactivity buildup in the target.

VI. PROPOSED LEVEL SCHEME

Building on the framework of lower levels in the scheme of the Grenoble group,[10] it is possible to take the radioactivity data to build up an expanded decay scheme. Insofar as possible we have relied on our coincidence data, but they are seriously limited by the microsecond isomerism of the $\frac{7}{2}+$ and $\frac{7}{2}-$ band heads. Hence, energy sum and difference information had to be relied on also. With the complexity of the decay we would concede that some of the transition placements and perhaps a level or two are accidental and incorrect. Dashed lines in the level scheme indicate uncertain features.

The proposed scheme of levels populated in radioactive decay of ^{165}Yb is presented in Fig. 4. The γ energies given in the scheme are exactly the differences of the proposed energy values of levels. These exact differences are frequently not the same as the experimental transition energies from spectral least-squares analysis as given in Tables I and III. Table II is a supplementary list of γ rays of less certainty assigned to the radioactive decay. These γ rays appear in the scheme as dashed lines, but they were not clearly

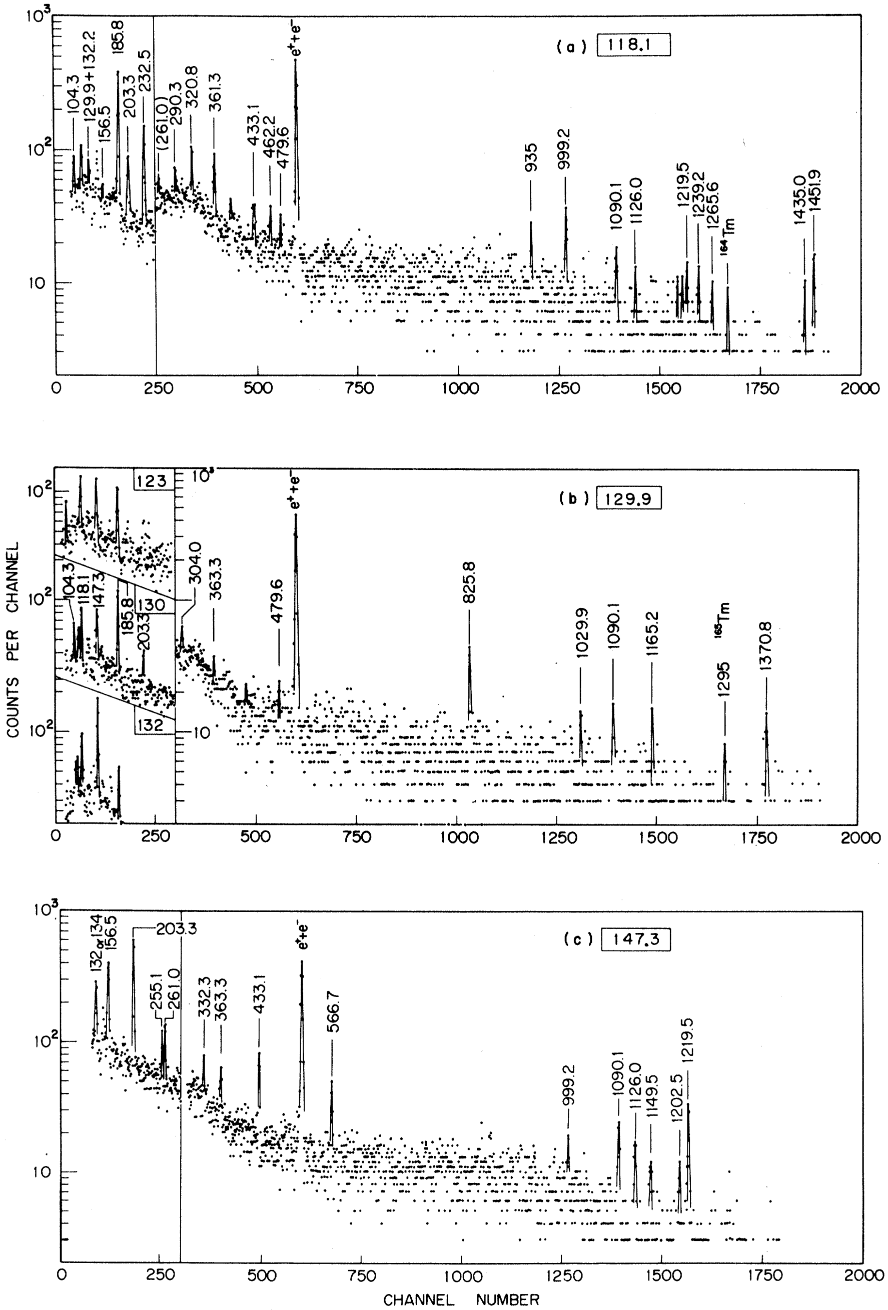

FIG. 2. (a)–(c) Representative sorts of the three-dimensional (γ-γ-t) coincidence data from the decay of ^{165}Yb. The gate energies are indicated in the square boxes near the upper right of each spectrum and inset. Spurious contributions from Compton events have been subtracted out by gating on a nearby flat portion of the spectrum in each case.

TABLE III. γ rays assigned to the ^{158}Gd(^{11}B, $4n\gamma$) reaction.

E_γ [a] (keV)	I_γ [b,c] (52 MeV)	I_γ (60 MeV)	A_2/A_0 [d]	A_4/A_0 [d]	Assignments $2I_i\,2K_i\,\pi/2I_f\,2K_f\,\pi$
68.7 [e]	34	39			7 7+/3 1+
84.5	16	22			U
92.0	43	48			9 7−/7 7−
104	9.6	Weak			7 5+/5 5+
111.9	10	14	0.33 ± 0.37	0.06 ± 0.16	9 1−/5 1−
116.6	64	90	−0.33 ± 0.22	0.16 ± 0.23	11 7−/9 7−
118.1	34	36	0.13 ± 0.37	−0.38 ± 0.46	5 1+/3 1+
120.6	17	21	−0.20 ± 0.28	0.05 ± 0.30	11 1+/9 1−
130.0 [f]	54	53	0.26 ± 0.10	0.17 ± 0.10	{5 1+/1 1+; 9 7+/7 7+}
134.4	98	118	−0.18 ± 0.11	0.07 ± 0.10	9 1−/7 1+
142.0	69	112	0.18 ± 0.14	0.01 ± 0.15	13 7−/11 7−
147.2	100	100	0.28 ± 0.06	0.01 ± 0.01	7 1+/3 1+
152	Weak	Weak			U
155.5	22	28	0.54 ± 0.23		11 7+/9 7+
164.4	66	102	0.02 ± 0.08	−0.05 ± 0.9	15 7−/13 7−
170.4	22	42	−0.21 ± 0.13	−0.05 ± 0.15	5 1−/3 1+
178.8	20	40			13 7+/11 7+
183	20	40			U
191.1	84	104	0.13 ± 0.12	0.02 ± 0.12	17 7−/15 7−
202.6	10	43			15 7+/13 7+
{203.4; 204.1} [g]	160	239	0.24 ± 0.08	−0.08 ± 0.08	{9 1+/7 1+; 13 1−/9 1−}
207.1	81	87	0.09 ± 0.09	−0.07 ± 0.14	19 7−/17 7−
212.4	15	40			U
218.5	12	40			U
221.6	12	40			17 7+/15 7+
232.9	44	39	0.22 ± 0.14	−0.26 ± 0.5	9 1+/5 1+
236.6	44	59	0.12 ± 0.17	−0.23 ± 0.2	21 7−/19 7−
241.2	25	45			23 7−/21 7−
245.3	14	46			U
255.0	77	89	0.32 ± 0.06	−0.13 ± 0.08	11 1+/7 1+
259.1	22	18			13 7−/9 7−
270.1	10	10			27 7−/25 7−
277.2	42	45			{25 7−/23 7−; (13 1+/11 1+)}
285.9	33	46			11 7+/7 7+
298.5	98	136	0.31 ± 0.03	0.01 ± 0.09	17 1−/13 1−
306.6	38	46	0.32 ± 0.08	0.11 ± 0.18	15 7−/11 7−
322					U
327.2	26	20	0.38 ± 0.23	0.25 ± 0.25	13 1+/9 1+
334.7	46	60	0.19 ± 0.10	0.06 ± 0.10	{17 1+/15 1+; 13 7+/9 7+}
340.3	23	16			U
347	Weak	10			U
355.0	92	132	0.26 ± 0.10	0.16 ± 0.27	{15 1+/11 1+; 17 7−/13 7−}
363.9	17	15			U
380.5	43	48	0.36 ± 0.20	−0.17 ± 0.20	15 7+/11 7+
385	Weak				U
389.7	71	126	0.29 ± 0.15	−0.01 ± 0.15	21 1−/17 1−
397.3	50	67	0.33 ± 0.20	−0.17 ± 0.20	19 7−/15 7−
403.1	9.3	8.8			U
412.8	21	10			17 1+/13 1+
418.5	10	10			U
422.3	36	60			17 7+/13 7+
443.0	30	41	0.25 ± 0.20	−0.02 ± 0.19	21 7−/17 7−
447.8	11	21			19 1+/15 1+

TABLE III (Continued)

E_γ [a] (keV)	I_γ [b,c] (52 MeV)	I_γ (60 MeV)	A_2/A_0 [d]	A_4/A_0 [d]	Assignments $2I_i 2K_i \pi/2I_f 2K_f \pi$
460.3	10	15			19 7+/15 7+
472	18	Weak			U
475	68	104			25 1−/21 1−
479	50	58			23 7−/19 7−
482	17	Weak			U
500	27	38	0.36 ± 0.16	0.18 ± 0.15	21 7+/17 7+
562	20	35			25 7+/21 7+

[a] The accuracy of the energy values is within ±0.3 keV for strong discrete lines and 0.5–1.0 keV for weaker lines.

[b] The intensity is given relative to the 147.2-keV γ ray for 52- and 60-MeV incident beam energy.

[c] The accuracy of the relative intensity of γ rays is ±10% for strong well resolved lines, 20% for the rest of lines.

[d] The errors in A_2/A_0, A_4/A_0 coefficients are only statistical ones, i.e., due to uncertainty in area determination and to the deviation from the interpolating polynomial, whichever is larger for any particular point.

[e] Because of the energy fit, part of the intensity of this peak may be possibly placed in the $\frac{9}{2}\frac{1}{2}+ \rightarrow \frac{9}{2}\frac{1}{2}-$ transition.

[f] From the $\gamma\gamma$-coincidence and γ-ray single measurements in ^{165}Yb decay, the intensity of 130 keV in the $\frac{5}{2}\frac{1}{2}+ \rightarrow \frac{1}{2}\frac{1}{2}+$ transitions was estimated to be 10 in the units used for both 52- and 60-MeV incident beam. And therefore a large part of this peak intensity should be considered to be due to $\frac{9}{2}\frac{7}{2}+ \rightarrow \frac{7}{2}\frac{7}{2}+$ transition.

[g] This peak consists of two γ rays, 204.1 keV of $\frac{13}{2}\frac{1}{2}- \rightarrow \frac{9}{2}\frac{1}{2}-$ and 203.4 keV of $\frac{9}{2}\frac{1}{2}+ \rightarrow \frac{7}{2}\frac{1}{2}+$. From the γ single in ^{165}Yb decay the intensity of 203.4-keV γ ray was estimated to be 80 for both 52- and 60-MeV incident beam.

resolvable in the singles spectrum and thus are not listed in Table I.

To avoid undue confusion, the radioactive decay scheme of Fig. 4 excludes levels seen only by in-beam work and does not show transitions seen in beam. The complete level scheme is given in Fig. 5, including levels observed in radioactivity and in beam by either our group or the Grenoble group.[10] The transition lines are indicated only for γ rays observed by us in beam and listed in Table II. Levels established by work of the Grenoble group[10] but for which our statistics were insufficient to find the confirming γ rays are also shown. In no case are these unconfirmed levels inconsistent with our data. We have recalculated all level energies using our own best values where possible and working up to higher levels with best Grenoble group energies.

The level energies have not been given on Fig. 5 because of space limitations but are summarized by band in Table IV along with the values determined by the Grenoble group.[10] Energies of levels not associated with bands can be read from Fig. 4 and are not repeated in Table IV.

VII. DISCUSSION

A. General

For nearly all but the uppermost levels, where we had insufficient statistics in beam, our studies provide confirming evidence for the correctness of the Grenoble decay scheme.[10] Only in the case of the weaker branch of transitions in the ground band do we propose differing assignments, down-shifting alternate spin levels beginning at spin $\frac{9}{2}$. This alteration results from our proposal of 203.3- and 232.5-keV lines to depopulate the $\frac{9}{2}+$ level, instead of their 297.8 and 236.6, respectively. The assignment question was discussed at length by Dr. J. Gizon, Dr. A. Gizon, and Dr. J. O. Rasmussen, who reexamined Grenoble and Yale data together. Although it is almost impossible to decide between alternatives on the basis of in-beam data, the radioactivity data favor the new assignments for the $\frac{9}{2}+$ state of the ground band. Consequently, the energies of the $\frac{13}{2}$, $\frac{17}{2}$, $\frac{21}{2}$, and $\frac{25}{2}$ levels are altered from Ref. 10.

The Grenoble level scheme with this minor alteration thus provided the invaluable framework from which to build with the complex γ spectrum from the radioactive decay. Several γ lines were found to define new levels at 315.8, 420.1, and 552.2 keV. The decay patterns of the γ rays clearly point to assignment as a $K=\frac{5}{2}$ band, and the logical assignment by the Nilsson model is $\frac{5}{2}+[402]$. Negative parity seems unlikely, as that would make the cross-band transitions into the ground-band once-K-hindered $E1$ transitions, and these would not be expected to compete with allowed $M1$ transitions into the $\frac{7}{2}$–[523] band. There is also a weak transition to the $\frac{7}{2}$+[404] band head, consistent with our assignment.

Having assigned the new $\frac{5}{2}$+ band, we looked back at in-beam γ data for evidence of its population. In the Yale data with boron ion reactions, only the 104.3-keV transition can be identified, but the Grenoble data[10] with α-particle reactions show relatively greater population of the $\frac{5}{2}$+ band. We list the Grenoble group's unassigned γ rays and intensities (as percent of the 92.0 keV intensity in their Table I) associated with the new band: 104.6 keV (1.5%) and 303.9 keV (19%). Other γ transitions of the new band would be masked in their in-beam spectra.

It is somewhat surprising that Funke *et al.*[19] do not find an analogous low-lying $\frac{5}{2}$+ band in their study of decay of ^{167}Yb, since the decay schemes are in so many ways closely analogous, a consequence of identical parent ground-state assignments.

With the predominance of the β decay to the $\frac{7}{2}$–[523] band head with logft of 4.83 we retain the parent ^{165}Yb assignment of $\frac{5}{2}$–[523] as made by Paris.[7] As discussed earlier, the total ground-to-ground electron capture decay energy is Q_{EC} = 2.76 MeV. With the same ground-state assignment for $^{165}_{70}$Yb$_{95}$ as for its neighbor $^{167}_{70}$Yb$_{97}$ the two decay schemes are very similar. The decay scheme of the latter nucleus has been presented in detail by the Rossendorf group.[20]

With a Yb parent spin as low as $\frac{5}{2}$ we expected that the radioactivity offered a hope of populating hitherto unobserved $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{7}{2}$ members of the $\frac{1}{2}$ –[541] band. Dzhelepov, Dranitsyna, and Michailov[4] in their Table 1.1a list six cases in which this Nilsson proton band occurs with at least three band members known. In three cases the $\frac{1}{2}$–

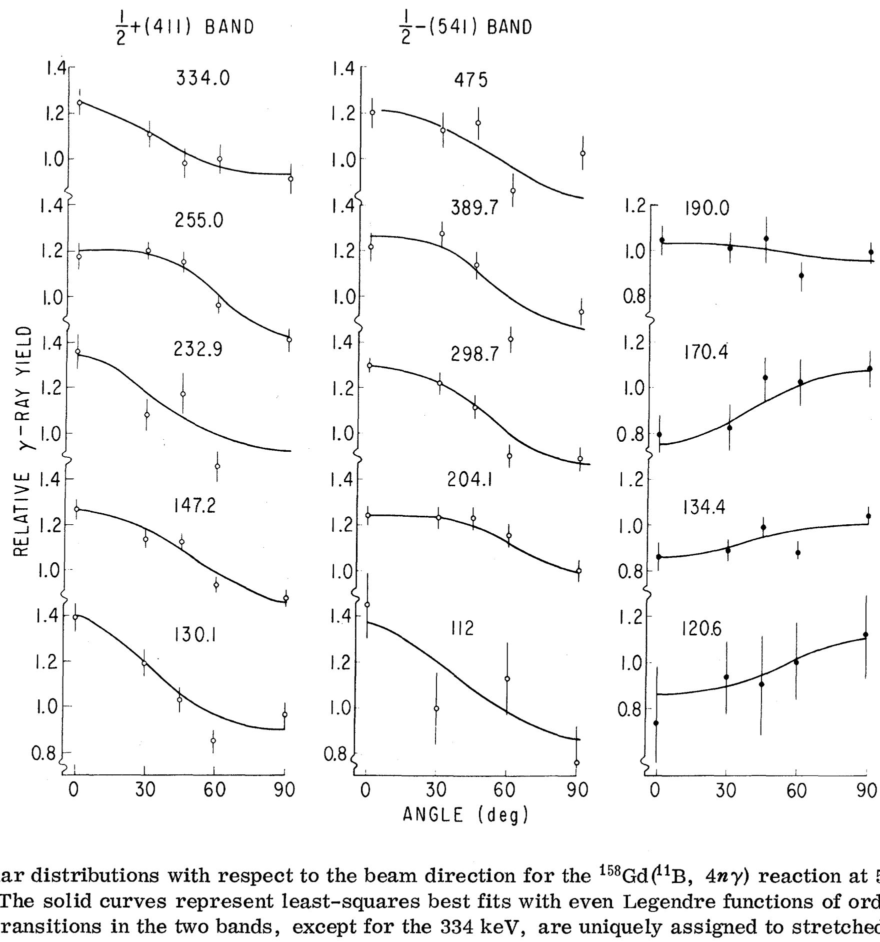

FIG. 3. γ angular distributions with respect to the beam direction for the ^{158}Gd(^{11}B, $4n\gamma$) reaction at 52-MeV bombarding energy. The solid curves represent least-squares best fits with even Legendre functions of orders 0, 2, and 4. Note that all the transitions in the two bands, except for the 334 keV, are uniquely assigned to stretched $E2$ crossover transitions, consistent with the strong positive anisotropy. The 334-keV transition is believed to be an unresolved doublet of a stretched $E2$ crossover in the $\frac{7}{2}$+[404] band and a cascade in the $\frac{1}{2}$+[411]. Of the other transitions, the lower three are assigned as stretched $E1$ transitions between the $\frac{1}{2}$+ and $\frac{1}{2}$– bands, and the negative anisotropies are consistent with this assignment. The 190-keV transition is assigned as a cascade $M1$-$E2$ transition in the $\frac{7}{2}$–[523] band, and the near isotropy is consistent with such assignment.

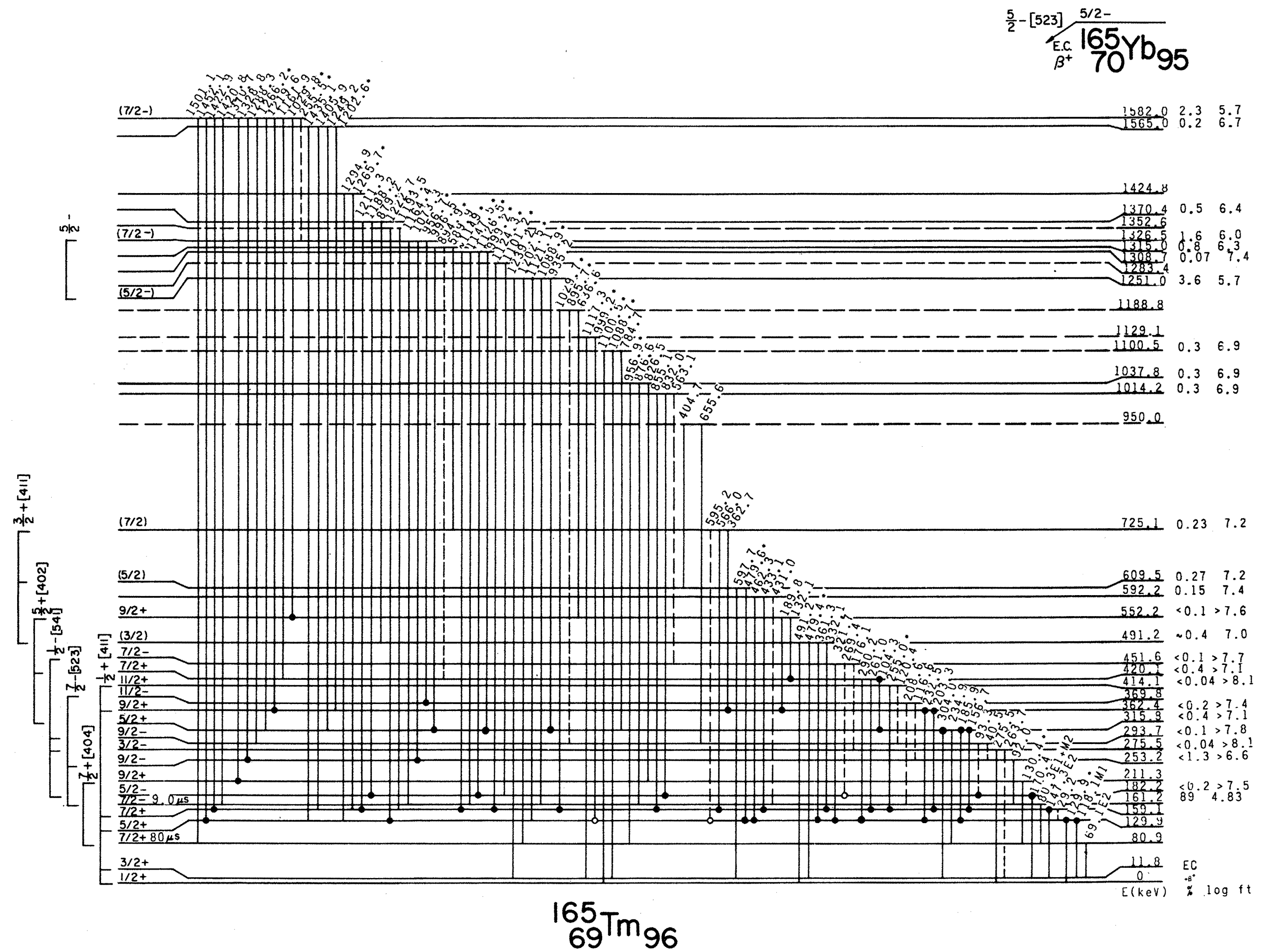

FIG. 4. Proposed radioactive decay scheme of ^{165}Yb. Only those transitions and levels involved in the radioactive decay are shown. Dashed levels and transitions are placed with less certainty than others. All energies are in keV, and Nilsson quantum number assignments are the usual $K\pi[Nn_z\Lambda]$. The level energies are best values derived from experimental transition energies, but the γ transition energies shown above each line are exact differences of the level energies and not the experimental values. Thus, the transition energies of the decay scheme may not always correspond exactly to the experimental energies of Table I; the energy differences afford a ready test on consistency of the scheme. Multiply assigned transitions are indicated by asterisks. A solid dot at the upper (lower) end of a transition line means that transition has been measured to be in coincidence with some higher (lower) transition. Open circles indicate less certain coincidence observations.

member lies within 5 keV of the $\frac{5}{2}-$, twice above it and once below. In other cases it is 25 keV below, 30 keV above and 76 keV above. The $\frac{3}{2}-$ member ranges in the five known cases from 130 to 234 keV above the $\frac{5}{2}-$. The one known $\frac{7}{2}-$ member (in ^{177}Lu) is 354 keV above the $\frac{5}{2}-$ and 272 keV above the $\frac{9}{2}-$. The characteristic decay of a $\frac{3}{2}-$ level in our case should be decay by $E1$ γ rays to the ground and/or first excited states, since it is known that the interband $E1$ transitions of these bands are competitive with intraband $M1$ and $E2$. The $\frac{7}{2}-$ level might decay by $E1$'s to the $\frac{5}{2}+$ and/or $\frac{7}{2}+$ members of the ground band or by intraband transitions to the $\frac{3}{2}-$, $\frac{5}{2}-$, or $\frac{9}{2}-$ members below it. Possible trial level assignments were tested by least-squares band fitting with a rotational-band energy routine and the formula

$$E = E_0 + AI(I+1) + BI^2(I+1)^2 + CI^3(I+1)^3 + (-)^{I+K}\frac{(I+K)!}{(I-K)!}\left[A_{2K} + B_{2K}I(I+1)\right]. \quad (1)$$

The only possibility consistent with our data is

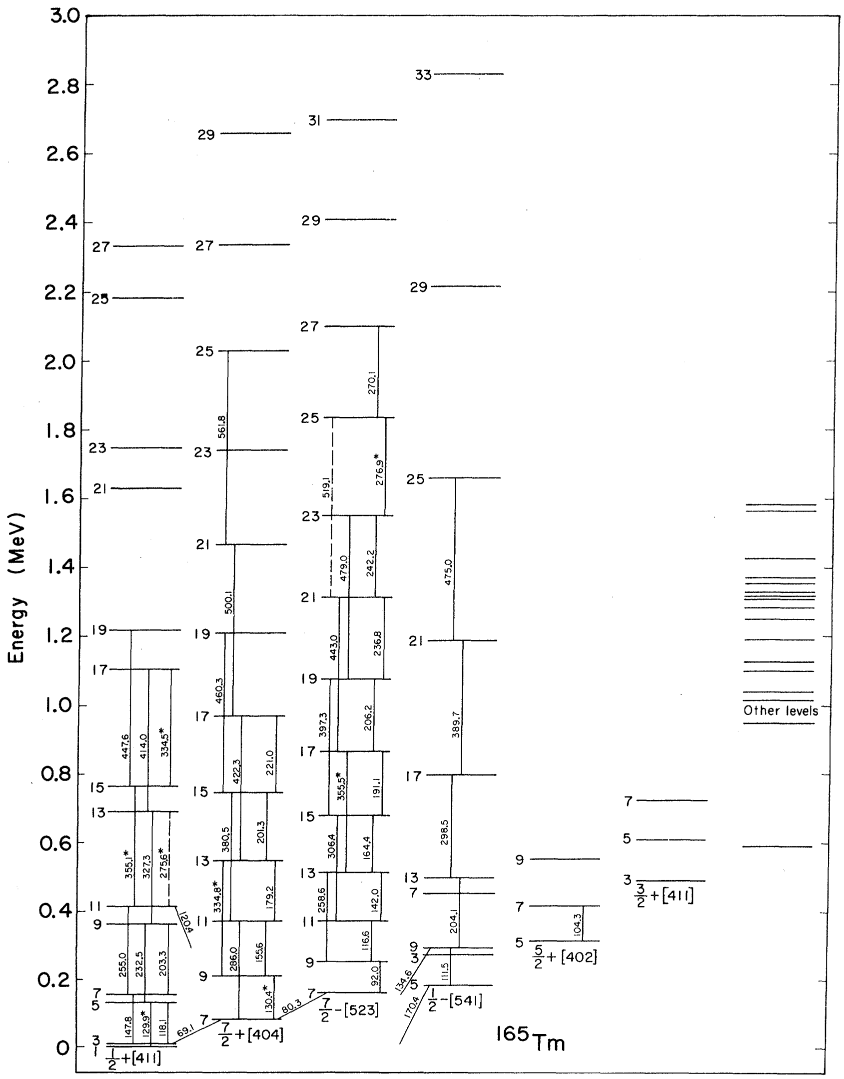

FIG. 5. Complete summary schematic of all levels observed in ^{165}Tm by radioactivity and in-beam γ spectroscopy. Spins are labeled by the integer that is twice the spin value. The only transition lines indicated are for transitions observed in our in-beam work. The higher levels seen by the Grenoble group (Ref. 10) with their spectra of better statistics are also included on the diagram. As in Fig. 4 the energies are differences of adopted level energy values, not experimental energies themselves. Asterisks indicate unresolved doublet assignments. The three slanted-line transitions not terminating on a level line go between the $\frac{1}{2}+$ and $\frac{1}{2}-$ bands. There was not space to enter exact level energies, but they may be read from Fig. 4 or from Table IV.

TABLE IV. Level energies in ^{165}Tm.

Spin	E_{exp} (keV) This work	E_{exp} (keV) Grenoble (Ref. 10)	E_{calc} (keV) Six-parameter power series [a]
		$\frac{1}{2}+$[411] band	
$\frac{1}{2}$	0	0	−0.17
$\frac{3}{2}$	11.8	11.9	12.11
$\frac{5}{2}$	129.9	130.2	129.80
$\frac{7}{2}$	159.1	159.2	159.54
$\frac{9}{2}$	362.4	367.0 [b]	362.92
$\frac{11}{2}$	414.1	414.2	413.62
$\frac{13}{2}$	689.7	703.4 [b]	689.87
$\frac{15}{2}$	769.2	769.5	769.70
$\frac{17}{2}$	1103.7	1128.2 [b]	1104.13
$\frac{19}{2}$	1216.8	1216.9	1229.40
$\frac{21}{2}$		1630.1 [b]	1609.58
$\frac{23}{2}$	1746.1 [c]	1746.2	1809.57
$\frac{25}{2}$		2184.7 [b]	2230.78
$\frac{27}{2}$		2333	2553.79
		$\frac{7}{2}+$[404] band	
$\frac{7}{2}$	80.9	81.1	81.09
$\frac{9}{2}$	211.3	211.3	211.29
$\frac{11}{2}$	366.9	366.9	366.88
$\frac{13}{2}$	546.1	546.1	546.28
$\frac{15}{2}$	747.4	747.2	747.04
$\frac{17}{2}$	968.4	969.0	968.97
$\frac{19}{2}$	1207.7	1207.0	1207.07
$\frac{21}{2}$	1468.5	1467.6	1467.60
$\frac{23}{2}$	1737.0 [c]	1736.3	1736.29
$\frac{25}{2}$	2030.3 [c]	2029.4	2038.16
$\frac{27}{2}$		2335.1	2334.17
$\frac{29}{2}$		2660	2690.83
		$\frac{7}{2}-$[523] band	
$\frac{7}{2}$	161.2	161.4	159.51
$\frac{9}{2}$	253.2	253.4	254.49
$\frac{11}{2}$	369.8	370.2	371.99
$\frac{13}{2}$	511.8	512.7	513.19
$\frac{15}{2}$	676.2	676.9	676.61

Spin	E_{exp} (keV) This work	E_{exp} (keV) Grenoble (Ref. 10)	E_{calc} (keV) Six-parameter power series [a]
$\frac{17}{2}$	867.3	868.0	866.59
$\frac{19}{2}$	1073.5	1074.5	1073.25
$\frac{21}{2}$	1310.3	1311.0	1312.01
$\frac{23}{2}$	1552.5	1552.5	1553.34
$\frac{25}{2}$	1829.4	1830.2	1829.98
$\frac{27}{2}$	2099.5	2099.2	2099.03
$\frac{29}{2}$		2411.4	2365.18
$\frac{31}{2}$		2698.2	2690.94
		$\frac{1}{2}-$[541] band	
$\frac{1}{2}$			156.55
$\frac{3}{2}$	275.0		276.11
$\frac{5}{2}$	182.2	182.2	180.99
$\frac{7}{2}$	451.1		450.44
$\frac{9}{2}$	293.7	293.9	294.30
$\frac{11}{2}$			690.77
$\frac{13}{2}$	497.8	498.4	499.37
$\frac{15}{2}$			986.74
$\frac{17}{2}$	796.3	796.9	797.06
$\frac{19}{2}$			1325.78
$\frac{21}{2}$	1186.0 [c]	1186.6	1185.79
$\frac{23}{2}$			1692.59
$\frac{25}{2}$	1661.0 [c]	1661.3	1660.91
$\frac{27}{2}$			2068.46
$\frac{29}{2}$	2212.9 [c]	2213.2	2213.98
$\frac{31}{2}$			2430.43
$\frac{33}{2}$		2832.5	2831.86
		$\frac{5}{2}+$[402] band	
$\frac{5}{2}$	315.8		
$\frac{7}{2}$	420.1		
$\frac{9}{2}$	552.2		
		"Low-K band" ($\frac{3}{2}+$[411])	
$\frac{3}{2}$	491.2		
$\frac{5}{2}$	609.5		
$\frac{7}{2}$	725.1		

[a] Six-parameter energy expansion least-squares fit up through underlined level. See Table VI for band parameters used.

[b] These differing energies result from our different γ-ray assignments from the original Grenoble paper (Ref. 10).

[c] One or more transition energies from Grenoble work (Ref. 10) used to calculate level energy.

the assignment shown in our level schemes and Table IV, namely, the $\frac{3}{2}-$ level at 275.0 keV and the $\frac{7}{2}-$ at 451.1 keV. Admittedly, the evidence for these assignments is rather weak, and critical reexamination would be desirable in any future studies. Our decoupling parameter $a(=A_1/A) = +2.94$ is close to that of $+2.91 \pm 0.15$ in nearby ^{161}Ho, although the decoupling parameter is generally higher in the four known Lu cases, ranging between $+3.8$ and $+4.6$.

We are handicapped in making spin and parity assignments to the many weakly populated "other levels" above the assigned bands; for there are neither conversion coefficients nor angular distributions for a guide. Furthermore, given the short half-life and weak population, such data will be difficult to obtain. Paris[7] and Tamura[8] were able to obtain conversion-electron spectra only for the lower-energy transitions, though Adam *et al.*[11] were able to augment the multipolarity assignments. Our decay scheme is consistent with the multipolarity assignments of Refs. 7, 8, and 11, although we propose attributing $M2$ admixture to the 80.1-keV $E1$. By our level scheme the 118.1-keV transition could have $E2$ admixture, but it is expected to be mainly $M1$ by analogy with ^{167}Tm and ^{169}Tm, where the analogous transitions are reportedly 0.8% $E2$ and 2% $E2$, respectively. The log*ft* values of the higher levels are in a range consistent with $\beta-$ decay spin changes of 0, ± 1 either with or without parity change. Hence, we may only say for levels that receive direct β decay that the spin is $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. Log*ft* values for the less populated lower levels may often be just lower limits, as unassigned feeder γ rays might account for some population. It is unreasonable that feeding by β decay be seen to the $\frac{9}{2}-$ levels, since that would be second forbidden. It is possible to have a $\frac{9}{2}+$ assignment if the log*ft* value is near 8, typical of Gamow-Teller unique first forbidden.

We have noted three levels (491.2, 609.5, and 725.8) as a "low K" band because these levels decay to the $K=\frac{1}{2}+$ and $K=\frac{1}{2}-$ bands, predominantly to the former. If we are to choose a sequence of spin values for the "low K" band, consistent with transition multipolarities no higher than quadrupole, the sequence $\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$ shown on the level scheme is most likely. At this point it is appropriate to look to theoretically predicted band-head energies for guidance. Soloviev and Fedotov have recently made extensive calculations of band energies and wave functions for odd-mass rare-earth nuclei.[21] These sophisticated calculations with nucleon wave functions in a deformed Woods-Saxon potential include quasiparticle-phonon mixing, with quadrupole and octupole phonons, as well as explicit consideration of three quasiparticle states. In our Table V we compare our present experimental values with their theoretical results. Soloviev and Fedotov predict a $\frac{3}{2}+$ state at 660 keV in ^{165}Tm. In their Table 12 for ^{167}Tm, the $\frac{3}{2}+$ state is predicted at 670 keV, with an experimental value of 471 keV listed. In their Table 13 for ^{171}Tm, the $\frac{3}{2}+$ state is predicted at 680 keV and experimentally known at 676 keV.

Diamond, Elbek, and Stephens[22] first Coulomb-excited in ^{169}Tm a $\frac{3}{2}+$ band with levels at 570, 633, and 718 keV. They also observed levels near 900 keV and near 1170 keV. Subsequent Coulomb-excitation studies have confirmed these results. Aleksandrov, Balalaev, Dzhelepov, and Ter-Nersesyants[23] more precisely measured the $\frac{3}{2}+[411]$ band in ^{169}Tm with first four level energies of 571, 633, 718, and 825 keV, very weakly populated in decay of ^{169}Yb. They proposed a regular ascending spin sequence $\frac{3}{2}, \frac{5}{2}, \frac{7}{2}, \frac{9}{2}$.

The systematic Coulomb excitation of bands differing in K by two units from the ground-band K stimulated theoretical calculations of γ vibrational phonon character in odd-A nuclei. Theoretical studies of both Bes and Cho[24] and Soloviev and Vogel[25] show a fair amount of mixing of $\frac{3}{2}+[411]$ one-quasiparticle band and the band composed of γ phonon plus $\frac{1}{2}+[411]$ quasiproton. In ^{169}Tm Bes and

TABLE V. Experimental band-head energies of ^{165}Tm and ^{167}Tm compared with theory.

	Energy (keV)			
	^{167}Tm	^{165}Tm		
$K\pi$	(Ref. 19)	This experiment	Theory (Ref. 21)	Main components from theory (Ref. 21)
$\frac{1}{2}+$		0	0	$411\downarrow$ 96%
$\frac{7}{2}-$	293	161	300	$523\uparrow$ 94%
$\frac{9}{2}-$			550	$514\uparrow$ 94%
$\frac{7}{2}+$	180	81	630	$404\downarrow$ 96%
$\frac{3}{2}+$	471	(491)	660	$411\uparrow$ 84%
$\frac{5}{2}+$		316	990	$411\downarrow + Q_1(22)$ 49% $402\uparrow$ 42%
$\frac{3}{2}-$			1010	$523\uparrow + Q_1(22)$ 96%
$\frac{11}{2}-$			1060	$523\uparrow + Q_1(22)$ 100%
$\frac{3}{2}+$		(1100–1251)	1100	$411\downarrow + Q_1(22)$ 94%
$\frac{5}{2}+$	(1581)		1100	$411\downarrow + Q_1(22)$ 46% $402\uparrow$ 44%
$\frac{7}{2}+$		(1230)	1250	$411\uparrow + Q_1(22)$ 98%
$\frac{1}{2}+$			1320	$411\uparrow + Q_1(22)$ 100%
$\frac{1}{2}-$	172	182 [a]	1340	$541\downarrow$ 89%
$\frac{5}{2}-$	(1527)	(1251)	1400	$532\uparrow$ 75%
$\frac{3}{2}+$			1470	$404\downarrow + Q_1(22)$ 86%
$\frac{17}{2}+$			1960	$p523\uparrow\ n642\uparrow\ n523\downarrow$

[a] Energy is for $\frac{5}{2}-$ spin member of band in ^{165}Tm, since $\frac{1}{2}-$ spin is unknown, but presumably near.

Cho predicted the $\frac{3}{2}+$ band head at 718 keV and $\frac{5}{2}+$ at 1211 keV. Soloviev and Vogel predict $\frac{3}{2}+$ band heads at 620 and 1200 (compared to experimental 570 and ~1170) and $\frac{5}{2}+$ band at 900, 950, and 1350.

In view of the experimental and theoretical evidence on the systematic occurrence of the $\frac{3}{2}+[411]$ band in odd-A thulium isotopes, we make this assignment to our "low K" band. Our assignment of spins is somewhat speculative. At first we thought to include the level at 592.2 keV in the band, giving anomalous spacing, but we decided to exclude it on the basis of its higher logft and the preferability of a regularly spaced band.

The $\frac{3}{2}+$ and $\frac{5}{2}+$ bands predicted around 1100 keV have predominant parentage of ground band plus γ vibrational phonon. Thus, we might expect enhanced $E2$ decay from these bands to the ground band. The following levels in our scheme have energies and show decay patterns that might suggest their association with these predicted bands: 1100.5, 1129.1, 1251. There is no good basis to make more definite assignments.

The 1250.9 and 1325.8 levels stand out in that they receive more β feed than their neighbors and they decay mainly into the $\frac{7}{2}-[523]$ band. We suggest these levels may be, respectively, the $\frac{5}{2}-$ and $\frac{7}{2}-$members of the $\frac{5}{2}-[532]$ band predicted at 1400 keV.

Finally, there is the rather amazing level at 1582 keV that decays to nearly all lower levels with spins $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$, regardless of K or parity. That behavior would suggest a mixed-K character. The spin assignment of $\frac{7}{2}$ is favored by the decay pattern and by the fact that the logft value to the level is relatively low but with no comparably populated level higher. We favor a negative-parity assignment, since the allowed β- decay classification better permits a rather mixed character for the state. Soloviev and Fedotov do not predict a second $\frac{7}{2}-$ band in their table, but they have not gone above 1470 keV for the general calculations, and they have not considered quadrupole phonons of $K=0$ (β or pairing vibrations). It is known[26] that neighboring ^{164}Er has its first excited 0+ state at 1245 keV and a 1-, $K=0$ state at 1386 keV. It may well be that our 1582-keV level mainly is composed of these phonon states, coupled respectively to the $\frac{7}{2}-[523]$ and $\frac{7}{2}+[404]$ quasiproton components.

Referring to Table V, can we make any more assignments of higher levels with the aid of the theory? We have searched for the $\frac{9}{2}-$ band predicted around 550 keV but see no evidence for it. β decay to this band would be second forbidden, so it could only be seen if fed by γ transitions from higher levels. From the same considerations we would not expect to see the predicted $\frac{11}{2}-$ state.

Before leaving the comparison with Soloviev-Fedotov theory, we would note the large disagreement in the position of the $\frac{1}{2}-$ band, both in ^{165}Tm and ^{167}Tm. The $\frac{1}{2}-[541]$ band shifts energy rapidly as neutron number is changed in Lu isotopes. Since the $\frac{1}{2}-$ orbital comes from a higher oscillator shell, its relative energy is quite sensitive to deformation and to spin-orbit splitting. Thus, slight modifications of the deformed well parameters could bring the $\frac{1}{2}-[541]$ orbital down, so the disagreement with theory is not serious. It may be, however, that the orbital energy shifts among the Tm isotopes are not explainable in the framework of an average potential model and that Hartree-Bogoliubov theory will be needed to explain the shifts.

B. Rotational Energy Parameters

We have applied the usual power series expansion Eq. (1) to fit the rotational band energies by least squares, and one of these fits is presented in Table IV for each band. The fits of Table IV were made to the Grenoble energies,[10] except for the $K=\frac{1}{2}+$ and $K=\frac{1}{2}-$ bands, where substantial shifts or new levels are proposed in our work. The fits presented use the full six-parameter expansion, fitting on levels up to the underlined value. It is readily seen that the predictions diverge from experiment at the next level above the last fitted level. Thus, the series expansions are not very satisfactory for any of the bands at highest-spin values. It is necessary to be cautious in cross-comparing rotational expansion coefficients with those determined by least squares in other nuclei, since the parameters depend both on how many terms were taken in the expansion and how many levels were fit. Table VI gives the parameter values for the particular fits given in Table IV. These points of caution are well brought out in the discussion and more sophisticated analyses by Hjorth and Ryde[27] and by Hjorth, Ryde, and Skanberg.[28] The signs and magnitudes of these parameters are in

TABLE VI. Parameters of the energy formula of bands in ^{165}Tm.

Parameters	$\frac{1}{2}[411]$	$\frac{1}{2}[541]$	$\frac{7}{2}[523]$	$\frac{7}{2}[404]$
A (keV)	14.02	10.19	10.20	15.17
B (eV)	−14.69	−3.94	9.78	−18.19
C (eV$\times 10^{-3}$)	55	−3.25	−35.7	30.04
A_{2k}	−9.98 keV	30.03 keV	603 μeV	164 μeV
B_{2k}	42.3 eV	−127.9 eV	−3.0 μeV	−0.35 μeV

accord with data on these same bands in other nuclei. It would take too much space here to make a detailed cross-comparison with other nuclei or with theory. In an earlier publication[29] we discussed the significance of some of the parameters in light of theoretical work of Hamamoto and Udagawa.[30] The same remarks apply here as to differences between parameters of the $\frac{7}{2}-$ and $\frac{7}{2}+$ bands.

We have gone one step further in the rotational-band analysis by applying the two-band–Coriolis-mixing expressions of Eqs. (1) and (2) in Ref. 31. Table VII shows results of two-band least-squares fits to the $\frac{7}{2}+[404]$ and $\frac{5}{2}+[402]$ bands. In this treatment, as presented in detail in Ref. 31, analytical energy expressions are derived for Coriolis mixing of two bands with zeroth-order energies given by power series expansions in $I(I+1)$. For Table VII we have allowed the full six-parameter variation to fit the lowest 10 levels of the $\frac{7}{2}+$ band and the lowest 3 levels of the $\frac{5}{2}+$ band. The parameters found by the search are as follows: $\alpha=\hbar^2/2J=14.76$ keV, β (softness parameter) $=9.05\times10^{-4}$, α_{2K} (generalized decoupling parameter) $=-3.26\times10^{-4}$ keV, $\langle j+\rangle$ (intrinsic Coriolis matrix element) $=0.626$, bandhead difference (zeroth order) $=246.4$ keV, bandhead sum (zeroth order) $=311.8$ keV.

TABLE VII. Two-band Coriolis-mixing fit and predictions for $\frac{7}{2}+$ and $\frac{5}{2}+$ bands.

Spin	E(calc)	ΔE(calc-exp)
$\frac{7}{2}$	82.52	1.62
$\frac{9}{2}$	211.25	−0.05
$\frac{11}{2}$	365.80	−1.10
$\frac{13}{2}$	544.90	−1.21
$\frac{15}{2}$	746.08	−1.31
$\frac{17}{2}$	969.27	0.87
$\frac{19}{2}$	1208.68	0.98
$\frac{21}{2}$	1469.54	1.04
$\frac{23}{2}$	1736.80	−0.20
$\frac{25}{2}$	2029.67	−0.63
$\frac{27}{2}$	2312.80	
$\frac{29}{2}$	2627.52	
$\frac{31}{2}$	2936.26	
$\frac{5}{2}$	316.02	0.22
$\frac{7}{2}$	419.70	−0.40
$\frac{9}{2}$	552.37	0.17
$\frac{11}{2}$	707.81	
$\frac{13}{2}$	896.48	
$\frac{15}{2}$	1090.91	

The rather small value of Coriolis matrix element is reasonable, since the operator is not allowed by asymptotic quantum number selection rules between the two bands. The rather small decoupling parameter reflects the fact that the $\frac{5}{2}+[402]$ band has small Coriolis coupling to $K=\frac{1}{2}$ bands and perhaps partially cancelling contributions from the coupling.

With all the work that has gone into the nuclear properties of ^{165}Tm we do not regard the story as completed. Despite the awkwardly short half-life of 10.5 min, new conversion-electron data must be obtained to facilitate multipolarity and spin assignments. γ-γ angular correlation work would be helpful though difficult to obtain. The γ spectra and coincidence studies ought to be repeated at highest resolution with isotopically separated sources. Proton-stripping studies on erbium targets into ^{165}Tm and neighboring Tm isotopes would be most welcome.

The bands here identified (lowest $\frac{1}{2}+$, $\frac{3}{2}+$, $\frac{5}{2}+$, and $\frac{7}{2}+$) should facilitate Coriolis band-mixing studies of the low-j orbital family. Generally, such studies have been confined to high-j orbitals.

We hope that the work presented here can be a stimulus to further experimental and theoretical work in this region.

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[1]M. Bunker and C. Reich, Rev. Mod. Phys. 43, 348 (1971).

[2]W. Ogle, S. Wahlborn, R. Piepenbring, and S. Fredriksson, Rev. Mod. Phys. 43, 424 (1971).

[3]V. G. Soloviev, *Theory of Complex Nuclei* (Science Press, Moscow, USSR, 1971), Table 4.8.

[4]Cf. B. S. Dzhelepov, G. F. Dranitsyna, and V. M. Michailov, *Properties of Atomic Nuclei* (Science Press, Leningrad, USSR, 1971), Vol. 12, Properties of Deformed Nuclei with $K=\frac{1}{2}$.

[5]T. W. Conlon, Nucl. Phys. A100, 545 (1967).

[6]T. W. Conlon, R. A. Naumann, and L. McCarthy, Nucl. Phys. A104, 213 (1967).

[7]P. Paris, Ph. D. thesis, Paris, 1966 (unpublished); J. Phys. (Paris), 28, 388 (1967).

[8]T. Tamura, Nucl. Phys. A115, 193 (1968).

[9]T. Tamura, I. Rezanka, S. Iwata, J. Alonso, and J. Rasmussen, Bull. Am. Phys. Soc. 16, 831 (1971).

[10]J. Gizon, A. Gizon, S. A. Hjorth, D. Barneoud, S. Andre, and J. Treherne, Nucl. Phys. A193, 193 (1972).

[11]I. Adam, G. Bayer, K. Ya. Gromov, Kh. U. Zibert, T. A. Islamov, Kh. Tyrroff, A. Sh. Khamidov, E. Herrmann, Kh. Shtrusny, and M. Yakhim, in *23rd Conference on Nuclear Spectroscopy and the Structure of Atomic Nuclei, Tbilisi, U.S.S.R., 1973* (Science Press, Leningrad), Program and Abstracts.

[12]J. T. Routti and S. G. Prussin, Nucl. Instrum. Methods 72, 125 (1969).

[13]H. Baba, T. Suzuki, S. Baba, and H. Okashita, Japan Atomic Energy Research Institute Report No. JAERI-1227, 1973 (unpublished).

[14]I. Rezanka, J. Rasmussen, F. Bernthal, C. Alonso, J. Alonso, S. Hultberg, and H. Ryde, Nucl. Phys. A197, 430 (1972).

[15]R. S. Hager and E. C. Seltzer, Nucl. Data 4, 1 (1968).

[16]S. A. Moszkowski, in *Beta and Gamma Spectroscopy*, edited by K. Siegbahn (Interscience, New York, 1955).

[17]S. G. Nilsson and J. O. Rasmussen, Nucl. Phys. 5, 617 (1958).

[18]K. P. Gopinathan, H. C. Jain, and C. V. K. Baba, Phys. Rev. C 6, 321 (1972).

[19]L. Funke, K. H. Kaun, P. Kemnitz, H. Sodan, G. Winter, R. Arlt, K. Ya. Gromov, S. M. Kamalchodjaev, A. F. Novgorodov, H. Strusny, D. deFrenne, and E. Jacobs, Nucl. Phys. A175, 101 (1971).

[20]G. Winter, L. Funke, K. Hohmuth, K. H. Kaun, P. Kemnitz, and H. Sodan, Nucl. Phys. A151, 337 (1970).

[21]V. G. Soloviev and S. I. Fedotov, Izv. Akad. Nauk SSSR Ser. Fiz. 36, 706 (1972) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 36, 640 (1972)].

[22]R. M. Diamond, B. Elbek, and F. S. Stephens, Nucl. Phys. 43, 560 (1963).

[23]V. S. Aleksandrov, V. A. Balalaev, B. S. Dzhelepov, and V. E. Ter-Nersesyants, Izv. Akad. Nauk SSSR Ser. Fiz. 34, 42 (1970) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 34, 42 (1970)].

[24]D. R. Bes and Cho Yi-Chung, Nucl. Phys. 86, 581 (1966).

[25]V. G. Soloviev and P. Vogel, Nucl. Phys. A92, 449 (1967).

[26]Ya. Vrzal, K. Ya. Gromov, Ya. Liptak, F. Molnar, V. A. Morozov, Ya. Urbanets, and V. G. Chumin, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 604 (1967) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 31, 599 (1967)].

[27]S. A. Hjorth, and H. Ryde, Phys. Lett. 31B, 201 (1970).

[28]S. A. Hjorth, H. Ryde, and B. Skanberg, J. Phys. (Paris), 33, 23 (1972).

[29]J. Alonso, H. Bakhru, F. M. Bernthal, J. Boutet, B. Olsen, I. Rezanka, and J. O. Rasmussen, Nucl. Phys. A160, 193 (1970).

[30]I. Hamamoto and T. Udagawa, Nucl. Phys. A126, 241 (1969).

[31]K. Krien, R. A. Naumann, J. O. Rasmussen, and I. Rezanka, Nucl. Phys. A209, 572 (1973).