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Publication Date
1976-12-01

Published in Physical Review C,
Vol. 13, No. 6, 2466 - 2483
(June 1976)

LBL-5816

LEVEL STRUCTURE OF ^{155}Gd AND THE ELECTRON-CAPTURE DECAY OF ^{155}Tb

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December 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

Level structure of ^{155}Gd and the electron-capture decay of ^{155}Tb†

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(Received 11 August 1975)

The decay of ^{155}Tb to levels of ^{155}Gd has been studied by γ-ray and conversion-electron spectroscopy with mass-separated sources. Below 660 keV, approximately 150 γ rays have been observed and assigned to a level scheme with 28 levels. The mixing of even-parity levels is calculated using a variation plus diagonalization procedure. The resultant wave functions are used to calculate transition probabilities and magnetic moments, which are compared with the experimental results. β- and γ- vibrational states are identified and compared with corresponding excitations in neighboring even-even nuclei.

RADIOACTIVITY ^{155}Tb [from ^{155}Gd(p,n), ^{153}Eu$(\alpha,2n)$, ^{154}Gd$(\alpha,3n)^{155}$Dy(EC)]; measured E_γ, I_γ, I_{ce}. ^{155}Gd deduced transitions, ICC, multipolarities, levels J, π, Nilsson assignments. ^{155}Gd calculated wave functions, transition probabilities, magnetic moments. Ge(Li), Si(Li) detectors, Compton suppression spectrometer, mass-separated sources.

I. INTRODUCTION

The deformed nucleus ^{155}Gd has been of particular interest for several reasons: (1) a large number of intrinsic states occur at low energies; (2) the $N=6$ (even-parity) states derived from the $i_{13/2}$ shell are strongly intermixed by the Coriolis force[1] (resulting in a distorted band structure, which makes identification of the states more difficult); and (3) the $N=6$ states are also strongly admixed with $N=4$ states, because of level crossings that occur around 91 neutrons at a deformation $\delta\approx 0.3$.[2]

Although the cross sections for (d,p) and (d,t) reactions have played a major role[3-7] in the assignments of Nilsson states in ^{155}Gd, decay-scheme studies are involved in an important way because many of the levels observed in radioactive decay are too closely spaced to have been resolved in the reaction spectra.

The major uncertainties in the decay scheme of ^{155}Eu have been removed by recent studies.[8,9] The decay of ^{155}Tb, which is much more complex, has received considerable attention.[10-21] However, there remain uncertainties and inconsistencies in the level placements and spin assignments, particularly due to the presence of intense, unobserved low-energy transitions,[8] which leads to misleading interpretations of γ-γ coincidence studies.[12]

In this paper we report results of high-resolution γ-ray and conversion-electron spectroscopy of ^{155}Tb decay. The experiments were initiated to establish a better level scheme based on accurate γ-ray energies, to observe weakly populated levels, to establish firmer spin, parity, and multipolarity assignments, and to better understand the level structure of ^{155}Gd. Calculations of mixing between even-parity single quasiparticle states are presented and compared with the experimentally determined level structure of ^{155}Gd; vibrational states are identified and compared to corresponding states in neighboring even-even nuclei.

II. EXPERIMENTAL

A total of 11 separate sources of ^{155}Tb were prepared by the reactions ^{155}Gd(p,n), ^{153}Eu$(\alpha,2n)$, and ^{154}Gd$(\alpha,3n)^{155}$Dy(EC). All but a few of the targets were enriched in the appropriate isotope. Chemical purification was done with standard ion-exchange techniques.[22] Several sources were subjected to isotopic purification in the Livermore isotope separator to reduce the amount of ^{154}Tb impurity.

γ-ray spectra were measured with a variety of Ge(Li) spectrometers. A low energy photon spectrometer (LEPS) Ge(Li) detector with a resolution of 450 eV full width at half maximum (FWHM) at 122 keV was used primarily to study the region below 370 keV. The region between 100 and 400 keV was also studied with a Compton-suppression spectrometer.[23] The spectrum above 400 keV was studied primarily with a 19-cm^3 planar and a 30-cm^3 coaxial detector, the latter having a reso-

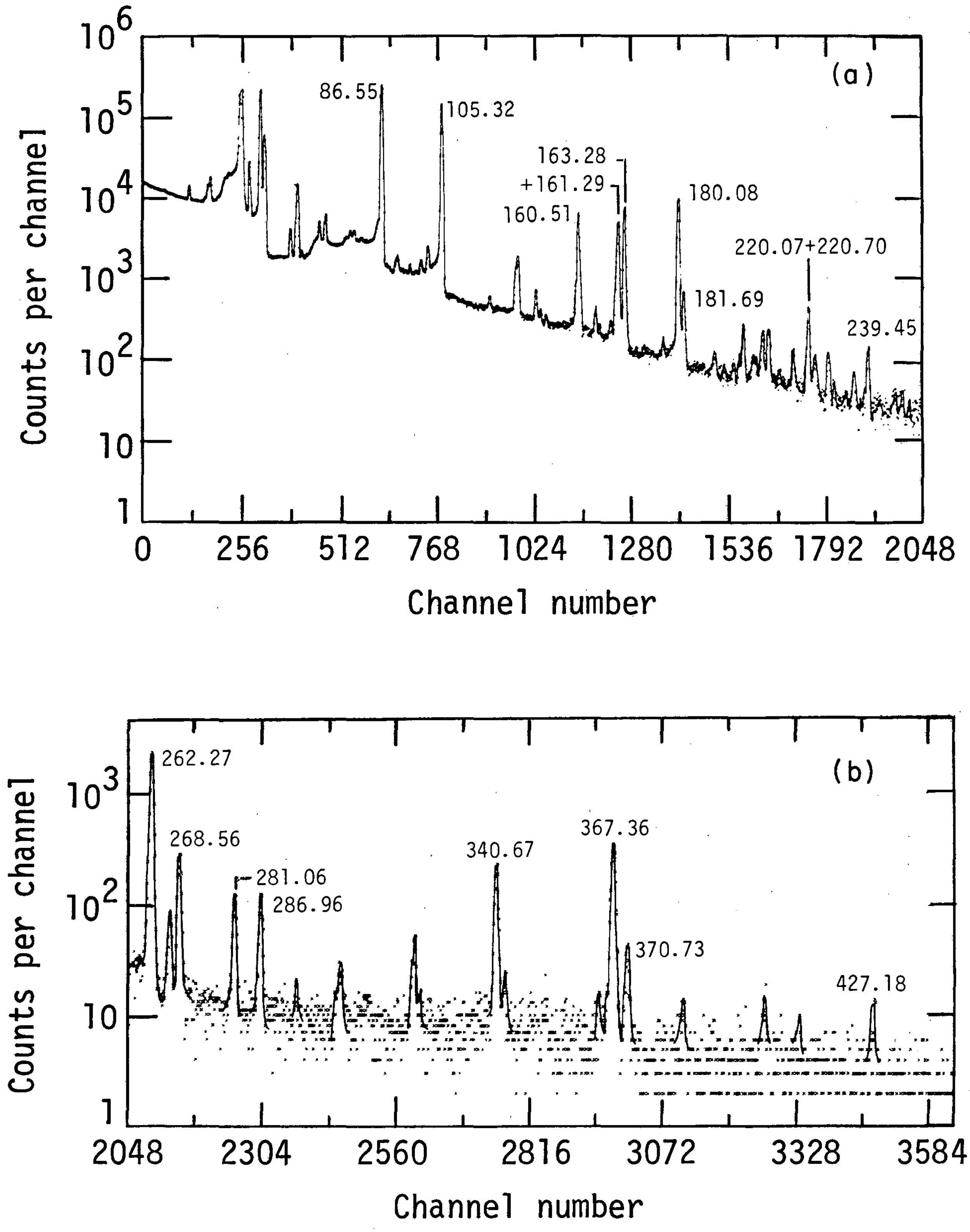

FIG. 1. γ-ray spectrum of mass separated ^{155}Tb measured with a high-resolution Ge(Li) spectrometer: (a) 0 to 250 keV and (b) 250 to 430 keV.

lution of 1.9 keV at 600 keV. Large source-to-detector distances were used to reduce summing that otherwise results from numerous coincidences between low-energy γ rays and x rays. In several measurements, calibrated lead absorbers were used to further reduce summing.

The activity for the conversion-electron measurements was produced by the reaction $^{154}Gd(\alpha, 3n)^{155}Dy(EC)$, and sources were prepared by vacuum sublimation of $^{155}DyCl_3 + ^{155}TbCl_3$ from a tungsten filament onto thin aluminum backings. Measurements were begun after allowing a week for the 10-h ^{155}Dy to decay; the only impurity lines observed were a few strong transitions from ^{155}Dy appearing in the early spectra.

Electron spectra were measured with a 2-mm-thick by 1-cm^2 Si(Li) detector whose resolution was 1.8 to 2.2 keV in the region of interest (40 to 700 keV). The electron energy scale is easily established by comparison with the measured γ-ray energies. The relative efficiency of the electron detector was determined by measuring standard sources, primarily $^{180}Hf^m$; it was found to be almost independent of energy below 700 keV.[24]

To correct for the response of the Si(Li) detector to low-energy γ rays, the spectrum was also measured with an aluminum absorber placed between source and detector to stop the electrons. This γ-ray spectrum was normalized to, and subtracted from, the electron (+γ ray) spectrum before analysis.

All electron and γ-ray spectra were analyzed with shape-fitting programs[25] on CDC-6600 computers.

III. RESULTS

The γ-ray spectrum of an isotopically separated source measured with the high-resolution Ge(Li) detector is shown in Fig. 1. The measured energies and intensities, summarized from all our data, are given in columns 1 and 2 of Table I.

Comparison of our results with a previous γ-ray spectrum of the stronger transitions, measured by Blichert-Toft, Funk, and Mihelich,[12] shows generally good agreement, although below 100 keV our intensities are systematically lower. The intensities reported in the more recent work of Bakhru, Shastry, and Boutet[16] agree poorly with our values, and their spectrum appears to contain impurity lines.

Figure 2 shows most of the conversion-electron spectrum. Because a number of the observed lines, particularly at low energies, are too complex to be meaningfully analyzed, we have used some higher resolution data obtained with permanent-magnet spectrographs[10,13] to supplement our measurements. A comparison of our relative electron intensities with those of Harmatz, Handley, and Mihelich[10] shows agreement to better than 10% for strong lines, which is remarkable in view of the photographic recording method used by them. Below 40 keV the intensities of Harmatz *et al.* are seen to be systematically low by comparison with the electron intensities of Foin, Oms, and Barat[26] measured in the decay of ^{155}Eu.

The conversion-electron spectrum reported by Kormicki *et al.*,[13] which contains more detail than that of Harmatz *et al.*[10] except at the lowest and highest energies, appears from our data to

TABLE I. γ-ray transitions observed in the decay of ^{155}Tb.

γ-ray energy (keV)	Relative intensity γ ray	Relative intensity transition	Conversion coefficient [a]	Assigned multipolarity	Placement in level scheme
10.4 [b]		≈183 [c]		$M1, \lesssim 0.06\% E2$ [d]	$B\frac{7}{2}^+ \to B\frac{9}{2}^+$
18.769(15)	2.52(15)	≈870	$\alpha_L \approx 243$ [b]	$M1 + 6.5(3)\% E2$ [d,e]	$B\frac{3}{2}^+ \to B\frac{5}{2}^+$
21.0 [f]		≈170 [g]		$E2$ [e]	$B\frac{9}{2}^+ \to B\frac{5}{2}^+$
26.533(6)	15.7(5)	47	$\alpha_{L_I} \approx 0.3$ [h]	$E1$	$B\frac{5}{2}^+ \to A\frac{5}{2}^-$
31.43(9)	0.9(2) [i]	62	$\alpha_{L_{III}}$ 27(7) [b]	$M1 + 17(5)\% E2$	$B\frac{7}{2}^+ \to B\frac{5}{2}^+$
39.8 [f]	$I_{L_I} \approx 0.7$ [h]				Not placed
40.7 [f]		Weak [h]			Not placed
45.299(5)	63.9(8)	92	α_L 0.36 [h]	$E1$	$B\frac{3}{2}^+ \to A\frac{5}{2}^-$
55.650(8)	0.08(6)				$K\frac{5}{2}^- \to K\frac{3}{2}^-$
57.983(5)	8.17(22)	18.5	α_{L_I} 0.12 [h]	$E1$	$B\frac{7}{2}^+ \to A\frac{5}{2}^-$
59.63? [f]	$\{ I_{L_{III}}$ 1.2 [j]; $I_\gamma < 1$	$4 \lesssim I \lesssim 7$	$\alpha_{L_{III}} > 1.2$	$(M1 + \gtrsim 20\% E2)$	$G\frac{3}{2}^+ \to G\frac{1}{2}^+$

TABLE I *(Continued)*

γ-ray energy (keV)	Relative intensity γ ray	Relative intensity transition	Conversion coefficient[a]	Assigned multipolarity	Placement in level scheme
60.012(3)	44.2(15)	458	$\alpha_L 1.54(12)$	$M1+3.8(4)\%\,E2$ [d,e]	$A\frac{5}{2}^- \to A\frac{3}{2}^-$
61.490(38)	1.14(15)	2.4	$\alpha_{L_I} 1.2$ [h]	$M1+\approx 15\%\,E2$	$G\frac{5}{2}^+ \to G\frac{3}{2}^+$
79.2 [f]	$\{I_K \approx 0.8$ [h]; $I_\gamma < 1\}$			Not $E1$	Not placed
80.6(1)	0.6(4)	2	≈ 1.0	$(E1)$	$G\frac{1}{2}^+ \to E\frac{3}{2}^-$
86.0 [f]	$I_K \approx 2$	2		$M1$ [k]	$A\frac{7}{2}^- \to A\frac{5}{2}^-$
86.55(3)	1276(25)	1830	$\alpha_L 0.053(2)$	$E1$	$B\frac{5}{2}^+ \to A\frac{3}{2}^-$
99.02(25)	3.46(15)	11.0	$\{1.7$ [h]; $\alpha_L 0.30(9)\}$	$M1(+E2)$ [e]	$G\frac{1}{2}^+ \to D\frac{3}{2}^+$
101.16(1)	6.37(35)	20	$\{2.2$ [h]; $\alpha_L 0.40(8)\}$	$M1(+\approx 20\%\,E2)$	$G\frac{3}{2}^+ \to D\frac{5}{2}^+$
102.4(1)	0.6(2)	1.7	≈ 1.8 [h]	$E2$ or $M1$	Not placed
103.3(1)	0.4(2)	1.1	≈ 3 [h]	Predominantly $M1$	$(K\frac{3}{2}^- \to H\frac{5}{2}^-)$
105.318(3)	1000	1256	$\{0.24(3)$; $\alpha_L 0.034(2)\}$	$E1$	$B\frac{3}{2}^+ \to A\frac{3}{2}^-$
118.0 [f]	$\{I_K 0.2$ [h]; $I_\gamma < 0.1\}$		>2 [h]	Not $E1$	Existence doubtful
120.59(31)	2.74(25)	3.2	0.13 [h]	$E1$	$C\frac{5}{2}^+ \to A\frac{7}{2}^-$
125.1(1)	0.2(1)				Not placed
129.3(1)	0.25(15)				{Possibly $H\frac{3}{2}^- \to F\frac{5}{2}^-$ or $721.06 \to J\frac{3}{2}^-$}
132.0(1)	0.3(1)				Possibly $J\frac{1}{2}^- \to G\frac{3}{2}^+$
136.2(1)	0.15(10)				{Possibly $H\frac{1}{2}^- \to E\frac{3}{2}^-$ or $J\frac{1}{2}^- \to H\frac{1}{2}^-$}
138.29(7)	0.96(9)	1.7	0.8 [h]	$(M1)$	$((G\frac{5}{2}^+) \to C\frac{7}{2}^+)$
141.5(1)	0.16(8)	0.3	0.9	$(M1)$	$K\frac{3}{2}^- \to H\frac{3}{2}^-$
146.05(3)	1.9(4)	3.1	≈ 0.5 [l]	$(E2)$	$A\frac{7}{2}^- \to A\frac{3}{2}^-$
148.64(1)	105.5(9)	176	$\{\alpha_L 0.080(3)$; $K/L\,6.4(4)\}$	$M1+2(1)\%\,E2$ [e]	$C\frac{5}{2}^+ \to B\frac{7}{2}^+$
150.63(5)(doublet?)	1.19(7)	1.4	≈ 0.32 [j]	$(E2)$	$D\frac{3}{2}^+ \to B\frac{7}{2}^+$
158.57(5)	1.73(9)	2.7	≈ 0.44 [j]	$(M1)$	$G\frac{3}{2}^+ \to D\frac{3}{2}^+$
159.1(1)	0.3(1)	≈ 0.4			{$C\frac{5}{2}^+ \to B\frac{9}{2}^+$ (or $K\frac{3}{2}^- \to G\frac{5}{2}^+$, $H\frac{5}{2}^-$)}
160.51(10)	31.1(6)	48	0.40 [j]	$M1(+E2)$ [e]	$G\frac{3}{2}^+ \to C\frac{5}{2}^+$
161.29(1)	109.8(11)	167	$\{0.44(2)$; $K/L\,6.7(5)\}$	$M1+\approx 9\%\,E2$ [e]	$C\frac{5}{2}^+ \to B\frac{3}{2}^+$
162.6 [f]	$I_L \approx 0.7$	≈ 1			$(G\frac{5}{2}^+ \to D\frac{5}{2}^+)$
163.28(1)	176.9(18)	253	$\{0.429(15)$; $K/L\,6.5(4)\}$	$M1+\approx 1\%\,E2$ [e]	$D\frac{3}{2}^+ \to B\frac{3}{2}^+$
169.0(1)?	0.1(1)				Possibly $K\frac{3}{2}^- \to H\frac{1}{2}^-$
175.29(2)	1.77(18)	2.4	≈ 0.32 [j]	$(M1)$	$F\frac{5}{2}^- \to A\frac{7}{2}^-$
178.0(1)?	0.3(2)				Not placed
180.08(1)	297(6)	412	$\{0.321(12)$; $K/L\,6.5(4)\}$	$M1+3\%\,E2$ [e]	$C\frac{5}{2}^+ \to B\frac{5}{2}^+$
181.69(9)	16.8(2)	17.8	≈ 0.08 [j]	$E1$	$E\frac{3}{2}^- \to B\frac{3}{2}^+$
182.1(1)	4.4(2)	6.1	≈ 0.30 [j]	$(M1)$	$D\frac{3}{2}^+ \to B\frac{5}{2}^+$

TABLE I *(Continued)*

γ-ray energy (keV)	Relative intensity γ ray	transition	Conversion coefficient [a]	Assigned multipolarity	Placement in level scheme
185.3(1)?	0.3(2)				Not placed
186.0(1)?	0.05(5)				Not placed
188.3(1)	0.097(43)				Not placed
191.4(1)	0.036(15)	0.05	≈0.27	$(M1)$	$J\frac{3}{2}^- \to H\frac{1}{2}^-$
193.3? [f]	$I_K \approx 0.11$ [l]				Not placed
200.411(4)	9.16(20)	9.6	0.04 [l]	$E1$	$E\frac{3}{2}^- \to B\frac{5}{2}^+$
201.0(10)	0.5(3)	≈0.6			$G\frac{5}{2}^+$ or $H\frac{5}{2}^- \to E\frac{3}{2}^-$
203.37(2)	1.15(12)	1.2			$F\frac{5}{2}^- \to B\frac{7}{2}^+$
206.54(2)	6.77(45)	7.1	0.03 [l]	$E1$	$C\frac{5}{2}^+ \to A\frac{5}{2}^-$
208.05(5)	9.18(45)	11.4	{ 0.18 [j] α_L0.037(3) [m]	$M1(+E2)$	$D\frac{5}{2}^+ \to B\frac{7}{2}^+$
208.58(5)	2.29(45)	2.4	≈0.05 [l]	$E1$	$D\frac{3}{2}^+ \to A\frac{5}{2}^-$
216.02(5)	5.44(38)	5.6			$F\frac{5}{2}^- \to B\frac{3}{2}^+$
218.4(1)?	0.3(2)	0.4			$(D\frac{5}{2}^+ \to B\frac{9}{2}^+)$
220.07(5)	6.63(19)	6.9	0.045(30)	$(E1)$	$H\frac{5}{2}^- \to D\frac{3}{2}^+$
220.70(5)	20.24(20)	24.8	0.21(2)	$M1$, ≲10% $E2$	$D\frac{5}{2}^+ \to B\frac{3}{2}^+$
222.0(1)	0.8(4)	≈1			$G\frac{5}{2}^+$ or $H\frac{5}{2}^- \to C\frac{5}{2}^+$
226.95(1)	5.91(8)	7.1	0.19 [j]	Predominantly $M1$	$E\frac{3}{2}^- \to A\frac{5}{2}^-$
230.2(1)?	0.07(3)				Not placed
232.33(2)	0.69(8)	0.8	0.3 [l]	$(M1)$	$C\frac{7}{2}^+ \to B\frac{7}{2}^+$
234.78(1)	1.32(8)	1.3			$F\frac{5}{2}^- \to B\frac{5}{2}^+$
237.5(4)	0.11(8)				Possibly $J\frac{1}{2}^- \to F\frac{5}{2}^-$
239.45(1)	9.03(8)	10.4	0.155(6)	$M1$, <6% $E2$	$D\frac{5}{2}^+ \to B\frac{5}{2}^+$
242.80(2)	0.62(3)	0.7	0.103(21) [n]	$E2$ or $E2+M1$	$C\frac{7}{2}^+ \to B\frac{9}{2}^+$
245.00(9)	0.11(6)				Possibly $C\frac{7}{2}^+ \to B\frac{3}{2}^+$
246.05(9)	0.05(2)	0.09	≤0.2		$K\frac{3}{2}^- \to E\frac{5}{2}^-$
248.6(1)	0.2(1)	≈0.4	≤0.3		Not placed
261.25(1)	1.58(25)	1.8	≈0.12 [l]	$(M1)$	$F\frac{5}{2}^- \to A\frac{5}{2}^-$
262.27(1)	210.6(21)	240	{ 0.118 [a] K/L7.09(22)	$M1$	$G\frac{1}{2}^+ \to B\frac{3}{2}^+$
266.02(8)	0.11(1)	0.11			$(D\frac{5}{2}^+ \to A\frac{5}{2}^-)$
268.56(1)	28.3(19)	29	0.019(4) [o]	$E1$	$D\frac{3}{2}^+ \to A\frac{3}{2}^-$
271.0(5)?	0.08(5)				Possibly $K\frac{3}{2}^- \to F\frac{5}{2}^-$
275.38(8)	0.12(5)				Not placed
278.6(1)?	0.1(1)				Not placed
281.06(1)	12.05(15)	12.9	{ 0.055(2) [p] K/L4.4(4)	$E2$	$G\frac{1}{2}^+ \to B\frac{5}{2}^+$
286.96(1)	12.62(25)	14.0	0.090(4) [q]	$M1$, <20% $E2$	$E\frac{3}{2}^- \to A\frac{3}{2}^-$
290.2(1)	0.08(3)	0.08			{ Possibly $C\frac{7}{2}^+ \to B\frac{5}{2}^-$ or $J\frac{1}{2}^- \to D\frac{3}{2}^+$
294.75(15)	0.05(2)	0.05			$(721.06 \to G\frac{3}{2}^+)$
303.1(1)?	0.09(6)				Not placed

TABLE I *(Continued)*

γ-ray energy (keV)	Relative intensity γ ray	Relative intensity transition	Conversion coefficient [a]	Assigned multipolarity	Placement in level scheme
304.6(5)?	≤0.05				Not placed
305.11(10)	0.12(5)	0.13	0.08(5)	($M1$)	$K\frac{3}{2}^- \to E\frac{3}{2}^-$
309.21(3)	0.19(3)	0.20			$G\frac{3}{2}^+ \to B\frac{7}{2}^+$
317.9(1)	0.08(4)	0.08			$H\frac{1}{2}^- \to B\frac{3}{2}^+$
321.83(1)(complex?)	7.2(3)	7.7	0.057(3)	$M1+\approx 37\%\ E2$	$G\frac{3}{2}^+ \to B\frac{3}{2}^+$
323.53(8)	0.9(3)	0.9			$K\frac{3}{2}^- \to D\frac{3}{2}^+$
325.44(9)	0.18(5)	0.18			$K\frac{3}{2}^- \to C\frac{5}{2}^+$
328.1(3)?	0.08(4)				Possibly $J\frac{3}{2}^- \to E\frac{3}{2}^-$
336.56(1)	1.3(1)		0.023(5) [r]	($E1+M2$ or $E2$?)	Not placed
340.67(1)	47.1(9)	50	{ 0.0572(20); K/L 7.0(4)	$M1$, <20% $E2$	$G\frac{3}{2}^+ \to B\frac{5}{2}^+$
342.58(5)	0.31(8)	≈0.32			$G\frac{5}{2}^+$ or $H\frac{5}{2}^-$ $\to A\frac{7}{2}^-$
344.0(9)	0.3(3)				Not placed
346.036(25)	0.26(4)	0.27	0.015(12)	($E2$)	$E\frac{5}{2}^- \to A\frac{3}{2}^-$
349.1(9)	0.039(16)				Not placed
364.06(1)	0.46(8)				$H\frac{3}{2}^- \to B\frac{5}{2}^+$
367.36(1) [s]	92.3(8) { ≈57 [s]; ≈37 [s]	93.2	{ 0.008 64(26); K/L 7.3(4)	$E1(+\approx 0.2\%\ M2)$	{ $G\frac{1}{2}^+ \to A\frac{3}{2}^-$; $G\frac{3}{2}^+ \to A\frac{5}{2}^-$
370.73(1)	9.07(25)	9.6	{ 0.046(2); K/L 7.3(4)	$M1$, <10% $E2$	{ $G\frac{5}{2}^+ \to B\frac{7}{2}^+$; (+721.06 $\to C\frac{7}{2}^+$?)
379.14(3)	0.28(8)	0.28			$K\frac{5}{2}^- \to D\frac{3}{2}^+$
381.06(3)	0.21(2)	0.21			{ $G\frac{5}{2}^+ \to B\frac{9}{2}^+$; (or $K\frac{5}{2}^- \to C\frac{5}{2}^+$)
383.35(1)	1.03(15)	1.08	{ 0.035(14); α_L 0.0078(18)	Predominantly $M1$	$G\frac{5}{2}^+ \to B\frac{3}{2}^+$
390.62(1)	0.75(15)	0.79	0.045(10)	Predominantly $M1$	$H\frac{3}{2}^- \to A\frac{5}{2}^-$
391.60(1)	0.12(5)	0.14	0.15(7)	$M1(+E0)$	$I\frac{5}{2}^- \to A\frac{5}{2}^-$
394.6(5)	0.08(5)	0.08			721.06 $\to D\frac{5}{2}^+$
396.0(5)	0.08(1)				Not placed
402.16(1)	2.87(18)	3.0	0.044(3)	$M1(+E0)$	$G\frac{5}{2}^+ \to B\frac{5}{2}^+$
427.18(1)	1.09(3)	1.10	0.0056(12)	$E1$	$G\frac{3}{2}^+ \to A\frac{3}{2}^-$
428.7(1)	0.04(2)	0.04			$G\frac{5}{2}^+$ or $H\frac{5}{2}^-$ $\to A\frac{5}{2}^-$
445.98(1)	0.39(9)	0.40			$K\frac{3}{2}^- \to A\frac{7}{2}^-$
450.64(2)	1.12(9)	1.15	0.0246(30)	$M1(+E2)$	$H\frac{3}{2}^- \to A\frac{3}{2}^-$
451.60(2)	0.39(9)	0.40	0.024(14)	$M1$ or $E2$	$I\frac{5}{2}^- \to A\frac{3}{2}^-$
454.45(1)	0.79(8)	0.82	0.0272(32)	Predominantly $M1$	721.06 $\to C\frac{5}{2}^+$
474.11(15)?	≤0.015				Not placed
484.8(1)?	0.012(6)				Not placed
486.88(15)	0.96(8)	0.97	0.0057(11)	$E1(+M2?)$	$K\frac{3}{2}^- \to B\frac{3}{2}^+$
488.65(15)	0.68(12)	0.68	0.0023(17)	$E1$	$G\frac{5}{2}^+ \to A\frac{3}{2}^-$

TABLE I *(Continued)*

γ-ray energy (keV)	Relative intensity γ ray	transition	Conversion coefficient [a]	Assigned multipolarity	Placement in level scheme
493.9(1)?	0.014(7)				Not placed
496.1(1)	0.018(9)	0.018			$H\frac{7}{2}^- \to A\frac{5}{2}^-$
499.24(6)	0.037(6)	0.038			$J\frac{1}{2}^- \to A\frac{5}{2}^-$
501.70(7)	0.46(3)	0.47	0.0185(26)	$M1, \lesssim 50\% E2$	$K\frac{5}{2}^- \to A\frac{7}{2}^-$
505.52(1)	1.81(11)	1.82	0.0055(8)	$E1(+\approx 2\% M2)$	$K\frac{3}{2}^- \to B\frac{5}{2}^+$
509.7(2)	0.010(4)	0.010			$J\frac{3}{2}^- \to B\frac{3}{2}^+$
512.89(9)	0.051(8)	0.052			$J\frac{5}{2}^- \to A\frac{7}{2}^-$
529.76(6)	0.47(8)	0.47	0.0040(23)	$E1$	$K\frac{5}{2}^- \to B\frac{7}{2}^+$
532.09(5)	1.81(25)	1.83	0.0091(14)	Predominantly $E2$	$K\frac{3}{2}^- \to A\frac{5}{2}^-$
538.15(3)	0.013(8)				Not placed
542.45(3)	0.16(8)	0.16			$K\frac{5}{2}^- \to B\frac{3}{2}^+$
554.78(1)	0.79(9)	0.81	0.0182(24)	$M1, \lesssim 20\% E2$	$J\frac{3}{2}^- \to A\frac{5}{2}^-$
559.32(1)	5.38(32)	5.5	0.0162(11); K/L 8(1)	$M1, \lesssim 20\% E2$	$J\frac{1}{2}^- \to A\frac{3}{2}^-$
587.69(4)	0.16(3)	0.21	0.24(5); K/L 6.5(7)	$E0+E2, M1$	$K\frac{5}{2}^- \to A\frac{5}{2}^-$
592.08(1)	0.78(8)	0.95	0.174(19); K/L 5.9(5)	$E0+E2, M1$	$K\frac{3}{2}^- \to A\frac{3}{2}^-$
598.96(6)	0.093(11)	0.09			$J\frac{5}{2}^- \to A\frac{5}{2}^-$
603.25(15)?	0.03(2)				Possibly $721.06 \to B\frac{7}{2}^+$
614.80(1)	1.21(8)	1.22	0.0074(8)	$E2, <30\% M1$	$J\frac{3}{2}^- \to A\frac{3}{2}^-$
615.7(1)	0.08(6)	0.08			$721.06 \to B\frac{3}{2}^+$
634.51(9)	0.037(14)	0.037			$721.06 \to B\frac{5}{2}^+$
647.73(1)	0.56(5)	0.56	0.0045(10)	$E2, <20\% M1$	$K\frac{5}{2}^- \to A\frac{3}{2}^-$
658.93(15)	0.012(3)	0.012			$J\frac{5}{2}^- \to A\frac{3}{2}^-$

[a] The K-conversion coefficient is given unless otherwise noted. Electron intensities are normalized to the theoretical value (Ref. 27) $\alpha_K(M1)=0.118$ for the 262.27-keV transition. The K(262.27) intensity has been corrected for a 2.6% contribution from the L(220.07 + 220.70) lines.

[b] Measured in the decay of ^{155}Eu (Refs. 8 and 26).

[c] Calculated from the intensity of the 31.43-keV transition and the ratio $e^-(10.4)/e^-(31.43)$ measured in ^{155}Eu decay (Refs. 26 and 8).

[d] Multipolarity calculated from the L-subshell ratios measured in the decay of ^{155}Eu (Ref. 26).

[e] Multipolarity calculated from the L-subshell ratios (Refs. 10 and 13).

[f] Transition energy taken from Ref. 10 or 13.

[g] Estimated from the intensity of the 18.77-keV transition and the ratio $e^-(21.0)/e^-(18.77)$ reported in Ref. 10.

[h] Conversion line intensity from Ref. 10, normalized to our electron spectrum at the 105.32 K line.

[i] From the intensity of the 57.98-keV γ ray and the ratio $\gamma(31.43)/\gamma(57.98)$ measured in ^{155}Eu decay (Ref. 8).

[j] Conversion-line intensity from Ref. 10, normalized to our electron spectrum at the 262.27 K line.

[k] From the K/L ratio measured in ^{155}Eu decay (Ref. 26).

[l] Conversion-line intensity from Ref. 13, normalized to our electron spectrum at a nearby strong line.

[m] The L(208.05) intensity has been corrected for a 3% contribution from the L(208.58) lines.

[n] The K(242.80) intensity has been corrected for a 44% contribution from the L(200.41) lines.

[o] The K(268.56) intensity has been corrected for a 36% contribution from the M(220.07 + 220.70) and L(226.95) lines.

[p] The K(281.06) intensity has been corrected for a 23% contribution from the L(239.45) lines.

[q] The K(286.96) intensity has been corrected for a 4% contribution from the M(239.45) lines.

[r] The K(336.56) intensity has been corrected for a 54% contribution from the M(286.96) lines.

[s] The energy of this transition (367.36 keV) suggests it is complex; the two possible placements require $E_\gamma = 367.19$ and $E_\gamma = 367.60$ keV. From the measured α_K both γ rays must be predominantly $E1$. The approximate intensities of the two components are derived from the relative K-line intensities given in Ref. 13.

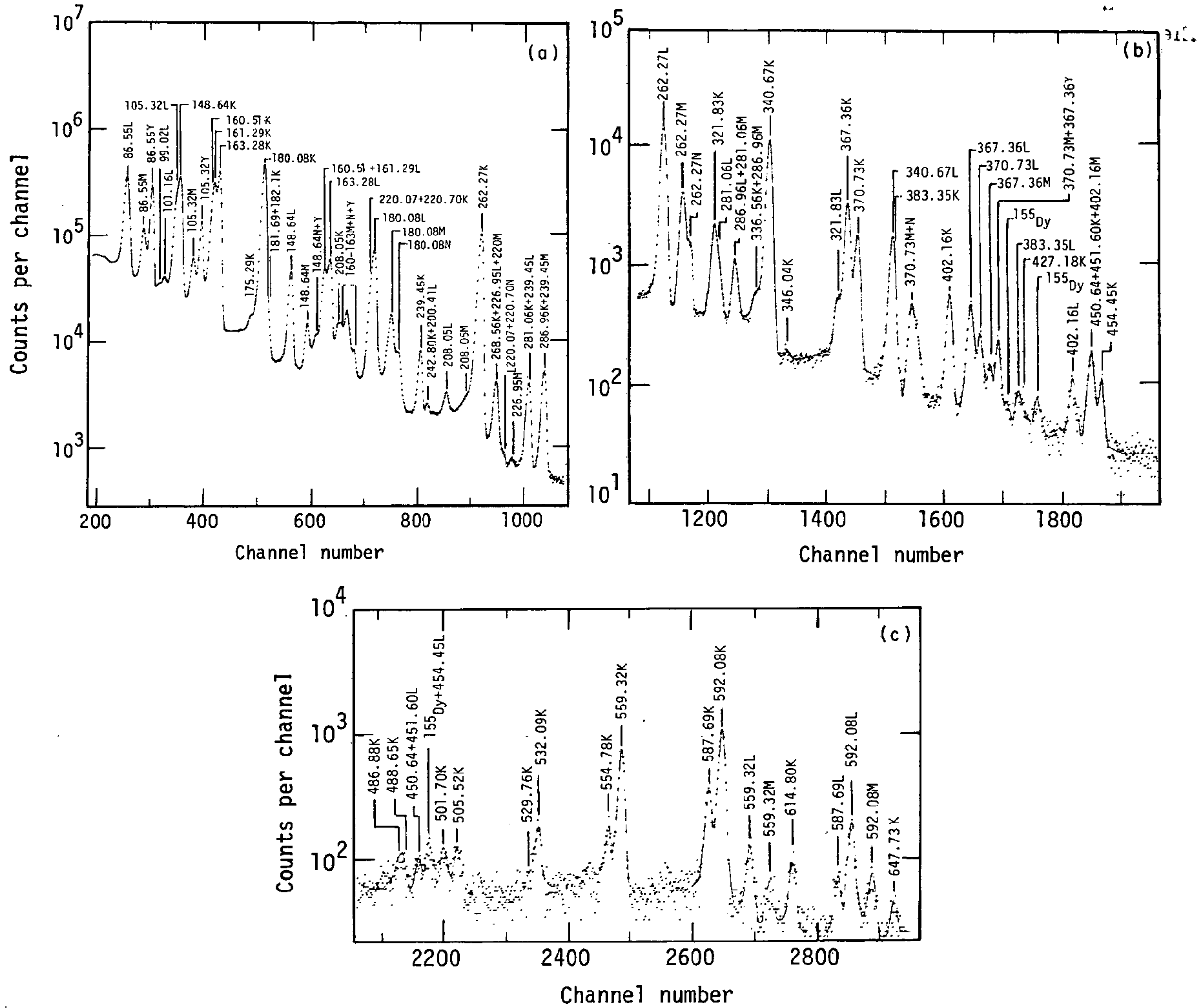

FIG. 2. Conversion-electron spectrum measured with a Si(Li) spectrometer: (a) 65 to 245 keV, (b) 245 to 420 keV, and (c) 420 to 605 keV.

have larger random uncertainties in the intensities, as well as to underestimate systematically the intensities of higher-energy electron lines. Consequently, we have used their data only to establish the approximate intensities of some weak lines relative to the intensities of stronger, adjacent lines.

Some minor reassignments of low-energy conversion lines are indicated by our γ-ray data and our analysis of previous electron data. The reported L_{II} and L_{III} lines of a 60.3-keV transition[10] are reassigned as $L_{III}(59.6)$ and $L_{I}(61.49)$, respectively; the 60.3-keV transition most probably does not exist. Tentative existence of the 59.6-keV transition is inferred from this L_{III} line only; the γ ray was not observed, and the L_{II} line is completely masked by $L_{I}(60.01)$. [The line reassigned by Kormicki[13] as $L_{I}(59.6)$ is, according to his electron and our γ-ray (limit) intensities, too strong for this assignment, unless the multipolarity is $M2$ or higher.]

Column 4 of Table I contains conversion coefficients based on our electron and γ-ray intensities, normalized to the theoretical K-conversion coefficient[27] of the 262.27-keV transition. Wherever electron data of Harmatz or Kormicki are used to derive a conversion coefficient, an explanatory footnote is appended to the value.

Column 5 of Table I contains multipolarities and mixing ratios, recalculated by us with the use of theoretical conversion coefficients.[27] They are based on the conversion coefficients (column 4) and (as noted in the footnotes) on previous measurements of L-subshell ratios.[10,13,26]

IV. DECAY SCHEME OF ^{155}Tb

The decay scheme shown in Fig. 3 is constructed from the transition energies, the intensity balance, and from previous coincidence results.[12,15,16] Electron-capture branching is deduced from the measured transition intensities (see column 3 of Table I). For those transitions whose conversion coefficients were not measured, the multipolarities expected from the level scheme were assumed in order to estimate transition intensities; the resulting uncertainties in these intensities are too small to affect significantly the calculated electron capture (EC) branchings.

The intensity of the ground-state EC transition is calculated from the K x-ray intensity (4654 ± 100 relative to 1000 for the 105.32-keV γ ray), with use of the K-fluorescence yield, $\omega_K = 0.934 \pm 0.022$,[28] and EC($K$)/EC(total) ratios based on recent electron radial wave functions calculated at Oak Ridge National Laboratory.[29] The net excess of K x-ray intensity over that accounted for by K conversion and K capture to excited states is 316 ± 163 (relative to 1000 for the 105.32-keV γ ray), which implies a ground-state EC branch of (9 ± 5)% of the total decays. Logft values shown in Fig. 3 are based on the value $Q_{EC} = 845 \pm 19$ keV.[30]

From the calculated feeding intensities, all radiation intensities can be renormalized to an absolute basis; the intensity of the 105.32-keV

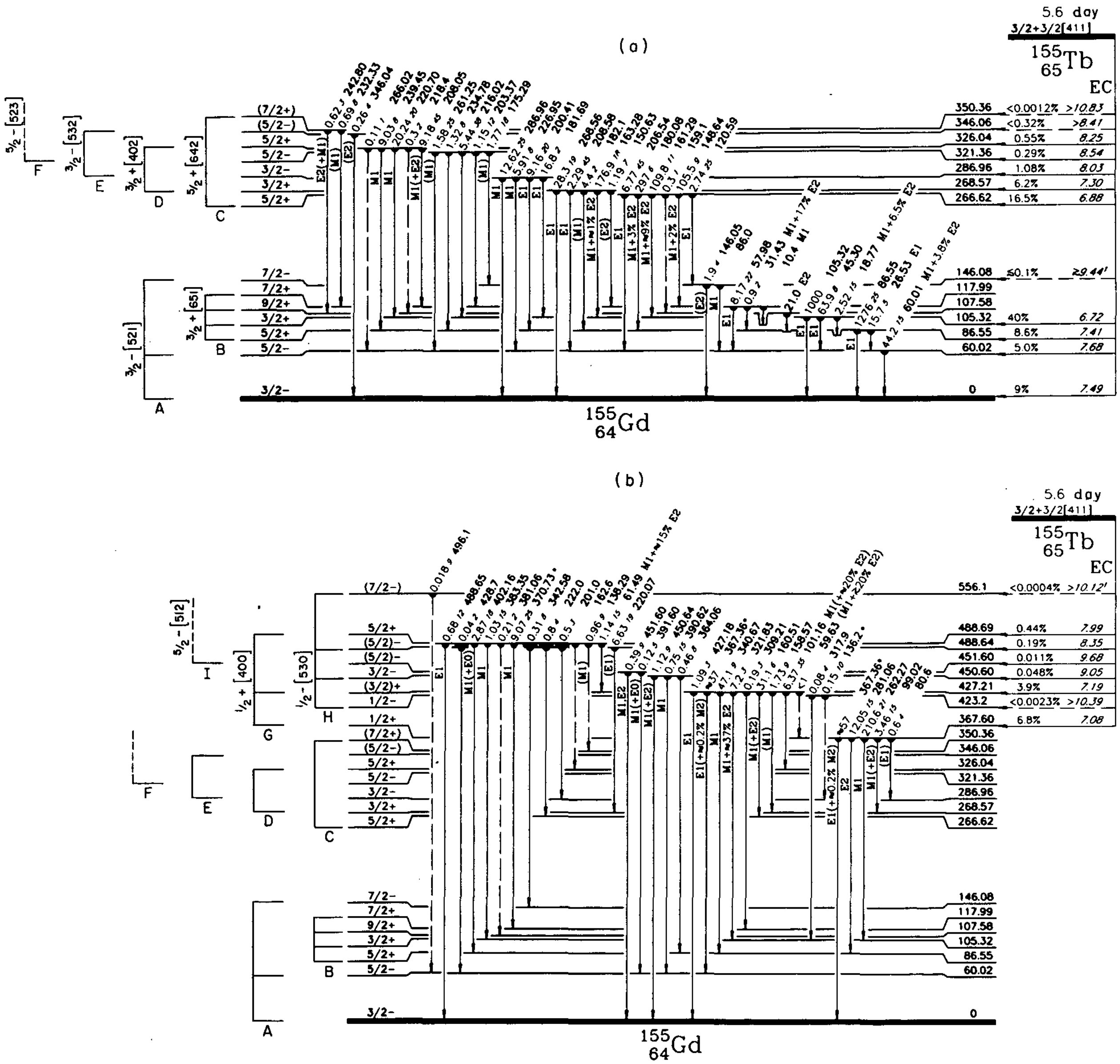

FIG. 3. Decay scheme of ^{155}Tb to levels of ^{155}Gd: (a) levels to 350 keV, (b) levels from 360 to 556 keV, and (c) levels from 556 to 730 keV.

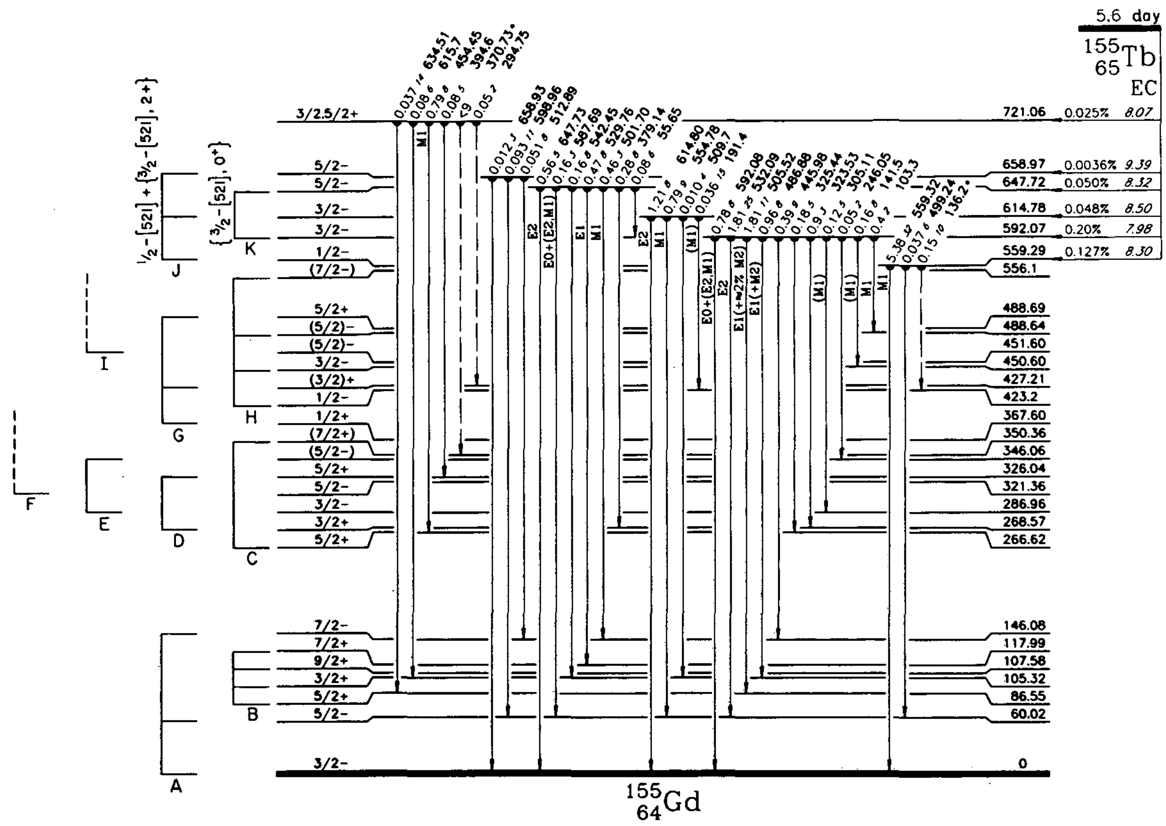

FIG. 3. *(Continued)*

γ ray deduced from this procedure is 23 ± 1 per 100 EC decays of ^{155}Tb.

Several new features of the level scheme warrant explanation. The existence of a level at 235.2 keV, proposed in previous studies,[12,14] is completely inconsistent with the present results. The observation of coincidences between the 148.64- and 86.55-keV γ rays, which was the original basis for the existence of the level,[12] is now readily understood in terms of the intermediate 10.4- and 21.0-keV transitions (see decay scheme and detail, Fig. 4).[8,26,31] Moreover, if one assumed that the 148.64-keV γ ray did feed the 86.55-keV state directly, the proposed placement of each of the other transitions[12,14-16] to the hypothetical 235.2-keV state (191.4 and 216.02 keV) and from it (129.3, 175.29, and 234.78 keV) is inconsistent with the transition energy, the multipolarity, or both. (Previous measurements of the energy of the 234.78-keV γ ray were too high, due to a failure to account properly for summing effects.) Similar arguments based on our data refute the existence of states at 706 and 881 keV proposed by Kormicki *et al.*[13]

Harmatz, Handley, and Mihelich[10] originally proposed that a 12.7-keV transition deexcites the 117.99-keV state to balance the intensity populating the state. The 10.4-keV transition is now known to account for the missing intensity. In fact, no transition of 12.7 keV has ever been observed, although a weak 12.64-keV $E2$ transition ($B_{7/2^+} \rightarrow B_{3/2^+}$) is expected from the decay scheme.

The presence of two states within about 0.1 keV of 488.7 keV required by the measured multipolarities of transitions populating and deexciting the doublet; these multipolarities define states of both parities. The presence of two levels at this energy is also readily understood in terms of the proposed band structure (see following section). In addition to the second member of this doublet, we propose new levels at 321.36, 346.06, 350.36,

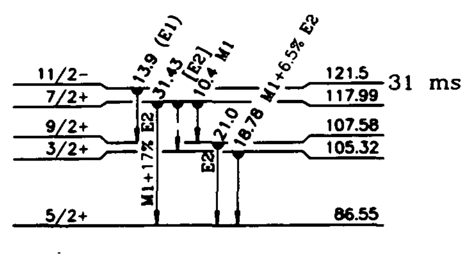

FIG. 4. Detail of decay of 118- and 121-keV levels.

423.2, 451.60, 556.1, 658.97, and 721.06 keV. Although not previously reported in the decay of ^{155}Tb, the existence of most of these states is known or inferred from reaction studies, as discussed below.

V. SPIN-PARITY AND CONFIGURATION ASSIGNMENTS

Figure 5(a) shows our summary of known odd-parity levels in ^{155}Gd, which have been assigned to single quasiparticle or collective configurations. Of the odd-parity bands shown, those labeled $\frac{3}{2}-[521]$, $\frac{11}{2}-[505]$, $\frac{1}{2}-[530]$, $\frac{1}{2}-[521]$ $+\{\frac{3}{2}-[521], 2+\}$, and $\{\frac{3}{2}-[521], 0+\}$ are well established from previous decay scheme[12-14] and reaction[3-6,32-38] studies. Collective aspects of the last two bands are discussed further in Sec. VII.

Our data provide a much firmer basis for assignment of the $\frac{3}{2}-[532]$ and $\frac{5}{2}-[523]$ Nilsson bands. We have designated the 321.36-keV state, whose spin and parity we determine unambiguously as $\frac{5}{2}-$, as the bandhead of the latter band. This assignment was originally proposed for a state around 282 keV.[3] Tjøm and Elbek[4] first assigned the 322-keV state as the $\frac{5}{2}-[523]$ bandhead from their (d,p) and (d,t) data as well as the (d,d') results of Sterba, Tjøm, and Elbek[5,32]; however, Kanestrøm and Tjøm[6] later reinterpreted the same data, taking into account Coriolis mixing between $N=5$ orbitals. Their reinterpretation is based on the assumption that the 322-keV state is a doublet consisting of the $\frac{3}{2}-[532]$ and $\frac{5}{2}-[523]$ bandheads, and that these are the lowest lying odd-parity states above the ground-state (and $\frac{11}{2}-[505]$) bands. Neither of these assumptions is consistent with the present spin assignments. Moreover, the $\frac{5}{2}+$ level at 326.04 keV would be expected to make a sizable contribution

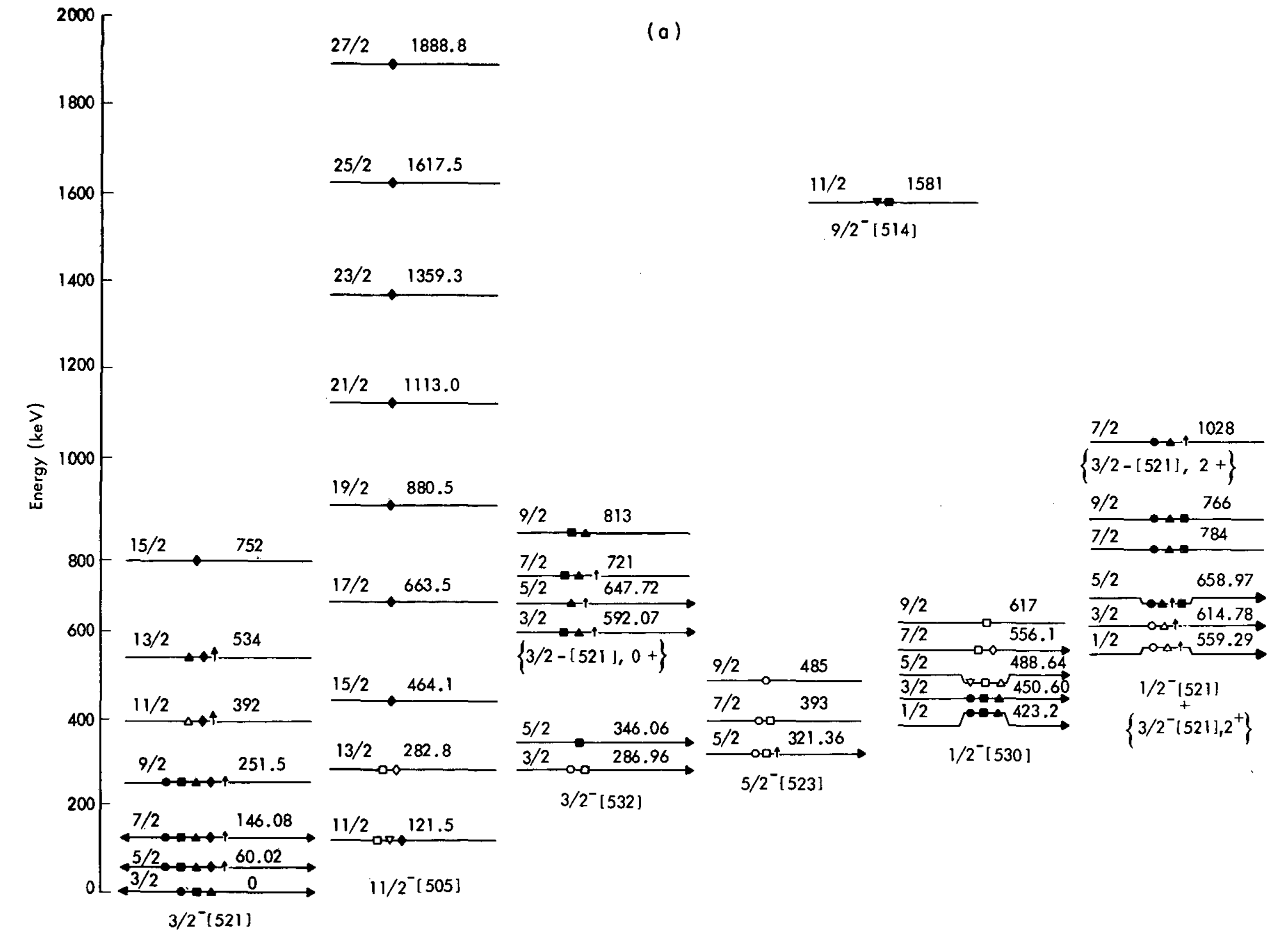

FIG. 5. Summary of levels of ^{155}Gd observed in radioactive decay and nuclear reactions: (a) odd-parity levels and (b) even-parity levels. The legend for (b) shows how the levels are populated: solid symbols denote definite excitation in a given reaction or decay, open symbols indicate probable excitation, usually of one member of a closely spaced doublet.

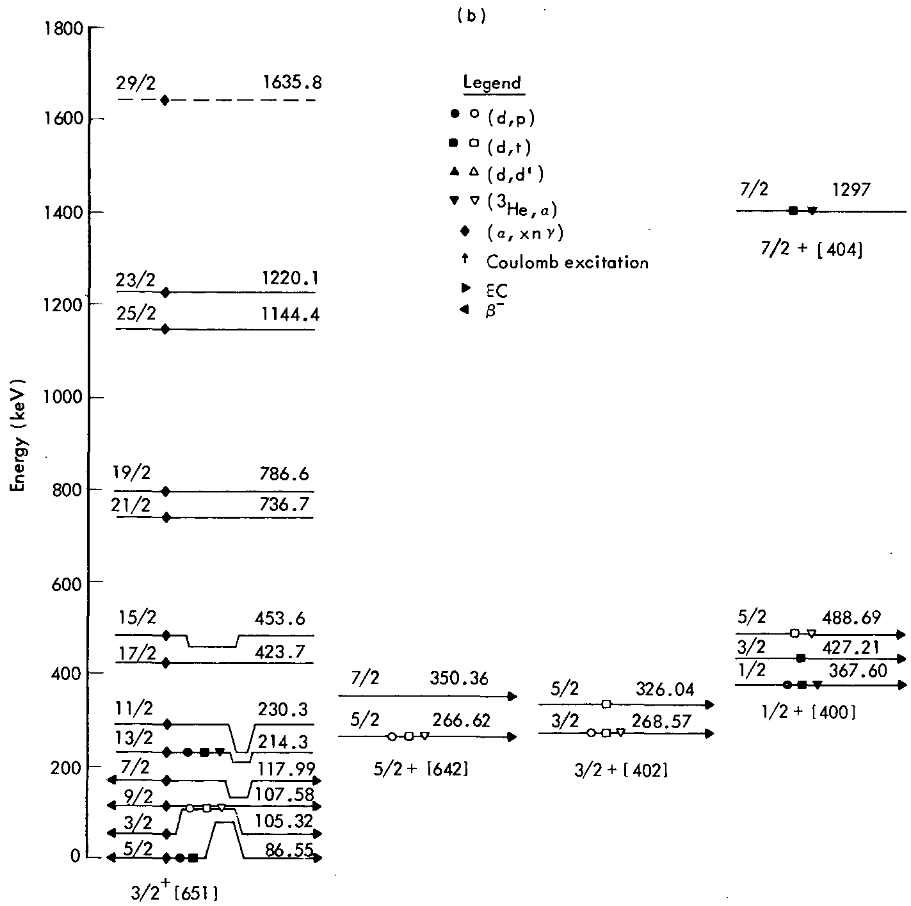

FIG. 5. *(Continued)*

to the (d,t) cross section for the "322-keV state," which was not taken into account by Kanestrøm and Tjøm, although the (d,t) angular distribution suggests the presence of an $l=2$ component.[5] The assignments of higher members of the $\frac{5}{2}-[523]$ band shown in Fig. 5(a) are those originally proposed by Tjøm and Elbek.[4]

The 286.96-keV state is assigned a firm spin and parity $\frac{3}{2}-$; we designate this state as the $\frac{3}{2}-[532]$ bandhead. The (d,p) and (d,t) data[4] suggest a possible doublet of unassigned states at 282 keV [from (d,t)] and 287 keV [from (d,p)]. The latter state is probably the 286.96-keV $\frac{3}{2}-$ state. The former, if it is a different state, could be the $\frac{13}{2}-\frac{11}{2}[505]$ state at 282.8 keV,[35] although this state is expected to have a negligible (d,t) cross section.[4] The interpretation of the 282-keV state as the spin-$\frac{5}{2}$ member of the $\frac{3}{2}+[402]$ band[5] is not consistent with our results.

We have tentatively assigned the 346.06-keV state as the spin-$\frac{5}{2}$ member of the $\frac{3}{2}-[532]$ band. A state at about this energy (345 keV) is observed in the (d,t) spectrum.[4] The cross section is much smaller than predicted for this assignment; however, the same apparent anomaly occurs with the state tentatively assigned the same configuration in ^{157}Gd.[4]

Even-parity states have been assigned to highly admixed bands based on the orbitals $\frac{3}{2}+[651]$, $\frac{5}{2}^{+}[642]$, $\frac{7}{2}+[633]$, $\frac{9}{2}+[624]$, $\frac{1}{2}+[660]$, $\frac{3}{2}+[402]$, and $\frac{1}{2}+[400]$. Of these, the $\frac{1}{2}^{+}[660]$, $\frac{7}{2}+[633]$, and $\frac{9}{2}+[624]$, bands have not yet been identified in ^{155}Gd. Recent reassignment of the spins of the 86.55-, 105.32-, 107.58-, and 117.99-keV levels, to which many of the other states are connected by γ-ray transitions, enables us to make firmer assignments to the higher lying even-parity (as well as odd-parity) states. Levels at 266.62, 326.04, and 488.69 keV can be assigned unambiguously as $\frac{5}{2}+$ states. The level at 268.57 is firmly established to be a $\frac{3}{2}+$ state, and the 427.21-keV level is almost certainly a $\frac{3}{2}+$ state also. The assignment $\frac{7}{2}+$ to the state at 350.36 keV is probable.

The band grouping of the even-parity states depicted in Fig. 5(b) is intended only as an approximate classification by the major components; the detailed structure of these states is discussed in the following section. Data on stripping and pickup reactions[3-5] are generally consistent with these assignments, but the interpretation of the experiments require revision because, as seen in the present work, almost all of the "states" observed in direct reactions must be complex. The $\frac{1}{2}+\frac{1}{2}[400]$ state at 367.60 keV is well established from (d,t) angular distributions and by the present results; the assignment of two higher lying members of this band was previously suggested in Ref. 5. Identification of the $\frac{3}{2}+[402]$ and $\frac{5}{2}+[642]$ bands in Fig. 5(b) is based on our new spin assignments.

Assignments for levels at 451.60 and 721.06 keV remain uncertain. The 451.60-keV state may be the $\frac{5}{2}-[512]$ bandhead. This particle state occurs in ^{159}Gd at 873 keV,[39] and might be expected to occur at lower energy in ^{155}Gd, because of a smaller deformation and greater softness toward deformation.

The 721.06-keV level could be a fragment of the $\frac{1}{2}+[660]$ rotational band. The calculated energy of the spin $\frac{5}{2}$ member of this band (see Sec. VI) is roughly consistent with this interpretation. However, such a state should decay predominantly to members of the $\frac{3}{2}+[651]$ band, rather than to the $\frac{5}{2}+[642]$ band, as does the 721.06-keV state.

Electron-capture decay rates are generally consistent with the spin-parity and Nilsson assignments discussed above. The ground-state spin of ^{155}Tb is $\frac{3}{2}$[40]; the state has been assigned a $\frac{3}{2}+[411]$ configuration.[39] All observed EC transitions are allowed ($\Delta I=0,1$, nor parity change) or first forbidden ($\Delta I = 0, 1$, parity change). The allowed transitions are all expected to be hindered, according to the selection rules for asymptotic quantum numbers[41]; the observed log*ft* values fall in the range of 7 to 8, representing a hindrance of 10^2 to 10^3 over the "normal" rate for unhindered transitions.

VI. MIXING BETWEEN EVEN-PARITY STATES OF ^{155}Gd

A. Energy levels and wave functions

Even parity states were fit to experimental level energies by conventional variation-plus-diagonalization procedures.[42] The energies of the unperturbed states are given by

$$E(I,K)=E(K)+\frac{\hbar^2}{2\mathcal{g}}\,[I(I+1)-K^2 + a_{\rm band}\delta_{K,1/2}(-)^{I+1/2}(I+1/2)],$$

where $E(I,K)$ is the unperturbed level energy, $E(K)$ is the quasiparticle energy of the single-particle state, $\hbar^2/2\mathcal{g}$ is the rotational constant, and $a_{\rm band}$ is the decoupling parameter of a specific $K=\frac{1}{2}$ rotational band. Semiempirical values for the single-particle energies were taken from the data of Ogle *et al.*[43]; energies for the $\frac{7}{2}+[633]$ and $\frac{9}{2}+[624]$ orbitals were fixed at these values, whereas the energies for other bands were permitted to vary.

The interaction between two states of the same spin was assumed to be

$$H=H_c+H_6.$$

Matrix elements of the Coriolis interaction H_c are given by

$$V_{K,K+1}=\frac{\hbar^2}{2\mathcal{g}}\langle K+1|j^+|K\rangle[(I-K)(I+K+1)]^{1/2} \times(U_KU_{K+1}+V_KV_{K+1})R_{\rm eff},$$

where the U's and V's are the BCS occupation numbers, and $R_{\rm eff}$ is a variable reduction factor. Matrix elements of the $\Delta N=2$ interaction H_6 are variable parameters assumed to be spin independent. A single rotational constant and a single Coriolis reduction factor were used for all bands, with the exception of $R_{\rm eff}$ for the $\frac{3}{2}[651]-\frac{5}{2}[642]$ interaction, which was varied independently.

Table II compares the band parameters and interaction strengths derived from our fit with the results of a similar calculation by Løvhøiden *et al.*[35] The major differences between our calculation and theirs are: (1) Allowance for a separate reduction factor $R_{\rm eff}$ for the $\frac{3}{2}[651]-\frac{5}{2}[642]$ interaction; (2) Variation of the decoupling parameter of the $\frac{1}{2}[400]$ rotational band

TABLE II. Fitted values of the parameters used in the diagonalization.

Parameter	Fitted value: Present work	Lovhøiden *et al.* (Ref. 35)
$E_{1/2[660]}$	817 keV	554 keV
$E_{1/2[400]}$	413 keV	385 keV
$E_{3/2[402]}$	223 keV	223 keV
$E_{3/2[651]}$	169 keV	168 keV
$E_{5/2[642]}$	233 keV	234 keV
$E_{7/2[633]}$	869 keV	1257 keV
$E_{9/2[624]}$	1809 keV	...
$R_{\rm eff}$	0.79	0.72
$R_{\rm eff}(\frac{3}{2}[651]-\frac{5}{2}[642])$	0.64	
$\langle\frac{1}{2}[400]\|H_\delta\|\frac{1}{2}[660]\rangle$	145 keV	50.0 keV
$\langle\frac{3}{2}[402]\|H_\delta\|\frac{3}{2}[651]\rangle$	74.5 keV	72.0 keV
$a_{1/2[660]}$	6.8	5.92
$a_{1/2[400]}$	−0.055	0.35
$\hbar^2/2\mathcal{g}$	13.9 keV	13.13 keV

(Løvhøiden *et al.* fixed this parameter at the theoretical value 0.35); (3) Inclusion of the $\frac{9}{2}$[642] orbital; (4) Inclusion of the Coriolis interaction between the $\frac{1}{2}$[400] and $\frac{3}{2}$[402] orbitals; and (5) Inclusion of the $\Delta N = 2$ interaction in the over-all fit, rather than adjustment of it to fit only the low-spin states.

Table III gives the energies and wave functions from our calculations. We have also performed the calculations under conditions similar to those of Løvhøiden *et al.*,[35] with results in good agreement, and under conditions identical except for one of the five differences noted above. The latter calculations demonstrate that difference (1) and, to a lesser extent, difference (2) are mainly responsible for the improvement in our calculated energies (see first columns of Table III).

The parameters derived from the fitting procedure (Table II) are in reasonable agreement with systematics in this region. The (d,t) cross sections calculated from our wave functions, which are very sensitive to the $\Delta N = 2$ admixtures, are in agreement with those measured (see Table IV). However, it is important to note that the level-energy fitting calculations predict correct (large) admixtures for a rather wide range of positive or negative $\Delta N = 2$ matrix elements, because the admixed bands are nearly degenerate in energy. The agreement between experimental and predicted reaction cross sections confirms the magnitude of the $\Delta N = 2$ admixtures in the wave functions, but not necessarily the interaction strengths. (The same comment applies to other transition probabilities, such as electromagnetic.)

B. Electromagnetic transition probabilities

γ-ray transition probabilities were calculated from the wave functions given in Table III. The $M1$ matrix elements for pure configurations were calculated from Nilsson's wave functions[44] for a deformation $\delta = 0.3$ and the neutron gyromagnetic ratios $g_l = 0$, $g_R = 0.3$, and $g_S = 0.6 g_S(\text{free}) = -2.29$. Interband $E2$ transitions were assumed to occur only by means of collective (rotational) components introduced by the mixing. The value of the intrinsic quadrupole moment was taken to be

TABLE III. Energy levels and admixtures in the wave function of even-parity states in ^{155}Gd.

	Level energy (keV)			Mixing amplitudes						
		Calculated								
Spin	Exp. [a]	This work	Ref. 35	$\frac{1}{2}$[400]	$\frac{3}{2}$[402]	$\frac{1}{2}$[660]	$\frac{3}{2}$[651]	$\frac{5}{2}$[642]	$\frac{7}{2}$[633]	$\frac{9}{2}$[624]
$\frac{1}{2}$	367.60	366.5	371.6	0.952		0.306				
		864.0	567.8	−0.306		0.952				
$\frac{3}{2}$	105.32	107.0	109.1	0.022	0.535	0.101	0.838			
	268.57	267.4	267.5	−0.133	0.838	−0.094	−0.520			
	427.21	427.6	432.7	0.972	0.104	0.178	−0.113			
		1186.2	847.4	−0.193	0.642	0.974	−0.117			
$\frac{5}{2}$	86.55	82.3	76.3	0.068	0.267	0.248	0.773	0.515		
	266.62	265.9	265.0	−0.002	−0.639	−0.098	−0.232	0.726		
	326.04	327.8	327.3	−0.292	0.688	−0.298	−0.405	0.435		
	488.69	489.2	468.6	0.878	0.216	0.257	−0.318	0.216		
		866.3	604.1	−0.374	0.235	0.880	−0.288	0.459		
$\frac{7}{2}$	117.99	118.8	116.5	0.030	0.191	0.142	0.707	0.647	0.152	
	(350.36) [b]	359.5	364.9	−0.051	0.771	0.065	0.300	−0.525	−0.182	
$\frac{9}{2}$	107.58	105.9	102.4	0.079	0.122	0.383	0.712	0.546	0.166	0.012
$\frac{11}{2}$	230.3	233.4	237.6	0.027	0.108	0.158	0.650	0.685	0.266	0.029
$\frac{13}{2}$	214.3	217.5	216.8	0.077	0.074	0.486	0.679	0.503	0.196	0.025
$\frac{15}{2}$	453.6	454.2	461.4	0.023	0.073	0.165	0.614	0.692	0.330	0.051
$\frac{17}{2}$	423.7	424.6	425.9	0.070	0.051	0.559	0.655	0.458	0.200	0.032
$\frac{19}{2}$	786.6	783.2	787.9	0.020	0.054	0.169	0.589	0.691	0.372	0.069
$\frac{21}{2}$	736.7	732.9	734.0	0.063	0.038	0.611	0.635	0.422	0.196	0.035
$\frac{23}{2}$	1220.1	1221.4	1217.5	0.018	0.043	0.170	0.571	0.689	0.402	0.085
$\frac{25}{2}$	1144.4	1146.1	1143.7	0.056	0.029	0.649	0.619	0.394	0.189	0.037
$\frac{29}{2}$	(1635.8) [b]	1666.7	1656.3	0.051	0.024	0.676	0.606	0.371	0.183	0.038

[a] Experimental energies between parentheses are not certain. Only the lowest calculated states of each spin (including all that correspond to observed levels) are given.

[b] Energy not fitted.

6.53 b.[45]

Experimental transition probabilities are compared with calculated values in Table V. Calculated $B(M1)$ values, in units of $(e\hbar/2M_pc)^2$, are given both for the mixed wave functions listed in Table III, and for pure configurations. $B(E2)$ values, based on the mixed wave functions, are in units of $10^{-48}\ e^2\ \text{cm}^4$.

The experimental values for the transitions from the 105.32-keV state are based on the measured half-life, 1.18 ± 0.02 ns.[16] Absolute decay rates for other states have not been determined; we have normalized to the theoretical $B(M1)$ for one transition from each level, for convenience in comparison of the relative rates.

Although the agreement between calculated and measured transition rates is only fair, the improvement introduced by the use of mixed wave functions is evident. The calculated transition probabilities also help to resolve one uncertainty in the decay scheme. The tentative 59.6-keV transition could, on the basis of energy and multipolarity, be placed either as an intraband transition from the 427.21-keV state ($G\frac{3}{2}+ \to G\frac{1}{2}+$) or as an interband transition from the 326.04-keV state ($D\frac{5}{2}+ \to C\frac{5}{2}+$). The latter placement would imply an unreasonably large $B(E2)$ value, whereas the former placement is consistent with both the measured $E2$ and $M1$ components of the transition.

Similar calculations have been performed for transitions depopulating levels below 150 keV,[46] and for the high-spin states observed in the ^{154}Sm$(\alpha, 3n\gamma)^{155}$Gd reaction.[35]

C. Magnetic moments of the 86.55-keV and 105.32-keV levels

The predicted magnetic moments of these levels should constitute a further test of the wave functions derived from energy-level fits. We have recalculated these moments, based both on the wave functions given in Table III and on pure wave functions, using the gyromagnetic ratios $g_R = 0.3$, $g_l = 0$, and $g_S = 0.6 g_S$(free). Table VI gives the present results, the results of a previous calculation based on mixed wave functions,[47,36] and the reported experimental values. Our calculated results are in agreement with the majority of the experimental values.[48-53] However, the discrepancy between the different experimental values precludes a definite conclusion concerning the quality of the wave functions.

VII. VIBRATIONAL BANDS

Deformed even-even nuclei around $N = 90$ exhibit prominent quadrupole-vibrational excitations at low energies.[54-56] In the odd-mass nucleus ^{155}Gd ($N = 91$), several such bands have been identified. The band labeled K [Fig. 3(c)] is characterized as a β vibration based on the ground-state band. The band labeled J is known to have a complex structure[39]; large $E2$ matrix elements[37] between band J and the ground-state band (A) result from a γ-vibrational component, whereas large cross sections for stripping reactions[4] result from the single-quasiparticle component $\frac{1}{2}-[521]$.

The present experiments better define the decay of these states, thus placing their vibrational character, particularly for the β-vibrational band, on a more quantitative basis. Based on our results and on absolute transition rates measured by Coulomb excitation,[37] we have calculated reduced $E0$ as well as $E2$ transition probabilities. Comparison with the values for ^{154}Gd and ^{156}Gd (Table VII) shows that the β-vibrational band in ^{155}Gd carries the full strength of the even-even phonon.

Curiously, recent microscopic calculations[57-59] predict that the lowest β-vibrational state in ^{155}Gd should be based largely (83%) on the $\frac{3}{2}-[532]$ quasiparticle state (the band labeled E), with only a minor component (8%) based on the $\frac{3}{2}-[521]$ ground state. Accordingly, $\rho^2(E0,\ K \to E)^{60-62}$ should be approximately equal to the values for

TABLE IV. ^{156}Gd$(d,t)^{155}$Gd cross sections for even-parity states.

Level energy (keV)	Spin	Theoretical $\frac{d\sigma(90°)}{d\Omega}$ [a] Pure state	Theoretical $\frac{d\sigma(90°)}{d\Omega}$ [a] Mixed state	Experimental $\frac{d\sigma(90°)}{d\Omega}$ [a]
86.55	$\frac{5}{2}$	15.5	16.0	12
105.32	$\frac{3}{2}^+$	0.62	152	241 (105.32 + 107.58)
107.58	$\frac{9}{2}^+$	49	96	
266.62	$\frac{5}{2}^+$	0.59	8.2	343 (266.62 + 268.57)
268.57	$\frac{3}{2}^+$	438	247	
321.36	$\frac{5}{2}^-$	5	b	95 (321.36 + 326.04)
326.04	$\frac{5}{2}^+$	35	81	
367.60	$\frac{1}{2}^+$	543	461	594
423.2	$\frac{1}{2}^-$	4.0	b	48 (423.2 + 427.21): ≈32
427.21	$\frac{3}{2}^+$	92	131	≈16
488.69	$\frac{5}{2}^+$	45	24	101 (488.69 + 488.77)
488.77	$\frac{5}{2}^-$	19	b	

[a] In units of μb/sr. Experimental values and distorted-wave Born approximation (DWBA) factors are from Ref. 4.

[b] Mixing between odd-parity states was not calculated.

TABLE V. Electromagnetic reduced transition probabilities.

Level energy (keV)	Transition energy (keV)	Experimental[a] $B(M1)$	Theoretical $B(M1)$[a] Pure state	Mixed state	Experimental[b] $B(E2)$	Theoretical $B(E2)$[b] mixed state
105.32	18.77	0.0049[c]	0.091	0.025	1.4	1.4
117.99	10.4	0.045[d]	0.113	0.045	$\lesssim$0.4	0.9
	31.47	≈0.002	0.081	0.019	0.50±0.15	1.0
266.62	161.29	0.17[d]	0.30	0.17	≈0.9	0.42
	180.08	0.37	0.69	0.079	0.52	0.32
	148.64	0.23	0.049	0.080	0.3±0.1	0.12
268.57	163.28	0.12[d]	0	0.12	≈0.06	0.0005
	182.10	0.0020	0	0.0020	···	0.08
	150.63	Pure $E2$			0.060±0.006	0.064
326.04	220.70	0.20[d]	0	0.20	$\lesssim$0.6	0.0003
	239.45	0.071	0	0.052	≤1.0	0.16
	208.05	0.11	0	0.091		0.04
367.60	262.27	0.072[d]	0	0.072	≤0.08	0.005
	99.02	0.020	0.0018	0.046	≈0.5	0.04
	281.06	Pure $E2$			0.062±0.002	0.050
427.21	59.6	<0.020	0.000 25	0.000 63	≈1.6	0.81
	101.16	0.026[d]	0.0011	0.026	≈0.7	0.0009
	160.57	0.041	0	0.0053		0.005
	340.67	0.0051	0	0.000 33	<0.01	0.0005
	321.83	0.000 75	0	0.000 075	≈0.006	0.005
	158.47	0.0023	0.000 74	0.000 047	···	0.07
	309.24	Pure $E2$			0.0005±0.0001	0.0002
488.69	402.16	0.0045	0	0.014	···	0.000 02
	370.73	0.018	0	0.0057	<0.02	0.004
	61.49	0.050[d]	0.54	0.50	<28	0.26
	383.35	0.0019	0	0.0021	0.019	0.025

[a] $B(M1)$ in units of $(e\hbar/2M_pc)^2$.
[b] $B(E2)$ in units of $10^{-48}e^2\,\text{cm}^4$.
[c] Value derived from the experimental half-life of the 105.32-keV level.
[d] Value used as the normalization point for this level.

neighboring even-even nuclei, whereas $\rho^2(E0, K\to A)$ should be ten times smaller, in obvious disagreement with experiment (see Table VII). The physical basis for these predictions is the prominence, in the calculated phonon structure, of two-quasiparticle components in which the $\frac{3}{2}-[521]$ orbital is occupied; according to the exclusion principle, such components cannot couple to a $\frac{3}{2}-[521]$ state in the odd-mass nucleus. Disagreement with experiment thus implies that the calculated phonon structure is incorrect.

The search for additional $E0$ transitions in ^{155}Gd would provide a sensitive test for β vibrations based on different single-quasiparticle states. The study of ^{155}Tb decay, as well as reaction studies, has revealed no such bands (other than the $\{\frac{3}{2}-[521], 0+\}$ band) to date. However, the present experiments do provide tentative evidence for small $E0$ components in two transitions other than those between the bands labeled K and A: 391.60-keV ($I\frac{5}{2}-\to A\frac{5}{2}-$) and 402.16-keV ($G\frac{5}{2}+\to B\frac{5}{2}+$). Since, according to the assigned configurations, $\Delta K\neq 0$ for either of these transitions,

TABLE VI. Magnetic moments of the 86.55- and 105.32-keV states.

	State 86.55 keV	105.32 keV
	Calculated values (μ_N)	
Pure state (present work)	+0.33	−0.13
Mixed state (present work)	−0.93	−0.026
Mixed state (Refs. 47 and 36)	−1.3	−0.33
	Measured values (μ_N)	
Ref. 48	−0.532±0.004	−0.52 ±0.02 or +0.14 ±0.02
Ref. 49	−1.01 ±0.23 −0.955±0.076	
Ref. 50	−0.98 ±0.11	+0.64 ±0.17
Ref. 51	+0.91 ±0.14	
Ref. 52		+0.13 ±0.04 or −3.39 ±0.06
Ref. 53		+0.068±0.020

TABLE VII. Comparison of the β-vibrational band in ^{155}Gd with β bands in the neighboring even-even nuclei.

	^{154}Gd [a]	^{155}Gd	^{156}Gd [b]
$\rho_K^2(E0, \beta \to g)$	0.080 ± 0.013 [c]	0.15 ± 0.10 [d] 0.053 ± 0.032 [e] <0.03 [f]	0.032 ± 0.006
$B(E2)/(C_{K_i 0 K_f}^{I_i 2 I_f})^2$	0.258 ± 0.035	0.13 ± 0.08	0.029 ± 0.004
$(e^2 b^2)$	$(0_\beta \to 2_g)$	$(K\frac{3}{2} \to A\frac{3}{2})$	$(0_\beta \to 2_g)$

[a] Data from Ref. 63.
[b] Data from Ref. 64.
[c] Average value for several members of the β-vibrational band.
[d] For the transition $K\frac{3}{2} \to A\frac{3}{2}$.
[e] For the transition $K\frac{5}{2} \to A\frac{5}{2}$.
[f] For the transition $K\frac{3}{2} \to E\frac{3}{2}$.

the $E0$ components must result from K impurities in the wave functions. The latter transition probably results from an admixture of the β-vibrational configuration $\{\frac{3}{2}+[651], 0+\}$ into the $\frac{1}{2}+[400]$ band (G); microscopic calculations[57-59] in fact predict that this configuration will lie quite low in energy. The $E0$ component of the 391.60-keV transition probably results from an admixture of the $\{\frac{3}{2}-[521], 0+\}$ configuration into the 451.60-keV state.

†This work was performed under the auspices of the U. S. Energy Research and Development Administration.

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