PHYSICAL REVIEW C VOLUME 18, NUMBER 4 OCTOBER 1978

$N = 85$ nuclei. II. Decay of 4.15-h $^{149}\mathrm{Tb}^g$ to levels of $^{149}\mathrm{Gd}$†

S. V. Jackson, J. W. Starner, W. R. Daniels, and M. E. Bunker
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545

R. A. Meyer
Lawrence Livermore Laboratory, University of California, Livermore, California 94550

(Received 14 March 1978)

The γ-ray spectrum accompanying the decay of 4.15-h $^{149}\mathrm{Tb}^g$ has been studied by Ge(Li) singles and coincidence spectroscopy. Sources were prepared via the $^{141}\mathrm{Pr}(^{12}\mathrm{C},4n)$ reaction and via spallation of Ta with 800-MeV protons. Chemical and isotopic separation techniques were employed to obtain pure sources. A total of 325 γ rays are attributed to the decay of $^{149}\mathrm{Tb}^g$, all of which have been placed in a $^{149}\mathrm{Gd}$ level scheme involving 80 excited states. The spin and parity of $^{149}\mathrm{Tb}^g$ is postulated to be $1/2^+$. The intensity of the direct β^+ + electron capture branch from $^{149}\mathrm{Tb}^g$ to the $^{149}\mathrm{Gd}$ ground state ($7/2^-$) is determined to be $(0.5 \pm 5.0)\%$. The intensity of the α-decay branch from $^{149}\mathrm{Tb}^g$ to $^{145}\mathrm{Eu}$ has been measured to be $(15.8 \pm 1.4)\%$. The observed level structure of $^{149}\mathrm{Gd}$ is discussed in terms of current nuclear models.

[RADIOACTIVITY $^{149}\mathrm{Tb}^g$ from $^{181}\mathrm{Ta}(p,\mathrm{spall.})$ and from $^{141}\mathrm{Pr}(^{12}\mathrm{C},4n)$, chemically and isotopically separated sources, measured E_γ, I_γ, $\gamma\gamma$ coin; $^{149}\mathrm{Gd}$ deduced levels, J, π, logft. Ge(Li) detectors.]

I. INTRODUCTION

Odd-mass nuclei three nucleons away from closed shells have recently been the subject of many experimental and theoretical studies in an effort to determine the applicability of the dressed n-quasiparticle model[1-8] and the three-particle-clustering model[9-22] to the nuclear structure of these nuclei. To date, most of this work has dealt with nuclei near the $Z = 28$ and $Z = 50$ closed shells (see especially Refs. 5 and 18–21 for theory and Refs. 23–27 for examples of experimental work). Recent attempts[28,29] to treat odd-mass nuclei near the $N = 82$ closed shell (especially $N = 85$ nuclei) with the above models have been hampered by a lack of detailed data on the level structure of these nuclei. This investigation, concerned with the levels of $^{149}\mathrm{Gd}$ as observed in radioactive decay, is part II of a series of studies, including Ref. 30 [part I($^{145}\mathrm{Nd}$)] and Ref. 31 ($^{147}\mathrm{Sm}$), undertaken to expand the basic experimental information on the $N = 85$ nuclei.

The most recent investigations of the decay of $^{149}\mathrm{Tb}^g$ (Refs. 32–35) and 4-min $^{149}\mathrm{Tb}^m(\frac{11}{2}^-)$ (Refs. 36 and 37) resulted in a proposed[38] level scheme for $^{149}\mathrm{Gd}$ involving 24 excited states below 3300 keV. However, in the $^{149}\mathrm{Tb}^g$ investigations, only 57 of the 94 observed γ rays were placed in the level scheme.[33,34] Also, in the recent *Nuclear Data Sheets* compilation[38] for $A = 149$, seven of the 24 proposed excited states were considered doubtful, and only seven states in $^{149}\mathrm{Gd}$ were assigned definite J^π values. In our work, we have observed 325 γ rays associated with the decay of $^{149}\mathrm{Tb}^g$ and have placed all of these in a level scheme of $^{149}\mathrm{Gd}$ consisting of 80 excited states below 3550 keV. We have confirmed the existence of only 14 of the 24 previously proposed excited states, and we have established definite J^π values for 14 states. In addition we have determined that the most probable spin and parity assignment for the parent $^{149}\mathrm{Tb}^g$ ground state is $\frac{1}{2}^+$, as opposed to the $(\frac{3}{2},\frac{5}{2})^+$ assignment previously assumed.[32-35,38]

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Source preparation

For initial γ-ray singles measurements, $^{149}\mathrm{Tb}^g$ sources were produced via the $^{141}\mathrm{Pr}(^{12}\mathrm{C},4n)$ reaction at 78-MeV bombarding energy at the Lawrence Berkeley Laboratory 88-inch cyclotron. Targets were bombarded for ≈ 8 h and then transported to the Lawrence Livermore Laboratory (LLL) for chemical processing and counting. The terbium fraction was separated by use of a high pressure ion exchange column.[30,39] Counting was initiated approximately 2 h after the end of irradiation, at which time the principal contaminants were 70-min $^{148}\mathrm{Tb}$, 3.1-h $^{150}\mathrm{Tb}$, and 17.6-h $^{151}\mathrm{Tb}$.

For the subsequent, more detailed, γ-ray singles measurements and for all $\gamma\gamma$ coincidence measurements, $^{149}\mathrm{Tb}^g$ sources were produced via spallation of tantalum with 800-MeV protons at the Clinton P. Anderson Meson Physics Facility (LAMPF). Two or three Ta foils, each 2.5 $\times 10^{-3}$ cm thick, were bombarded in the LAMPF

H$^-$ beam for 4–7 h at currents of 3–7 μA (total integrated current of 16–28 μA h). About 45 m after the end of bombardment, the Ta foils were dissolved and the group of rare-earth elements was isolated chemically. The radioactive products in this rare-earth fraction of mass $A = 149$, principally 4.15-h ^{149}Tb^g and 9.3-d ^{149}Gd, were then isolated with an electromagnetic isotope separator. Immediately prior to several of the ^{149}Tb^g singles measurements, the terbium fraction of the $A = 149$ source was isolated via ion exchange chromatography in order to reduce interference from the ^{149}Gd and ^{145}Eu daughters. Aside from the daughter contaminants, the only interfering activities that could be observed were trace levels of 3.1-h ^{150}Tb and 17.6-h ^{151}Tb. Typically, counting was started 2–3 hours after the end of irradiation for sources direct from the isotope separator (4–5 h if further chemical processing occurred).

B. γ-ray singles measurements

In the initial measurements at LLL, sources were counted for ≈16 h using a variety of large volume (50–70 cm^3) Ge(Li) detectors having full width at half maximum (FWHM) values at 1332 keV of 1.85–2.0 keV. On the basis of half-life data, ≈60 γ rays were definitely attributed to the decay of ^{149}Tb^g, and precise energy and relative intensity values were determined for these γ rays. The energies were obtained by simultaneously counting the ^{149}Tb^g sources and known γ-ray standards.[40,41] All spectra were analyzed using GAMANAL, the LLL spectrum analysis code.[42]

At Los Alamos Scientific Laboratory (LASL), the sources obtained were much stronger and contained fewer contaminants. The sources were counted over a period of 16–20 h, using large-volume Ge(Li) detectors (50–85 cm^3, FWHM = 1.9–2.0 keV) and employing various absorbers and source-detector geometries. After peaks resulting from γ-ray summing were eliminated, a total of 147 γ rays were found to be attributable to ^{149}Tb^g on the basis of half-life data. These γ rays are listed in Table I, with energy uncertainties indicated. The energies were obtained by calibrating against the strongest lines observed in the LLL experiments. All spectra were analyzed using OTTO, a LASL spectrum analysis code.[43]

By observing the growth and decay of daughter 9.3-d ^{149}Gd in a ^{149}Tb^g source initially free of ^{149}Gd, and by using the decay schemes for ^{149}Tb^g (this work) and ^{149}Gd (Refs. 38 and 44), we determined a direct ground-state β^+ + EC (electron capture) branch for ^{149}Tb^g of (0.5± 5.0)%. The previously reported[33,34] value was <9.0%.

By observing the growth and decay of daughter 5.9-d ^{145}Eu in a ^{149}Tb^g source initially free of ^{145}Eu, and by using the decay schemes for ^{149}Tb^g (this work) and ^{145}Eu (Refs. 45 and 46), we determined a value for the α-decay branch of ^{149}Tb^g to ^{145}Eu of (15.8± 1.4)%. This is in good agreement with the most recently reported values of (13± 4)% (Ref. 32) and (16.7± 2.0)% (Refs. 33 and 34).

C. γ-γ coincidence measurements

Two separate 4096×4096 channel γ-γ coincidence experiments were conducted at LASL, using a multiparameter pulse-height-analyzer system similar to ones described elsewhere.[23,47] In the first measurement two 55-cm^3 true-coaxial Ge(Li) detectors (FWHM≈ 2.0 keV at 1332 keV) were employed, and approximately nine million γ-γ coincidence events were recorded on magnetic tape. In the second measurement, larger volume true-coaxial Ge(Li) detectors (≈80 cm^3, FWHM≈ 2.1 keV) were employed to improve the efficiency for high-energy γ-ray events, and Cd absorbers (2.5×10^{-2} cm thick) were placed between the source and the detectors to reduce summing between γ rays and Gd x rays. In this second measurement, approximately 19 million γ-γ coincidence events were recorded on magnetic tape.

In both measurements the time resolution of the γ-γ coincidence system for γ rays from 70–3 500 keV was ≈13 nsec FWHM, and a coincidence time gate was set at the full-width-at-tenth-maximum (FWTM) of ≈28 nsec. The detectors were oriented at 180° relative to each other, and the source-to-detector distance was kept between 3 and 6 mm. Singles counting rates in the detectors were maintained at 5000–6000 counts/sec by periodically adding more source material and by adjusting the source-to-detector distance. Backscatter cross talk between the detectors was virtually eliminated by placing the source in a 5-mm diameter hole in a Pb plate 6 mm thick and centering this hole in front of the "dead" cores of the true-coaxial detectors.

The γ-γ coincidence event pairs (pairs of numbers, each between 0 and 4096) recorded on magnetic tape were analyzed using the LASL CDC-6600 computer system along with computer codes developed at LASL.[48] Coincidence gates were set on a total of 83 separate energy regions. The γ-ray peaks included in these gates are indicated in Table I and Fig. 1. Among the results of the γ-γ coincidence analysis, 17 peaks observed in the γ-ray singles measurements were determined to be unresolved multiplets. Including the members

TABLE I. γ-ray energies and intensities in the decay of ^{149}Tb^{g} to ^{149}Gd.

E_γ (ΔE_γ)[a,b]	I_γ (ΔI_γ)[a,c]	Note[d]	Assignment[e] (from/to)
98.1 (2)	17 (2)		1124/1026
117.2	2 (1)		1144/1026
164.98 (2)	2985 (35)	*X*	164/g.s.
187.22 (2)	487 (6)	*X*	352/164
219.7	1.2 (6)		1992/1772
252.3 (1)	10 (2)	*X, A*	1655/1402
289.3 (3)	8 (2)	*X*	1085/796
307.79 (7)	30 (2)	*X*	1124/817
317.4	7 (2)	*X*	1402/1085
321.9	2 (1)		1348/1026
347.7	15 (2)	*X, A*	1750/1402
352.24 (2)	3333 (10)	*X, B*	352/g.s.
378.5 (1)	14 (2)		1992/1614
388.57 (2)	2080 (15)	*X*	1205/817
390.3	13 (3)	(*X*)	1557/1167
413.3 (1)	14 (1)		1557/1144
432.5 (2)	8 (2)		1557/1124
446.7 (6)	3 (2)		1614/1167
448.4	5 (1)	*C*	1992/1544
449.1 (2)	12 (1)	*D*	. . .
449.6	7 (2)	*C*	1655/1205
464.85 (2)	640 (9)	*X*	817/352
469.9	1.0 (6)		1614/1144
472.4 (1)	26 (4)	*X*	1597/1124
488.1 (2)	10 (2)		1655/1167
511.00 (3)	765 (27)	*E*	m_0c^2
544.3	3 (1)		2158/1614
570.5	1.8 (9)		1557/1026
587.2	6 (2)	*X*	1614/1026
606.7	2 (1)		1402/796
614.2 (1)	19 (2)		2158/1544
620.7	8 (2)		2613/1992
625.7	3 (2)		1750/1124
628.4 (2)	9 (2)		1655/1026
648.0 (1)	69 (6)	(*X*)	1772/1124
652.12 (2)	1840 (25)	*X*	817/164
670.4	7 (2)	(*X*), *C*	1487/817
670.6 (1)	16 (1)	*X, D*	. . .
670.8	9 (2)	(*X*), *C*	2158/1487
674.61 (6)	77 (2)	*X*	1026/352
677.2 (1)	20 (2)	(*X*)	1844/1167
685.6	2.2 (8)	(*X*)	2088/1402
686.66 (8)	22 (2)	*X*	2300/1614
723.7	8 (2)	(*X*), *C*	2126/1402
723.7 (1)	20 (2)	*X, D*	. . .
723.8	12 (2)	(*X*), *C*	1750/1026
740.2 (1)	45 (2)	*X*	1557/817
746.0 (1)	34 (2)	*X*	1772/1026
772.65 (3)	182 (4)	*X*	1124/352
774.0	1.8 (9)	(*X*)	2261/1487
780.2	2.4 (6)		1597/817
786.8 (1)	15 (1)	*X*	1992/1205
791.8	7 (3)	*X*	1144/352
796.2	11 (3)	(*X*), *C*	796/g.s.
796.4 (2)	15 (2)	*X, D*	. . .
796.9	2 (1)	(*X*), *C*	1614/817
797.0	2 (1)	(*X*), *C*	2199/1402
817.1	1313 (20)	*X, S*	817/g.s.
817.11(2)	1320 (20)	*X, D*	. . .
817.5	7 (2)	(*X*), *C*	1844/1026
825.4	7 (2)		1992/1167
838.1 (2)	8 (1)		1655/817
853.43(1)	1750 (25)	*X*	1205/352
858.6	8 (2)	(*X*)	2261/1402
861.86(2)	940 (12)	*X*	1026/164
867.6	4.5 (9)		1992/1124
920.5	3 (1)	*X*	1085/164
944.4 (2)	5 (2)		2088/1144
952.7 (1)	18 (2)	(*X*)	2158/1205
955.71(5)	53 (3)	*X*	1772/817
963.6	4 (2)	(*X*)	2088/1124
965.63(5)	60 (3)	*X*	1992/1026
979.09(6)	56 (3)	*X*	1144/164
994.3	4 (1)	(*X*)	2199/1205
996.5 (1)	14 (1)	*X*	1348/352
[1001.7]	[⩽3]	(*X*), *C*	[2126/1124]
1002.1 (1)	35 (2)	*X, D*	. . .
1002.1	32 (2)	*X, C*	1167/164
1027.2 (2)	2 (1)		1844/817
1032.8	10 (3)	(*X*), *C*	2199/1167
1033.3 (1)	35 (2)	*X, D*	. . .
1033.4	28 (5)	*X, C*	2158/1124
1040.65(4)	165 (5)	*X*	1205/164
1045.9	4 (2)		2590/1544
1055.1	3 (1)	(*X*), *C*	2599/1544
1055.7 (1)	17 (2)	*X, D*	. . .
1055.8	14 (4)	*X, C*	2199/1144
1061.6 (1)	7 (1)		2088/1026
1069.6	3 (1)		2683/1614
1075.0 (1)	8 (1)		2199/1124
1085.5	6 (3)		1085/g.s.
1094.3 (3)	3 (1)		2261/1167
1102.5	3 (1)		2590/1487
1111.7	1.6 (8)		2599/1487
1117.5 (2)	12 (2)		2261/1144
1131.65(7)	89 (3)	*X*	2158/1026
1135.3 (1)	134 (4)	*X*	1487/352
1136.6	3 (2)	(*X*)	2261/1124
1139.5	4 (1)		2683/1544
1144.09(9)	33 (3)	*X*	1144/g.s.
1167.10(7)	55 (3)	*X*	1167/g.s.
1175.4	370 (15)	*X, C*	1992/817
1175.50(6)	390 (11)	*X, D*	. . .
1175.8	21 (4)	(*X*), *C*	2300/1124
1183.7 (2)	8 (2)		1348/164
1187.1	5 (3)		2590/1402
1191.89(8)	42 (3)	*X*	1544/352
1205.20(8)	43 (4)	*X*	1557/352
1205.6	⩽2	(*X*)	[1205/g.s.]
1234.7 (2)	7.5 (13)		2261/1026
1245.1	3 (1)		1597/352
1261.7 (2)	13 (2)		1614/352
1269.7	1.6 (9)		2757/1487
1273.9	1.6 (8)		2300/1026
1277.0	4 (2)		2482/1205
1280.8 (1)	10 (1)		2825/1544

TABLE I. (*Continued*)

E_γ (ΔE_γ)^{a,b}	I_γ (ΔI_γ)^{a,c}	Note^{d}	Assignment^{e} (from/to)
1302.92(8)	91 (3)	*X*	1655/352
1320.9	1.3 (6)		2808/1487
1322.7 (1)	10 (1)	*X*	1487/164
1337.5	2.2 (8)		2825/1487
1338.6	5 (2)	(*X*)	2482/1144
1341.19(6)	260 (10)	*X*	2158/817
1344.5	2 (1)	(*X*)	2999/1655
1357.8	1.3 (8)		2482/1124
1363.8	2.8 (7)		2569/1205
1366.0	2 (1)		3021/1655
1368.9	5 (1)		2913/1544
1379.1 (1)	42 (2)	*X*	1544/164
1384.4	2 (1)		2590/1205
1392.3 (3)	6 (2)		1557/164
1398.3 (3)	6 (2)		1750/352
1402.4	0.9 (5)	(*X*)	2999/1597
1402.4	1.0 (5)	(*X*)	2569/1167
1402.91(9)	49 (3)	*X*	1402/g.s.
1420.6 (1)	10 (1)	*X*	1772/352
1422.1	5 (2)	(*X*)	2825/1402
1425.6 (3)	7 (2)	*X*	2913/1487
1444.4	9 (2)	*X*	2261/817
1449.10(8)	106 (4)	*X*	1614/164
1465.1	1.2 (7)		2590/1124
1474.3	2 (1)		2599/1124
1477.7 (2)	8 (2)	*X*	2683/1205
1483.6 (1)	27 (3)	*X*	2300/817
1488.3	7 (2)		2613/1124
1490.3 (2)	20 (3)		1655/164
1492.2 (3)	12 (2)		1844/352
1497.0	4 (1)	(*X*)	2314/817
1497.6	1.8 (7)	(*X*)	2703/1205
1512.1 (2)	9 (2)	*X*	2999/1487
1515.3	4 (2)		2918/1402
1536.2	3 (1)	(*X*)	2703/1167
1539.6 (4)	6 (2)	(*X*)	2683/1144
1543.4 (3)	8 (2)	*X*	2569/1026
1544.1 (3)	9 (2)	*X*	1544/g.s.
1558.5 (1)	11 (2)		2683/1124
1563.2	1.4 (8)		2590/1026
1572.4	1.5 (8)		2599/1026
1574.8	6 (2)		2977/1402
1585.6 (1)	19 (1)	*X*	1750/164
1586.4	4 (1)	(*X*)	2613/1026
1592.4	5 (2)		3206/1614
1623.8	2.0 (9)		2767/1144
1632.3	3 (1)		2757/1124
1640.26(6)	360 (10)	*X*	1992/352
1641.3	1.6 (8)	(*X*)	2808/1167
1651.0	0.8 (5)		2999/1348
1656.2	2 (1)	*C*	2861/1205
1656.8	21 (2)	*C*	2683/1026
1656.8 (1)	26 (4)	*D*	. . .
1657.3	2.4 (9)	*C*	3201/1544
1662.3	2 (1)		3206/1544
1679.3 (1)	18 (2)		1844/164
1694.7	3 (2)		2861/1167
1699.5	3 (1)		3313/1614
1707.5 (3)	3 (1)		2913/1205
1718.9	1.0 (6)		3206/1487
1730.4	2.5		2757/1026
1736.3 (2)	6.5 (9)		2088/352
1751.0 (4)	4 (2)		[1750/g.s.]
1755.6	3 (2)		2922/1167
1755.8	2.3 (9)		2961/1205
1769.4	2 (1)	(*X*)	3313/1544
1772.7	2 (1)	(*X*), *C*	3175/1402
1772.8	2 (4)	(*X*), *S*	[1773/g.s.]
1772.8 (4)	10 (3)	*X*, *D*	. . .
1772.9	6 (2)	*X*, *C*	2590/817
1774.4	6 (2)	(*X*)	2126/352
1782.2 (1)	25 (2)		2599/817
1788.1	3 (1)		2913/1124
1794.1	1.7 (8)		2999/1205
1797.8	2 (1)		3003/1205
1798.2	16 (2)	*X*, *C*	2825/1026
1798.2 (1)	19 (2)	*X*, *D*	. . .
1798.5	3 (2)	(*X*), *C*	3201/1402
1803.5	1.7 (9)		3206/1402
1806.0 (1)	50 (3)	*X*	2158/352
1810.6 (2)	7 (1)		2977/1167
1826.0	9 (2)	(*X*), *C*	3313/1487
1826.9	1.0 (4)	(*X*), *C*	3175/1348
1827.38(6)	134 (5)	*X*, *D*	. . .
1827.5	124 (6)	*X*, *S*	1992/164
1835.0	2.5 (8)		2861/1026
1847.7 (1)	9 (1)		2199/352
1852.8	2 (1)		2977/1124
1855.6	3 (2)		2999/1144
1859.3	3 (1)		3403/1544
1874.6 (1)	30 (2)	*X*	2999/1124
1877.1	3 (2)	(*X*)	3021/1144
1877.7	2 (1)	(*X*)	3365/1487
1878.5	8 (2)	(*X*)	3003/1124
1895.9	0.7 (4)		2922/1026
1896.3	2.6 (9)		3021/1124
1909.3 (1)	25 (2)	*X*	2261/352
1912.7 (3)	7 (2)	*X*	3079/1167
1915.8	3 (1)	(*X*)	3403/1487
1916.1	4 (2)		3319/1402
1918.4	1.2 (6)		3124/1205
1923.4	1.1 (6)		2088/164
1931.0	1.2 (6)		3418/1487
1940.1 (1)	35 (3)	*X*	2757/817
1943.7	0.6 (4)		3149/1205
1948.5 (1)	46 (2)	*X*	2300/352
1950.9	1.6 (8)	(*X*)	2977/1026
1970.0	4 (1)		3175/1205
1972.9 (2)	18 (2)		2999/1026
1976.6	3 (2)		3003/1026
1991.8	4 (2)	*C*	2808/817
1992.2 (4)	12 (2)	*D*	. . .
1992.5	2 (4)	*S*	[1992/g.s.]
1993.3	6 (2)	*C*	2158/164
1994.4	3 (1)		3021/1026
2000.8	2 (1)		3206/1205

TABLE I. (*Continued*)

E_γ $(\Delta E_\gamma)^{a,b}$	I_γ $(\Delta I_\gamma)^{a,c}$	Note[d]	Assignment[e] (from/to)
2007.9 (1)	88 (3)	*X*	2825/817
2008.5	3 (2)	(*X*)	3175/1167
2024.4	1.6 (9)		3149/1124
2034.3	5 (3)	(*X*), *C*	3201/1167
2034.8 (1)	23 (3)	*X, D*	. . .
2034.8	19 (3)	*X, C*	2199/164
2044.7	1.7 (8)		2861/817
2050.7 (4)	5 (2)		3175/1124
2062.3	1.1 (7)		3206/1144
2073.0	3 (1)		3099/1026
2076.5	4 (1)		3201/1124
2096.5	4 (1)	*C*	2261/164
2096.9 (4)	7 (3)	*D*	. . .
2097.1	4 (1)	*C*	3124/1026
2105.6 (3)	10 (2)	*X*	2922/817
2108.2 (3)	9 (2)	*X*	3313/1205
2130.5 (2)	14 (2)	*X*	2482/352
2135.0	1.4 (7)	(*X*)	3340/1205
2135.7 (2)	12 (2)	*X*	2300/164
2148.8	4 (1)		3175/1026
2149.1	3 (1)		2314/164
2151.5	2 (1)		2503/352
2160.6	2.3 (9)		2977/817
2179.6	5 (1)	(*X*)	3206/1026
2182.6 (1)	48 (3)	*X*	2999/817
2186.3	3 (2)	(*X*)	3003/817
2188.6	3 (1)		3313/1124
2196.5	2.1 (7)		3340/1144
2204.1	3 (1)		3021/817
2212.9	2.2 (7)		3418/1205
2221.1	1.0 (6)		3365/1144
2231.5	2.4 (6)		3258/1026
2237.8 (1)	17 (2)		2590/352
2246.1	1.4 (7)		3272/1026
2247.0 (2)	17 (2)		2599/352
2253.7	2.9 (8)		3070/817
2261.0	16 (2)	*C*	2613/352
2261.0 (1)	19 (2)	*D*	. . .
2261.5	3 (3)	*S*	[2261/g.s.]
2282.6 (1)	43 (3)	*X*	3099/817
2317.9	1.9 (7)		3442/1124
2319.0	1.1 (5)		3486/1167
2338.7 (2)	9 (2)		2503/164
2358.5	0.8 (5)		3175/817
2384.3	1.0 (6)		3201/817
2389.3 (3)	5 (1)		3206/817
2409.9 (2)	11 (2)		2757/352
2414.0	0.8 (5)		3231/817
2415.8 (4)	3 (1)		2767/352
2434.5 (4)	5 (1)		2599/164
2440.0	0.7 (4)		3466/1026
2441.3	1.5 (7)		3258/817
2446.4	0.7 (4)	(*X*)	3473/1026
2448.2	13 (2)	*X*	2613/164
2455.8	3 (1)	(*X*), *C*	3272/817
2456.0 (3)	8 (2)	*X, D*	. . .
2456.2	5 (1)	*X, C*	2808/352
2472.7 (2)	11 (2)		2825/352
2478.3	2.7 (8)		2830/352
2496.4 (2)	11 (2)		3313/817
2508.3	0.7 (4)		3535/1026
2523.5	1.9 (7)		3340/817
2538.3 (4)	5 (2)		2703/164
2548.1	3 (1)		3365/817
2560.8 (1)	33 (2)		2913/352
2586.3	3 (1)		3403/817
2625.7	1.0 (5)		3442/817
2647.6 (1)	23 (2)		2999/352
2649.7	1.0 (5)		3466/817
2656.1	1.1 (6)		3473/817
2669.1	15 (2)		3021/352
2696.8	5 (2)		2861/164
2718.0	0.7 (4)		3535/817
2753.2	2.4 (8)		2918/164
2771.8 (1)	15 (2)		3124/352
2796.5	3 (1)	(*X*), *C*	2961/164
2797.1 (2)	10 (2)	*X, D*	. . .
2797.1	5 (1)	(*X*), *C*	3149/352
2812.7 (4)	4 (1)		2977/164
2823.3 (2)	9 (2)		3175/352
2834.7	3 (1)		2999/164
2838.4	3 (1)		3003/164
2849.2	1.8 (7)		3201/352
2854.2	3 (1)		3206/352
2856.0 (2)	9 (2)		3021/164
2878.9 (3)	7 (2)	*X*	3231/352
2892.0 (4)	3.5 (11)		3056/164
2905.8	1.9 (7)		3070/164
2906.1	1.4 (7)		3258/352
2920.7	1.0 (6)		3272/352
2935.1 (3)	11 (2)		3099/164
2942.6	3.1 (8)		3294/352
2959.0	<3	(*X*), *S*	[3124/164]
2961.3 (1)	93 (4)	*X*	3313/352
2961.4	<3	(*X*), *S*	[2961/g.s.]
2966.8	2.2 (7)		3319/352
3010.6 (3)	10 (2)		3175/164
3032.4	3.7 (8)		3384/352
3036.4 (5)	3 (1)		3201/164
3041.4	2 (1)		3206/164
3051.2	1.8 (7)		3403/352
3066.1	0.9 (5)		3231/164
3066.3	1.6 (7)		3418/352
3078.9	3 (1)		3431/352
3090.6	0.8 (4)		3442/352
3133.9 (5)	1.9 (5)		3486/352
3147.8	0.9 (4)		3500/352
3148.5	1.1 (6)		3313/164
3154.0 (5)	2.7 (7)		3319/164
3163.9 (4)	2.5 (5)		3516/352
3182.8 (4)	4 (1)		3535/352
3200.2 (2)	25 (2)	*X*	3365/164
3201.4	<2	*S*	[3201/g.s.]
3238.4	1.5 (5)		3403/164
3254.5	1.5 (7)		3418/164
3266.4 (4)	1.6 (4)		3431/164

TABLE I. *(Continued)*

E_γ $(\Delta E_\gamma)^{a,b}$	I_γ $(\Delta I_\gamma)^{a,c}$	Note[d]	Assignment[e] (from/to)	E_γ $(\Delta E_\gamma)^{a,b}$	I_γ $(\Delta I_\gamma)^{a,c}$	Note[d]	Assignment[e] (from/to)
3301.8	1.2 (6)		3466/164	3370.1	0.8 (4)		3535/164
3308.2 (3)	9 (2)	*X*	3473/164	3378.9 (4)	1.7 (6)		3544/164
3335.0	1.0 (3)		3500/164				

[a] The uncertainties are one standard deviation. Value shown as 98.1 (1), for example, means 98.1 ± 0.1.

[b] γ rays for which no energy uncertainty is given were seen only in the γ-γ coincidence experiment, and their relative intensities were deduced from coincidence intensities. The energies given in these cases are the level differences rounded to the nearest 0.1 keV.

[c] All intensities are relative to a value of 3333 for the 352.24-keV γ ray. Absolute intensities (in γ rays/1000 decays) may be obtained by multiplying by 0.0892 ± 0.0048.

[d] The notes mean the following: *X*: A gate was set on this γ ray in the γ-γ coincidence experiment. (*X*): This γ ray was included in a coincidence gate but was not the major γ ray in the gate. *A*: The γ-ray intensity has been obtained after correcting for the decay (Ref. 44) of the ^{149}Gd daughter. *B*: The intensity uncertainty is statistical. *C*: The γ-ray intensity was obtained from coincidence data. *D*: The quoted γ-ray energy and intensity is for a multiplet. *S*: The γ-ray intensity was obtained by subtracting all other components from the total multiplet intensity.

[e] All indicated assignments are confirmed by coincidence measurements except for those enclosed in brackets.

of these multiplets, a total of 178 additional weak γ rays, not resolved or observed in singles spectra, were revealed through the coincidence studies.

In Table I we list the transition energies, relative intensities, and decay scheme assignments for the 325 γ rays observed in the decay of 4.15-h $^{149}\mathrm{Tb}^g$, along with relative intensity limits for an additional eight γ rays. The decay scheme assignments for the observed γ rays are all supported by the γ-γ coincidence data. Transitions for which energy uncertainties are given were observed in γ-ray singles measurements. For those transitions observed solely in the γ-γ coincidence measurements, the relative intensity values were determined from relative coincidence intensities, and the energy values were determined from the transition assignment level energy differences (rounded to the nearest 0.1 keV).

III. DECAY SCHEME

Figures 1(a)–1(e) present our proposed decay scheme of 4.15-h $^{149}\mathrm{Tb}^g$. Energies and relative intensities of the γ rays are presented vertically above the γ-ray transition lines, with the relative intensity values in parentheses. Intensities given as (2985+1450) indicate γ-ray intensity plus conversion-electron[33,49] intensity. Transition lines with a solid dot at the upper end indicate γ rays which were gated in the γ-γ coincidence analysis, while those with an open circle at the upper end indicate γ rays which were included in a coincidence gate but were not the principal γ ray in the gate. All of the transitions shown were observed in one or more coincidence spectra except for the eight transitions indicated by dashed lines. The code letters $A, B, \ldots, F$ in the J^π assignment column are interpreted in the figure caption. The $\log ft$ and $\log f_1 t$ values were calculated from a detailed intensity balance for each level using (1) a value for the total β^+ + EC decay of 84.2% (this work), (2) a Q_{EC} value of 3697± 16 keV (Ref. 38), (3) a half-life value of 4.15 h (Ref. 50), and (4) the $\log(f_1^\epsilon+f_0^+)$ and $\log[(f_1^\epsilon+f_1^+)/(f_0^\epsilon+f_0^+)]$ tables of Gove and Martin.[51]

The placement of each of the 80 excited states in the ^{149}Gd level scheme is supported by one or more γ-ray coincidence relationships. Fourteen of these states were observed in previous radioactive decay studies.[33-38] No evidence was found to support the existence of the 10 previously proposed[33,34,38] levels at 1468.0, 1540.2, 1909.0, 1940.6, 2008.8, 2183.4, 2238.4, 2284.6, 2964.0, and 3273.8 keV. In each of these 10 cases, the γ rays used[33,34,38] to establish the level are now placed elsewhere on the basis of observed coincidence relationships. In addition, we have found no definite evidence for the ground-state transitions previously reported[33,34] to depopulate the 1205-, 1992-, and 3201-keV excited states. In each case the appropriate γ ray, in its full intensity, has been assigned elsewhere in the decay scheme on the basis of coincidence data, and an upper limit for the intensity of the ground-state transition has been determined (see Table I).

We postulate a spin and parity assignment of $\frac{1}{2}^+$ for the parent $^{149}\mathrm{Tb}^g$ in contrast with the previous assignment[32-35,38] of $(\frac{3}{2}^+, \frac{5}{2}^+)$. The latter assignment was made partly in analogy to the $(\frac{3}{2}^+, \frac{5}{2}^+)$ assignment then existing for ^{151}Tb. However, the ground-state spin of ^{151}Tb has now been measured[52] to be $J=\frac{1}{2}$, and an even parity for this state is strongly implied by α-decay hindrance factor determinations[53,54] and log*ft* values[55,56] (e.g., the β^+ + EC branch to the $\frac{5}{2}^-$ 108-keV level in ^{151}Gd has log*ft* = 7.9 and logf_1t = 9.2). The two nuclei ^{149}Tb^g and ^{151}Tb exhibit many similarities in their β^+ + EC and α decays. In their β^+ + EC decay, both predominantly populate low spin ($J=\frac{3}{2}$) states, and in both cases the direct population of the $\frac{5}{2}^-$ first excited state is weak (see Fig. 2). Neither parent directly populates the $\frac{7}{2}^-$ ground state nor the known $\frac{9}{2}^-$ excited state in its respective daughter. In the decay of ^{149}Tb^g we find no evidence for definite γ transitions to the ground state of ^{149}Gd ($J^\pi=\frac{7}{2}^-$) from any of the 66 excited states directly populated above 1 550 keV. A similar lack of ground-state γ transitions is seen[54-57] in the decay of $\frac{1}{2}^+$ ^{151}Tb to ^{151}Gd ($\frac{7}{2}^-$g.s.), whereas in the decay of $\frac{5}{2}^+$ ^{147}Eu to ^{147}Sm ($\frac{7}{2}^-$g.s.), ground-state transitions are observed[31] for 12 of the 15 excited states populated above 1 MeV. For both ^{149}Tb^g and ^{151}Tb, by far the strongest β^+ + EC decay branch is to a $\frac{3}{2}^-$ state at ≈1.0 MeV in the respective daughter, with the decay patterns for the two states being very similar (see Fig. 2). With regard to their α decay, both ^{149}Tb^g and ^{151}Tb decay to the $\frac{5}{2}^+$ ground state and the $\frac{7}{2}^+$ first excited state of their respective daughters ^{145}Eu and ^{147}Eu. The hindrance factors for the α decays of the two nuclei are similar, those for ^{149}Tb$^g \rightarrow {}^{145}$Eu being[53,58,59] 9 ($\frac{5}{2}^+$, g.s.) and 170 ($\frac{7}{2}^+$, 329 keV) and those for ^{151}Tb → ^{147}Eu being[53] 7.2 ($\frac{5}{2}^+$, g.s.) and 92 ($\frac{7}{2}^+$, 229 keV). In view of the strong parallels observed in the decays of ^{149}Tb^g and $\frac{1}{2}^+$ ^{151}Tb, we assign a J^π value of $\frac{1}{2}^+$ to ^{149}Tb^g.

The spin and parity (J^π) assignments of the levels of ^{149}Gd observed in the β^+ + EC decay of 4.15-h ^{149}Tb^g are shown in Figs. 1(a)-1(e). These assignments are based on log*ft* values for the β^+ + EC decay, the γ-ray deexcitation patterns between levels, the earlier conversion-electron measurements,[35] and analogy with level assign-

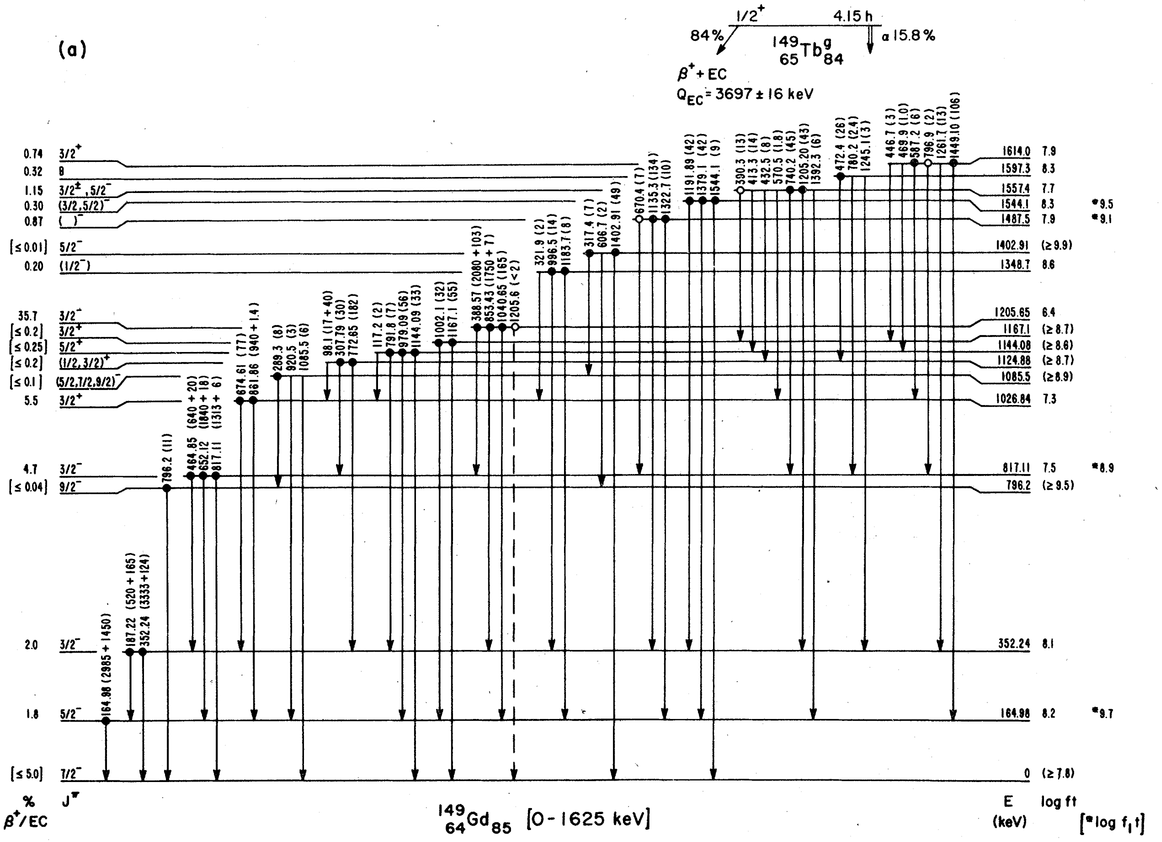
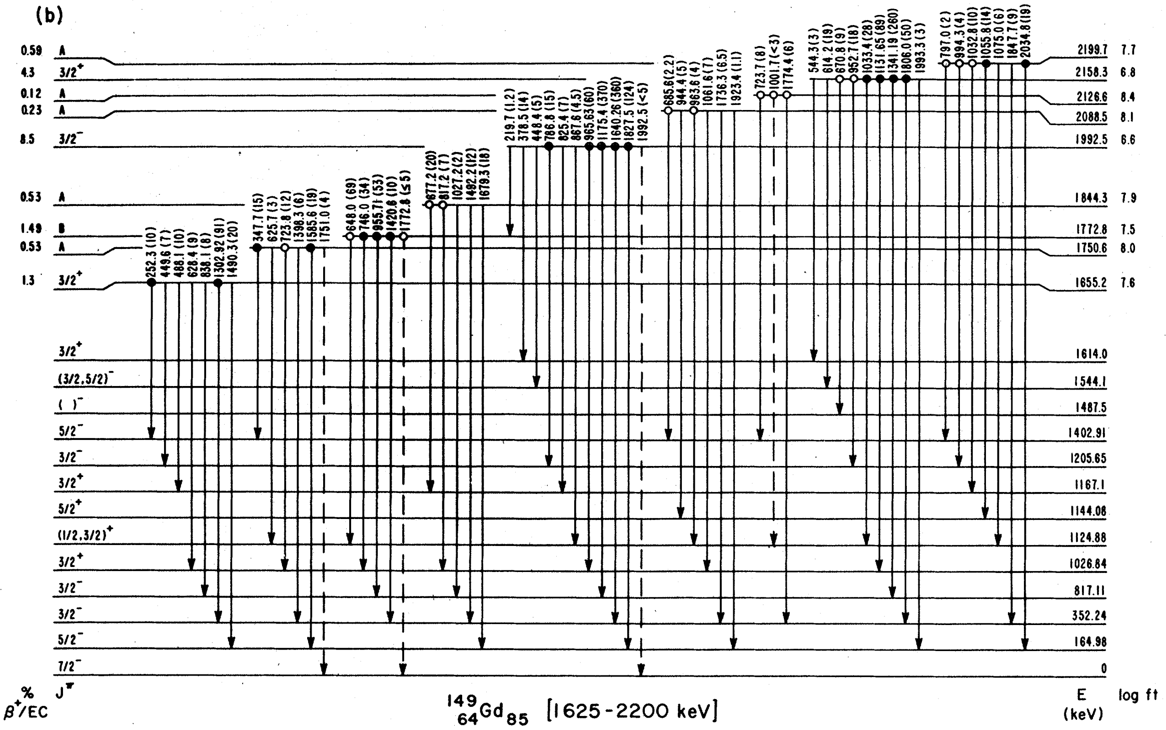
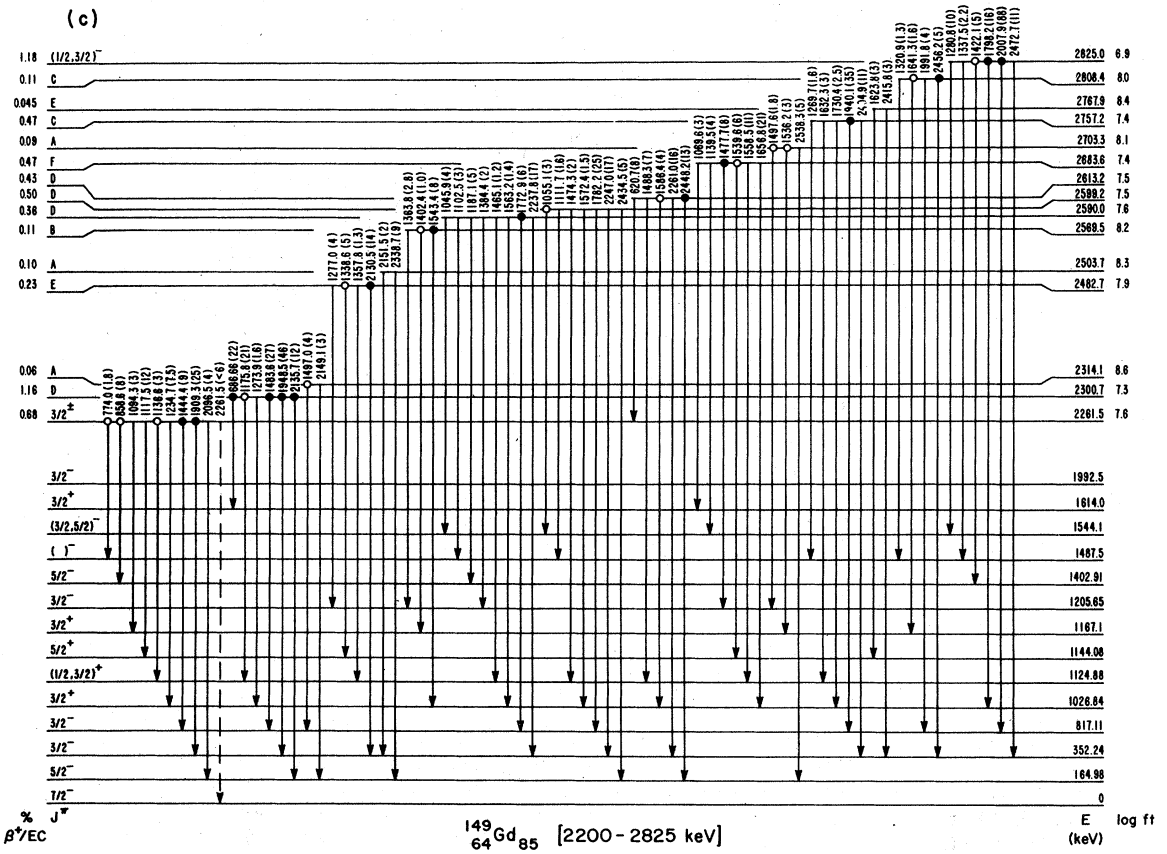


FIG. 1. Decay scheme of 4.15-h ^{149}Tb^g. The notation is described in the text and is consistent with that of Table I. The five partial schemes [Figs. 1(a)-(e)] show, respectively, the depopulation and β^+ + EC feeding of levels of ^{149}Gd between (a) g.s. and 1625 keV, (b) 1625 and 2200 keV, (c) 2200 and 2825 keV, (d) 2825 and 3200 keV, (e) 3200 and 3550 keV. The letters "A" through "F" in the J^π assignment column have the following meaning: A, $J^\pi=(\frac{1}{2}^-, \frac{3}{2}^\pm, \frac{5}{2}^-)$; B, $J^\pi=(\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^-)$; C, $J^\pi=(\frac{1}{2}^\pm, \frac{3}{2}^\pm)$; D, $J^\pm=(\frac{1}{2}^-, \frac{3}{2}^\pm)$; E, $J^\pi(\frac{1}{2}^+, \frac{3}{2}^\pm, \frac{5}{2}^-)$; F, $J^\pi=(\frac{1}{2}^+, \frac{3}{2}^\pm)$. The percent β^+ + EC values for the complete decay scheme [Figs. 1(a)-1(e)] sum to 84.2%.



$^{149}_{64}Gd_{85}$ [1625-2200 keV]



$^{149}_{64}Gd_{85}$ [2200-2825 keV]

Fig. 1 *(Continued)*.

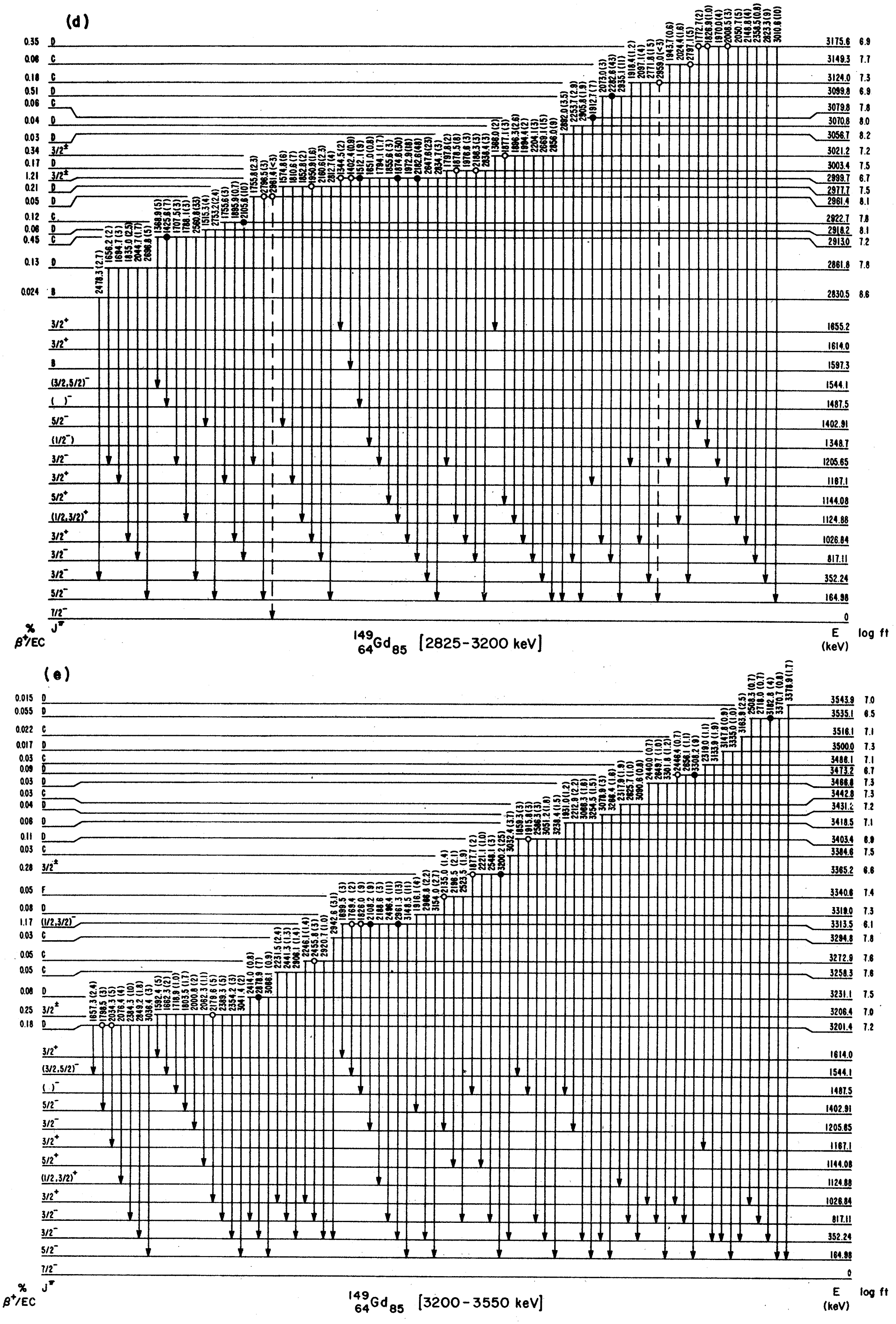


Fig. 1 *(Continued).*

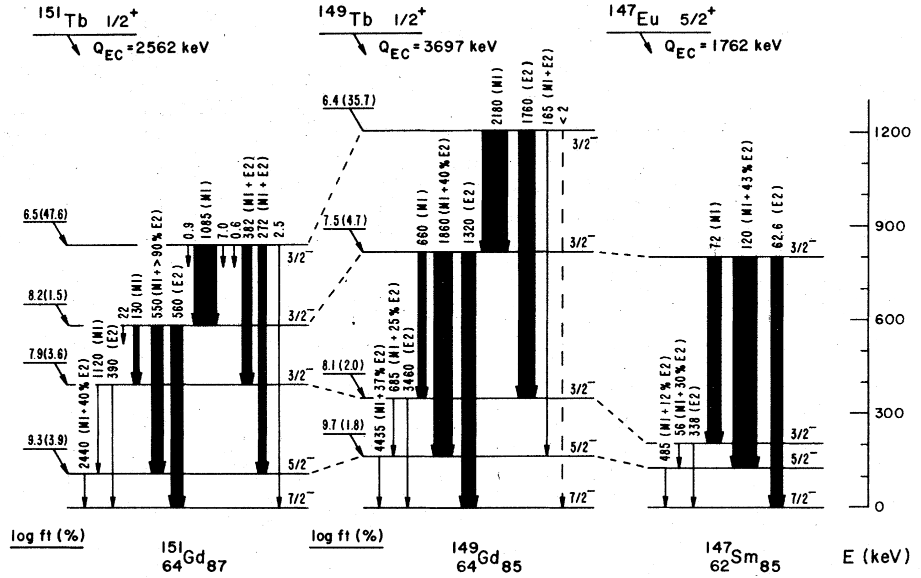


FIG. 2. Decay patterns for selected levels in ^{151}Tb → ^{151}Gd, $^{149}\mathrm{Tb}^g$ → ^{149}Gd, and ^{147}Eu → ^{147}Sm. The γ-transition intensities include conversion-electron intensity and are given in arbitrary relative units, independent for each nuclide. The β^+ + EC percentages represent percent of total decay. Among the indicated log*ft* values, the values given for the $\frac{5}{2}^-$ states are logf_1t's. The $M1/E2$ branchings are from $\gamma\gamma(\theta)$ and/or internal conversion-coefficient measurements (Refs. 54–57 and 64 for ^{151}Tb → ^{151}Gd, Refs. 33–35 and this work for $^{149}\mathrm{Tb}^g$ → ^{149}Gd, and Refs. 31, 65, and 66 for ^{147}Eu → ^{147}Sm). The level J^π assignments are all from Nuclear Data Sheets compilations (Refs. 38, 54, and 66) except for $^{149}\mathrm{Tb}^g$ (ground state = $\frac{1}{2}^+$) and ^{149}Gd (817 keV = $\frac{1}{2}^-$), which are from this work.

ments in other $N=85$ nuclei.[30,31] In no case did the calculated log*ft* value fall below the value of 5.9, which would indicate[60] an allowed β^+ + EC transition. It was assumed that log*ft* values of <8.5 eliminate $\frac{5}{2}^-$ assignments.[60] For the determination of γ-ray multipolarities, we compared the reported conversion-electron intensities[33] with our γ-ray intensities and normalized so that the 352.24-keV transition had an α_K value of 0.0292 (pure $E2$).[49] The results of these calculations are shown in Table II. Any relatively strong γ transition for which a multipolarity could not be deduced was assumed to be dipole or electric quadrupole in character.

The ground-state spin of ^{149}Gd has been measured[62] to be $\frac{7}{2}$ and a J^π value of $\frac{7}{2}^-$ has been assigned on the basis of shell model considerations (i.e., $2f_{7/2}$).[38] The 164.98-keV first excited state decays to the ground state via a mixed $M1+E2$ transition and has been assigned as $J^\pi=\frac{5}{2}^-$ by analogy with the $N=85$ nuclei ^{147}Sm and ^{145}Nd and with ^{151}Gd. The logf_1t value of 9.7 for the β^+ + EC decay to this state is consistent with this assignment. The 352.24-keV level decays to the $\frac{5}{2}^-$ state via an $M1+E2$ transition (187.22 keV) and to the $\frac{7}{2}^-$ ground state via a pure $E2$ transition and is therefore assigned as $\frac{3}{2}^-$. This assignment is also supported by the fact that a low-lying $\frac{3}{2}^-$ state occurs in ^{151}Gd, ^{147}Sm, and ^{145}Nd.

The 796.2-keV level is populated[36,37] in the β^+ + EC decay of $\frac{11}{2}^-$ $^{149}\mathrm{Tb}^m$ with a log*ft* value of ≈4.5. It is therefore assigned as $\frac{9}{2}^-$, with the β^+ + EC transition proposed[37] as connecting the shell model states $1h_{11/2}$ and $1h_{9/2}$.

On the basis of γ-ray transition multipolarities and β^+ + EC log*ft* values the 817.11 keV level is required to be $\frac{3}{2}^-$ or $\frac{5}{2}^-$, while the 1205.65-keV level is required to be $\frac{1}{2}^-$ or $\frac{3}{2}^-$. We assign both of these levels as $\frac{3}{2}^-$. In a previous angular correlation study,[35] it was concluded that the 1205.65-keV level is $\frac{3}{2}^-$ and the 817.11-keV level is $\frac{5}{2}^-$, $\frac{3}{2}^-$ being inconsistent with the $\gamma\gamma(\theta)$ data if the 652.22-keV transition is assumed to be pure $M1$, as proposed in Ref. 33. However, as shown in Table II, our γ-ray singles data combined with the conversion electron data[33] clearly establish that the 652.22-keV transition has a sizeable $E2$ admixture ($\alpha_K=8.5\pm1.2$). We therefore reanalyzed the A_{22} values[35] deduced from the $\gamma\gamma(\theta)$ data, using the γ-γ directional-correlation tables of Taylor *et al.*[63] and requiring that the resulting δ values be internally consistent as well as consistent with the transition multipolarities given in Table II. For the 1205 → 817 → 165 cascade ($A_{22}=-0.194\pm0.032$), we assumed the 388.57-keV transition to be pure $M1$ as suggested by the α_K data in Table

TABLE II. γ-transition multipolarities in the decay of ^{149}Tb^{g} to ^{149}Gd.

E_γ	Assignment (from/to)	I_γ	I_K[a]	α_K(exp.)[b] ($\times 10^3$)	Theoretical[c] K-conversion coeff. $\alpha_K(E1)$ ($\times 10^3$)	$\alpha_K(E2)$ ($\times 10^3$)	$\alpha_K(M1)$ ($\times 10^3$)	Deduced multipolarity
98.1	1124/1026	17 (2)	57 (28)	3260	257	1230	1810	$M1$
164.98	164/0	2985 (35)	1100 (40)	360	64.4	279	420	$M1+E2$
187.20	352/164	487 (6)	135 (6)	270	46.0	190	296	$M1+E2$
352.24	352/0	3333	100	29.2	9.13	29.2	54.0	$E2$
388.57	1205/817	2080 (15)	95 (8)	44.4	7.22	22.3	41.8	$M1$
464.45	817/352	640 (9)	17 (1)	25.8	4.76	13.8	26.4	$M1$
652.12	817/164	1840 (25)	16 (2)	8.5	2.27	5.94	11.2	$M1+E2$
674.4	1026/352	77 (2)	≤0.3	≤3.8	2.11	5.50	10.3	$E1$
772.5	1124/352	182 (4)	≤0.3	≤1.6	1.60	4.04	7.41	$E1$
817.11	817/0	1320 (20)	4.8 (6)	3.5	1.44	3.57	6.46	$E2$
853.43	1205/352	1750 (25)	5.5 (4)	3.1	1.32	3.25	5.82	$E2$
861.86	1026/164	940 (12)	0.9 (2)	0.9	1.29	3.18	5.68	$E1$
955.71	1772/817	53 (3)	0.10 (4)	1.8	1.06	2.55	4.43	$E1$ or $E2$
965.63	1192/1026	60 (3)	0.15 (5)	2.4	1.04	2.50	4.32	$E1$ or $E2$
979.01	1144/164	56 (3)	[<0.1]	[<1.7]	1.02	2.45	4.22	$E1$
1033.3	2199/1167	10	...	...				...
		35 (2)	0.21 (4)	5.8	0.91	2.17	3.67	...
	2158/1124	28	...	...				($M1$)
1040.65	1205/164	165 (5)	0.45 (5)	2.6	0.91	2.15	3.62	$M1+E2$
1131.65	2158/1026	89 (3)	0.45 (14)	4.9	0.77	1.81	2.96	($M1$)
1135.3	1487/352	134 (4)	0.54 (16)	3.9	0.77	1.79	2.94	($M1$)
1144.09	1144/0	33 (3)	[<0.1]	[<2.9]	0.75	1.76	2.89	$E1, M1$, or $E2$
1167.10	1167/0	55 (3)	0.39 (12)	6.9	0.73	1.70	2.76	($M2$)
1175.50	1192/817	370	...	...				$M1$
		390 (11)	1.22 (12)	3.0	0.72	1.68	2.71	...
	2300/1124	21	...	...				...
1302.92	1655/352	91 (3)	[<0.1]	[<1.07]	0.60	1.37	2.10	$E1$
1341.19	2158/817	260 (10)	0.20 (8)	0.74	0.57	1.29	1.99	$E1$
1449.10	1614/164	106 (4)	[<0.1]	[<0.9]	0.47	1.05	1.59	$E1$
1640.26	1992/352	360 (10)	0.35	0.95	0.40	0.89	1.22	$M1, E2$
1827.38	1922/164	134 (5)	0.17 (4)	1.2	0.33	0.70	0.94	$M1, E2$
2007.9	2825/817	88 (3)	0.05 (1)	0.55	0.29	0.58	0.75	$E2$, ($M1$)
2961.3	3313/352	93 (4)	0.04 (1)	0.42	0.16	0.29	0.38	$M1$

[a] The K conversion-electron intensity, I_K, is from Ref. 33. Where 2 or more methods were used, a weighted average was taken. The limiting values in brackets were estimated from data presented in that energy region.

[b] The experimental α_K values have been normalized so that the 352.24-keV transition has $\alpha_K = 0.0292$ (pure $E2$ value from Ref. 49).

[c] From Ref. 49 except for $E_\gamma > 1600$ keV, where the values are interpolated or extrapolated from Ref. 61.

II. For this cascade we found that only for an assignment of $\frac{3}{2}^{-}$ to both the 817.11- and 1205.65-keV levels could we obtain a value for δ for the 652.22-keV transition which was consistent both with the δ value determined[35] from the 817 → 165 → 0 cascade ($\delta = +0.3$ to $+0.5$) and with our deduced $M1+E2$ multipolarity of the 652.22-keV transition. The A_{22} values reported[35] for the additional cascades 1205 → 817 → 0 and 1205 → 352 → 0 also provide results consistent with the 817.11- and 1205.65-keV levels both being assigned as $\frac{3}{2}^{-}$.

Additional support for the $\frac{3}{2}^{-}$ assignments to the 817.11- and 1205.65-keV levels in ^{149}Gd is provided by the existence of analogous $\frac{3}{2}^{-}$ states in ^{151}Gd and ^{147}Sm. In Fig. 2 we present portions of the decay schemes of ^{151}Tb, ^{149}Tb^{g}, and ^{147}Eu showing γ-ray deexcitation patterns for selected low-energy low-spin excited states in the respective daughter nuclides. A number of parallels may be seen in these decays. As stated previously, for both $\frac{1}{2}^{+}$ ^{151}Tb and $\frac{1}{2}^{+}$ ^{149}Tb^{g} the largest percentage β^{+} + EC branch proceeds to a $\frac{3}{2}^{-}$ excited state. In both ^{151}Gd and ^{149}Gd the major transition out of this $\frac{3}{2}^{-}$ state is an essentially pure $M1$ transition to the next lower $\frac{3}{2}^{-}$ state, whereas weaker mixed $M1+E2$ transitions populate the lowest $\frac{3}{2}^{-}$ and $\frac{5}{2}^{-}$ states. In both cases the $E2$ transition to the $\frac{7}{2}^{-}$ ground state is very weak.

Likewise, similar deexcitation patterns are observed for the second excited $\frac{3}{2}^-$ state in all three of the daughter nuclides of Fig. 2. For example, in all three cases the $\frac{3}{2}^- \rightarrow \frac{3}{2}^-$ transition is essentially pure $M1$, whereas the $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$ transition is mixed $M1+E2$.

A number of the ^{149}Gd levels may be assigned as even parity on the basis of transition multipolarities. The 1026.84- and 1614.0-keV levels are both assigned as $\frac{3}{2}^+$ on the basis of $E1$ transitions (861.86 and 1449.10 keV, respectively) to the $\frac{5}{2}^-$ 164.98-keV level and the logft values (which preclude $\frac{5}{2}^+$ or $\frac{7}{2}^+$ assignments). The 1144.08-keV level is assigned as $\frac{5}{2}^+$ on the basis of $E1$ transitions (979.09 and 1144.09 keV) to $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states as well as a relatively strong transition (791.8 keV) to a $\frac{3}{2}^-$ state. The 1167.1-keV level, with an $M2$ transition to the $\frac{7}{2}^-$ ground state as well as a relatively strong transition to the $\frac{5}{2}^-$ 164.98-keV state, is assigned as $\frac{3}{2}^+$. The 1124.88-keV level decays to the $\frac{3}{2}^-$ state at 352.24 keV via an $E1$ transition (772.65 keV) and is hence limited to $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. The $\frac{1}{2}^+$ or $\frac{3}{2}^+$ assignments are suggested by the lack of any observed transitions from this level to the $\frac{7}{2}^-$ ground state or to the $\frac{5}{2}^-$ first excited state. Transition multipolarities limit the 1655.2- and 2158.3-keV levels to $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. In both cases a $\frac{3}{2}^+$ assignment is required since the logft values eliminate the $\frac{5}{2}^+$ assignment and transitions to the $\frac{5}{2}^-$ first excited state eliminate the $\frac{1}{2}^+$ assignment.

The excited states at 2825.0 and 3313.5 keV are both limited to $\frac{1}{2}^-$ or $\frac{3}{2}^-$ on the basis of $M1$ and/or $E2$ transitions to the $\frac{3}{2}^-$ 352.24-keV state and logft values which preclude a $\frac{5}{2}^-$ assignment. The 1402.91-keV level is assigned as $\frac{5}{2}^-$ as it decays to $\frac{7}{2}^-$ and $\frac{9}{2}^-$ states and is fed from both $\frac{3}{2}^+$ and $\frac{3}{2}^-$ states. The 1992.5-keV level, which decays via an $M1$ transition (1827.38 keV) to the $\frac{5}{2}^-$ first excited state and is directly populated by a branch with log$ft = 6.6$, can only be $\frac{3}{2}^-$. The 1487.5-keV excited state is limited to $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$ by virtue of an $M1$ transition (1135.3 keV) to the $\frac{3}{2}^-$ 352.24-keV state. The 1544.1-keV state decays to states with J^π values of $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$. The logft value of 8.3 therefore limits the J^π of this state to $\frac{3}{2}^-$ or $\frac{5}{2}^-$. The 1557.4-keV level decays to both $\frac{5}{2}^+$ and $\frac{5}{2}^-$ states and has a feeding transition with a log$ft = 7.7$. Its assignment must therefore be $\frac{3}{2}^+$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$.

The 1085.3-keV state decays to $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$ states and is fed solely from a $\frac{5}{2}^-$ state (1402.91 keV). Its assignment is therefore restricted to $\frac{5}{2}^-$, $\frac{7}{2}^\pm$, or $\frac{9}{2}^-$. The 1348.7-keV level may be $\frac{1}{2}^-$, $\frac{3}{2}^\pm$, or $\frac{5}{2}^-$, but the connecting transitions suggest $\frac{1}{2}^-$ as the most probable assignment. The five states assigned as $\frac{3}{2}^+$ or $\frac{3}{2}^-$ (2261.5, 2999.7, 3021.2, 3206.4, and 3365.2 keV) are all directly populated with logft values which preclude $J \geqslant \frac{5}{2}$, and all decay to both $\frac{5}{2}^+$ and $\frac{5}{2}^-$ states, precluding $J=\frac{1}{2}$.

The remaining 54 states are all directly populated in the ^{149}Tb^g $\beta^+ +$ EC decay sufficiently strongly that they are limited to $J^\pi = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, or $\frac{5}{2}^-$. One or more of these possible assignments can be eliminated in most cases on the basis of γ-transition selection rules and/or logf_1t values.

IV. DISCUSSION

A. $1/2^+$ ground state of ^{149}Tb

^{149}Tb, with 65 protons and 84 neutrons, is expected to be a spherical nucleus. However, neither the spherical shell model nor the shell model with inclusion of the pairing interaction can account for our assignment of $\frac{1}{2}^+$ for the ground state of ^{149}Tb, nor for the $\frac{1}{2}^+$ assignment[56] of ^{151}Tb. Whereas the elementary shell model does predict a ground-state spin of $\frac{1}{2}^+$ ($3s_{1/2}$) for $N=65$ nuclei, this is not the case for $Z=65$ (see, e.g., the level diagrams in Refs. 68–72). The $g_{7/2}$ and $d_{5/2}$ subshells are presumably filled at $Z=64$, the lowest orbital available to the 65th proton being $2d_{3/2}$ or $1h_{11/2}$. With pairing forces included, one might predict a $\frac{5}{2}^+$ ground-state spin for spherical $Z=65$ nuclei as a consequence of two protons occupying the $1h_{11/2}$ shell, thereby leaving a hole in the $2d_{5/2}$ shell.[73] ^{153}Tb does, in fact, have a $\frac{5}{2}^+$ ground state, but it is interpreted as the Nilsson state $\frac{5}{2}^+[402]$, with ^{153}Tb apparently having a stable prolate deformation.[74]

In order to explain the $\frac{1}{2}^+$ ground-state spins of ^{149}Tb and ^{151}Tb as well as the low-lying (≈ 40 keV) $\frac{11}{2}^-$ isomer in ^{149}Tb, it is clear that one must employ a more complex model than those described above. One possibility is that some combination of residual forces (e.g., pairing plus quadrupole[73]) may be forcing the lowest-lying $\frac{1}{2}^+$ state (mainly $3s_{1/2}$) to an exceptionally low energy at $Z=65$, $N=84, 86$. That $3s_{1/2}$ may be the lowest orbital available to the 65th proton is suggested by the systematics shown in Fig. 3, which is a plot of single-particle level-energy centroids for odd-mass $N=82$ isotones. These centroids were determined via (^{3}He, d) reactions, and the plot is adapted from one presented by Newman *et al.*[75] One observes that the $\frac{11}{2}^-$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$ centroids continuously drop in energy as Z increases, while the $\frac{7}{2}^+$ and $\frac{5}{2}^+$ centroids cross (with $\frac{5}{2}^+$ becoming the ground state) as Z goes from 57 to 59, corresponding to the filling of the $1g_{7/2}$ shell. By Z

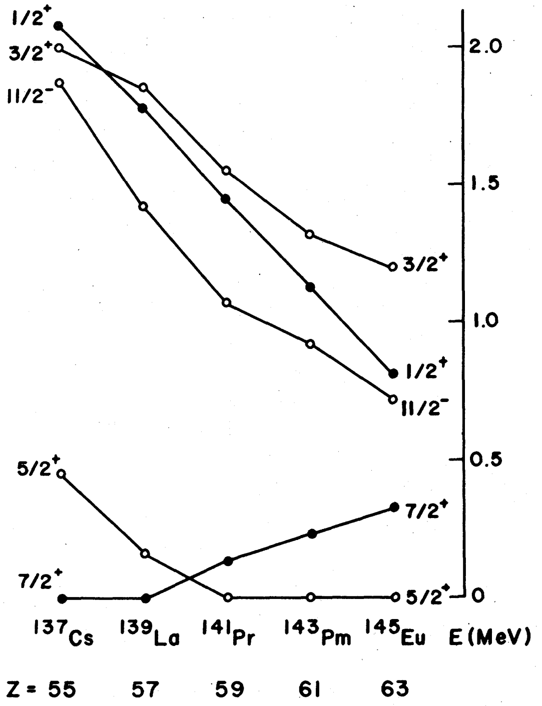


FIG. 3. Systematics of the single-particle energy centroids in the odd-mass $N=82$ isotones as determined via (^{3}He,d) reactions (from Ref. 75).

$=63$ (europium) the $\frac{11}{2}^-$ and $\frac{1}{2}^+$ centroids have dropped to ≈720 and ≈810 keV, respectively, and the $\frac{1}{2}^+$ centroid appears to be dropping at the greater rate as Z increases. Thus, with the presumed filling of the $2d_{5/2}$ orbital at $Z=64$, two low-lying isomers of spin $\frac{1}{2}^+$ and $\frac{11}{2}^-$ are predicted for $Z=65$ spherical nuclei, and a $\frac{1}{2}^+$ ground state is not unexpected. Although ^{149}Tb and ^{151}Tb both fit this pattern, we note that the suggested assignments[76–78] for the two known isomers of $^{147}\mathrm{Tb}_{82}$ are $\frac{5}{2}^+$ and $\frac{11}{2}^-$. The $\frac{5}{2}^+$ assignment is based largely on the deduced[77] existence of a 25% ground-state $\beta^+ + \mathrm{EC}$ branch from ^{147}Tb (1.6 h) to the ^{147}Gd ($\frac{7}{2}^-$) ground state. However, on the basis of the decay scheme of Ref. 78 and using a Q_{EC} value of 4.1 MeV,[77,79,80] we calculate that the total β^+ emission rate should be $\geq 12\%$, in sharp contrast with the reported[77] value of 5.6 ± 0.6%. This disagreement, in conjunction with an analysis of other features of the proposed decay scheme, lead us to the conclusion that $\frac{1}{2}^+$ is a more reasonable assignment for ^{147}Tb (1.6 h) than $\frac{5}{2}^+$. Additional data are clearly needed in order to firmly establish this assignment.

In another approach, a weak static oblate ($\epsilon_2 \leq -0.1$) deformation may be invoked to explain the observed $\frac{1}{2}^+$ ground states. An examination of the Nilsson level diagram for $Z \approx 64$ (Refs. 71 and 81) indicates that at an oblate deformation of $\epsilon_2 \approx -0.1$ the two Nilsson orbitals $\frac{1}{2}^+$ [420] and $\frac{11}{2}^-$ [505] cross such that the 65th proton is in the $\frac{1}{2}^+$ [420] orbital. A low-lying $\frac{11}{2}^-$ isomer will result if the $\frac{11}{2}^-$[505] hole state is at a lower energy than the $\frac{9}{2}^-$ [514] particle excitation. Tentative support for this idea has been obtained through nuclear potential-energy surface calculations for one-quasiparticle states in this mass region, using the model described by Nielsen and Bunker.[82] These calculations indicate that in the light Tb's ($N \leq 86$), $\frac{1}{2}^+$ [420] should occur as a low-lying state, with the associated potential-energy surface having a shallow minimum near $\epsilon_2 \approx -0.1$.

Although it is possible that both of the above explanations of the Tb isomers have some validity, the first seems the more reasonable at present. A better judgement will be possible when detailed pairing-plus-quadrupole model calculations for this region become available.

B. Odd-parity levels of ^{149}Gd

In Fig. 4 we present the experimentally observed low-energy level structures of the three odd-mass neutron-deficient gadolinium ($Z=64$) nuclei which lie between the $N=82$ closed shell and the onset of stable deformation at $N=89$. We also show the energies of the first excited 2^+ and 3^- states in the neighboring even-even Gd nuclei. The even-even 2_1^+ energies and the odd-N $\frac{7}{2}^-$ ground-state assignments suggest that all three of these odd-mass nuclei are basically spherical in character. However it is clear that there is a dramatic change in the low-energy level structure in going from $N=83$ to $N=87$. At $N=85$ the lowest $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states appear at an energy much less than that of the 2_1^+ energy in the even-even core. These states persist to $N=87$ (see Fig. 2), and a number of additional low-lying states appear, markedly increasing the level density below 1 MeV. Similar changes in level structure are also seen for the Sm isotopes[31] and the Nd isotopes[30] having $N=83-87$.

This type of structure change, involving the appearance at low energy of levels having spin values of $J-1$ and $J-2$, where J is the shell-model-predicted ground-state spin ($J \geq \frac{7}{2}$), is observed in several nuclide regions where three identical particles or three identical holes become available near a shell closure.[23–25] The observed properties of these levels have led to two nuclear models: the dressed n-quasiparticle model of Marumori, Kuriyama, and coworkers[1–8] and the three-particle-clustering (Alaga) model of Alaga, Parr, and Sips.[9–18]

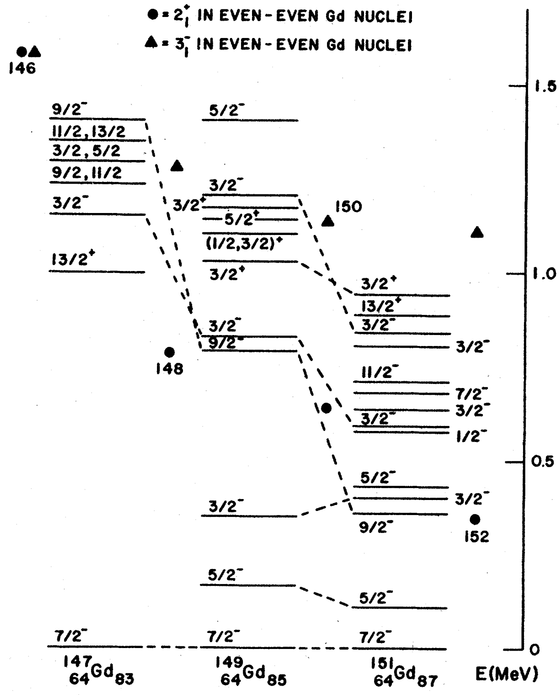


FIG. 4. Experimentally observed levels of selected Gd nuclei. From left to right: the $N=83$ nucleus ^{147}Gd (Ref. 67), the $N=85$ nucleus ^{149}Gd (this work), and the $N=87$ nucleus ^{151}Gd (Refs. 54–57). The even-even Gd first-excited 2^+ and 3^- state energies are from Refs. 83–86.

Although differing in some specifics, the two models are quite similar in general (see the comparison in Ref. 23). In both models the explicit treatment of the Pauli principle for the three particles (or holes) in the valence shell results in the $(J)^{\pm 3}$ multiplet being split, with the $J-1$ state dropping down near the ground state (of spin J). In fact, for a sufficiently high coupling constant, the $J-1$ state can become the ground state (e.g., see Ref. 18). The $J-2$ state can also be brought down, either through the explicit treatment of five particles[4] (for example in $^{101}_{43}$Tc where the $\frac{9}{2}^+$, $\frac{7}{2}^+$, and $\frac{5}{2}^+$ states from the $1g_{9/2}$ clustering lie at 0, 9, and 15 keV, respectively) or as a consequence of including the identical-parity $J-2$ shell-model orbital in the model space.[4] This latter effect is expected to be relatively important at $N=85$, where the lowest-energy three-neutron clustering is $(2f_{7/2})^3$ and the $3p_{3/2}$ orbital lies nearby in the same valence shell.

No detailed calculations employing either of the above two models have been reported for the $N=85$ nuclei. However, two calculations[28,88] using a limited form of the Alaga model have been performed. In both cases the neutrons were restricted to the $2f_{7/2}$ shell-model orbital. The $N=85$ nuclei were treated as having a $(2f_{7/2})^3$ cluster coupled to quadrupole phonons, whereas the $N=87$ nuclei were treated as having a $(2f_{7/2})^{-3}$ cluster coupled to quadrupole phonons. Peker and Sigalov[28] showed that the Alaga model provides a good qualitative description of some of the observed states of several $N=85$ and $N=87$ nuclei even though model parameters reported[18] for $1f_{7/2}$ nuclei were employed in the calculation. They were able to account qualitatively for the occurence of the low-lying $\frac{5}{2}^-$ state, the relative magnetic moments of the $\frac{7}{2}^-$ and $\frac{5}{2}^-$ states, the variation in the $\frac{7}{2}^- - \frac{5}{2}^-$ energy difference for Nd, Sm, and Gd nuclei, and the decay patterns of the yrast states with $J \leq \frac{27}{2}$ in ^{151}Gd. Garrett, Leigh, and Dracoulis[88] performed a similar calculation for levels in ^{147}Sm and ^{149}Sm and were able to account qualitatively for much of the low-energy level structure, the enhanced ground-state $E2$ transition probabilities measured via Coulomb excitation, and the yrast decay patterns for $J \leq \frac{17}{2}$. In neither application of the theory were the low-lying $\frac{3}{2}^-$ states fitted very well; however, this is not unexpected as the $3p_{3/2}$ shell-model orbital was not included in the model space. A detailed calculation of these nuclei is made much more difficult by the necessity that the model space include at least the $2f_{7/2}$, $1h_{9/2}$, and $2p_{3/2}$ shell-model orbitals. In this model space it is then necessary to treat the $N=87$ nuclei as having five neutron particles rather than three neutron holes, although it is clear from the limited model calculations[28,88] that three holes confined to the $2f_{7/2}$ orbital can qualitatively account for many of the "spherical" states in the $N=87$ nuclei. Likewise, it is clear that three $2f_{7/2}$ particles can qualitatively account for many features of the low-energy $N=85$ level structures.

In Fig. 5 we present the systematics of the odd-parity levels observed in the $N=85$ nuclei ^{149}Gd, ^{147}Sm, and ^{145}Nd, along with the preliminary results of a detailed Alaga-model calculation of ^{145}Nd levels by Parr.[29] This calculation includes the $2f_{7/2}$, $1h_{9/2}$, and $3p_{3/2}$ shell-model orbitals in its model space, but is relatively simplistic in its choice of single-particle energies and the value for the coupling constant between the three-particle cluster and the quadrupole phonons. It is clear, nevertheless, that the Alaga model can explain many features of the level structures displayed in Fig. 5. An even better fit to the ^{147}Sm and ^{149}Gd levels could of course be obtained if the model parameters were varied as a function of Z. In a future paper[31] we intend to show the results of more detailed Alaga-model calculations

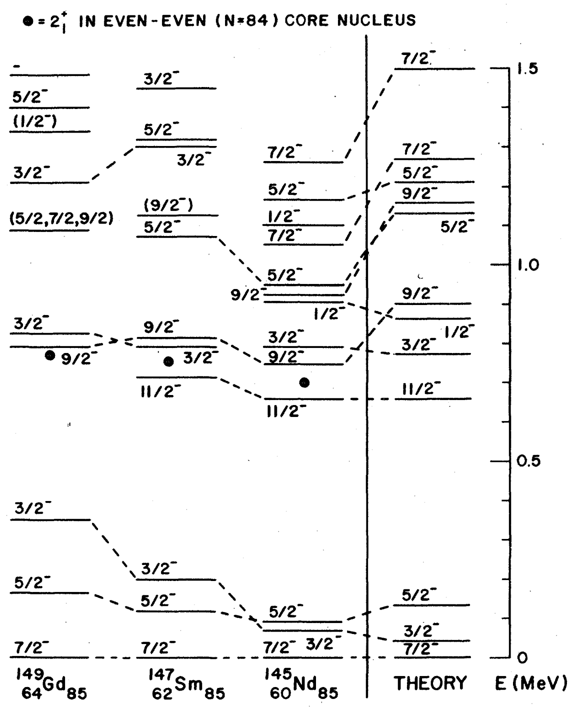


FIG. 5. Odd-parity level systematics for the $N=85$ nuclei ^{149}Gd (this work), ^{147}Sm (Ref. 31), and ^{145}Nd (Ref. 30). Also shown are the preliminary results of a calculation by Parr (Ref. 29) of the odd-parity levels of ^{145}Nd, using a three-particle cluster plus quadrupole-phonon model. The even-even $N=84$ core first-excited 2^+ energies are from Refs. 83, 84, and 87.

for all three $N=85$ nuclei.

In the case of ^{149}Gd, owing to the parent having $J^\pi=\frac{1}{2}^+$, we have observed predominantly low-spin excited states. A study of the ^{149}Gd high-spin levels via $(\alpha,xn\gamma)$ or (HI,$xn\gamma$) reactions would aid considerably in making a comparison between the ^{149}Gd level structure and the Alaga-model predictions. In addition, such a study could determine if shape coexistence occurs at high energy and high spin in ^{149}Gd, similar to that observed in ^{151}Gd by Kleinheinz *et al.*[89,90]

C. Even-parity levels of ^{149}Gd

Only seven of the observed excited states of ^{149}Gd can be definitely assigned as having even parity. These are a $\frac{1}{2}^+$ or $\frac{3}{2}^+$ level at 1124 keV, five $\frac{3}{2}^+$ levels at 1026, 1167, 1614, 1655, and 2158 keV, and a $\frac{5}{2}^+$ level at 1144 keV.

Simple coupling models employing single neutron excitations plus core vibrations have difficulty in accounting for all of the above positive-parity states. The sole even-parity shell-model orbital in the $N=82-126$ shell is the $1i_{13/2}$ orbital, and coupling of one or two quadrupole phonons to this single-particle excitation cannot account for any $\frac{1}{2}^+$ or $\frac{3}{2}^+$ levels. The lowest-energy even-parity states observed are close in energy to the 3^- octupole-phonon core excitation (see Fig. 4), and it is possible that they arise from coupling between this octupole excitation and the valence neutrons. The states at 1026 and 1167 keV could, e.g., represent the $\frac{3}{2}^+$ members of the multiplets arising from coupling of the 3^- phonon to the $\frac{7}{2}^-$ and $\frac{5}{2}^-$ members of the Alaga-model $(f_{7/2})^3$ cluster. To our knowledge no Alaga-model type calculations including octupole phonons have ever been reported.

Another possible explanation for some of the even-parity states is that they are "deformed" states. With prolate deformation, two particle states, $\frac{1}{2}^+[660]$ and $\frac{3}{2}^+[651]$, and two hole states, $\frac{1}{2}^+[400]$ and $\frac{3}{2}^+[402]$, could occur at relatively low energies. In the nearby $N=87$ nuclei (^{151}Gd, ^{149}Sm, and ^{147}Nd) $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states observed between ≈ 1.0 and ≈ 1.6 MeV have been postulated as being deformed hole states on the basis of (d,t) reaction cross sections.[91,92] The existence of at least four $\frac{3}{2}^+$ states in ^{149}Gd below 2 MeV provides tentative evidence that both spherical and deformed states occur in the excitation spectrum. Detailed particle-phonon calculations employing octupole as well as quadrupole phonons should aid in resolving this question.

ACKNOWLEDGMENTS

The authors wish to thank J. H. Landrum, who performed the chemical separations at LLL, Dr. B. J. Dropesky, who aided with the LAMPF irradiations and the isotope separations, G. M. Kelley who operated the isotope separator, P. Q. Oliver, who performed some of the chemical separations at LASL, and R. I. Price who aided in the analysis of some early γ-ray singles spectra. We would also like to thank the LAMPF operating crew for their excellent cooperation in providing appropriate 800-MeV proton beams.

---

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

[1] A. Kuriyama, T. Marumori, and K. Matsuyanagi, Prog. Theor. Phys. Suppl. 58, 1 (1975).

[2] A. Kuriyama, T. Marumori, K. Matsuyanagi, F. Sakata, and T. Suzuki, Prog. Theor. Phys. Suppl. 58, 9 (1975).

[3] A. Kuriyama, T. Marumori, K. Matsuyanagi, and R. Okamoto, Prog. Theor. Phys. Suppl. 58, 32 (1975).

[4] A. Kuriyama, T. Marumori, and K. Matsuyanagi, Prog. Theor. Phys. Suppl. 58, 53 (1975).

[5] A. Kuriyama, T. Marumori, K. Matsuyanagi, and R. Okamoto, Prog. Theor. Phys. Suppl. 58, 103 (1975).

[6] A. Kuriyama, T. Marumori, K. Matsuyanagi, R. Okamoto, and T. Suzuki, Prog. Theor. Phys. Suppl. 58, 138 (1975).

[7] M. Fuyki, A. Kuriyama, K. Matsuyanagi, and T. Suzuki, Prog. Theor. Phys. Suppl 58, 160 (1975).

[8] A. Kuriyama, T. Marumori, K. Matsuyanagi, F. Sakata, and T. Suzuki, Prog. Theor. Phys. Suppl. 58, 184 (1975).

[9] G. Alaga and G. Ialongo, Nucl. Phys. A97, 600 (1965).

[10] V. Parr, Phys. Lett. 39B, 466 (1972).

[11] V. Parr, Phys. Lett. 39B, 587 (1972).

[12] V. Parr, Z. Phys. 271, 11 (1974).

[13] V. Parr, Phys. Lett. 42B, 8 (1972).

[14] G. Alaga, in *Nuclear Structure and Nuclear Reactions, Proceedings of the International School of Physics, "Enrico Fermi," Course XL*, edited by M. Jean and R. Rizzi (Academic, New York, 1969), and references quoted therein.

[15] G. Alaga, Bull. Am. Phys. Soc. 4, 359 (1959).

[16] V. Lopac, Nucl. Phys. A155, 515 (1970).

[17] G. Alaga, V. Parr, and V. Lopac, Phys. Lett. 43B, 459 (1973).

[18] V. Parr, Nucl. Phys. A211, 29 (1973).

[19] R. Almar, O. Civitarese, and F. Krmpotic, Phys. Rev. C 8, 1518 (1973).

[20] C. Vanden Berghe, Z. Phys. 266, 139 (1974).

[21] A. Szanto de Toledo, M. N. Rao, and O. Sala, Phys. Rev. C 16, 438 (1977).

[22] G. Vanden Berghe, Med. Kon. Ac. Wet. België 36, No. 10 (1974).

[23] S. V. Jackson, Lawrence Livermore Report UCRL-51846 (unpublished) [Ph.D. thesis, Univ. of Maryland, 1975 (unpublished)].

[24] R. A. Meyer, in Proceedings of the International Conference on γ-Ray Transition Probabilities, Delhi, India, 1974 [University of California Radiation Laboratory Report No. UCRL-72607 (unpublished)], Vol. 1 (invited lectures).

[25] R. A. Meyer, in *Problems of Vibrational Nuclei*, edited by G. Alaga (North-Holland, Amsterdam, 1975), Chap. 7.

[26] G. Lhersonneau, J. De Raedt, H. Van de Voorde, H. Ooms, R. Haroutunian, E. Shoeters, R. Silverans, and L. Vanneste, Phys. Rev. C 12, 609 (1975).

[27] J. De Raedt, G. Lhersonneau, R. Geerts, and H. Van de Voorde, J. Phys. (London) G2, 719 (1976).

[28] L. K. Peker and V. M. Sigalov, Izv. Akad. Nauk SSSR, Ser. Fiz. 38 2119 (1974) [Bull. Acad. Sci. USSR Phys. Ser. 38, 90 (1975)].

[29] V. Parr, Institute "Rudjer Boskovic," Zagreb, Yugoslavia, private communication, 1976 (unpublished)

[30] S. V. Jackson and R. A. Meyer, Phys. Rev. C 13, 339 (1976).

[31] R. A. Meyer, S. V. Jackson, D. Nethaway, J. H. Landrum, P. Johnson, and V. Parr (unpublished).

[32] K. Vil'skii, K. Ya. Gromov, Zh. T. Zhelev, V. V. Kuznetsov, G. Musiol, O. B. Nielsen, and O. Skilbreit, Izv. Akad. Nauk SSSR Ser. Fiz. 32, 187 (1968) [Bull. Acad. Sci. USSR, Phys. Ser. 32, 187 (1969)].

[33] Ts. Vylov, K. Ya Gromov, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, N. A. Lebedev, and M. I. Fominykh, Izv. ~~Akad.~~ ~~Nauk~~ SSSR, Ser. Fiz. 36, 2118 (1972) [Bull. Acad. Sci. USSR, Phys. Ser. 36, 1864 (1973)].

[34] Ts. Vylov, K. Ya. Gromov, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, N. A. Lebedev, and M. I. Fominykh, Izv. Akad. Nauk SSSR Ser. Fiz. 36, 2124 (1972) [Bull. Acad. Sci. USSR, Phys. Ser. 36, 1869 (1973)].

[35] M. Budzynski, R. Ion-Mikhai, V. A. Morozov, T. M. Muminov, M. Subotovich, H. Fuya, and I. Kholbaev, Izv. Akad. Nauk SSSR, Ser. Fiz. 38, 2493 (1973) [Bull. Acad. Sci. USSR, Phys. Ser. 38, 25 (1974)].

[36] R. Arlt, H. Bayer, V. V. Kuznetsov, W. Neubert, A. A. Potemysa, W. Hagemann, and E. Herrmann, Izv. Akad. Nauk SSSR, Ser. Fiz. 35, 1612 (1971) [Bull. Acad. Sci. USSR, Phys. Ser. 35, 1470 (1972)].

[37] K. S. Toth, E. Newman, C. Bingham, A. E. Rainis, and W.-D. Schmidt-Ott, Phys. Rev. C 11, 1370 (1975).

[38] G. E. Holland, Nucl. Data Sheets 19, 337 (1976).

[39] B. M. Morris, V. A. Mode, and D. H. Sisson, J. Chromatogr. 71, 389 (1972), and references cited therein; D. H. Sisson, Lawrence Livermore Laboratory, private communication (unpublished).

[40] R. A. Meyer, Univ. of Michigan Report CONF-760539 (unpublished) p. 40.

[41] R. G. Helmer, R. C. Greenwood, and R. J. Gehrke, Nucl. Instrum. Methods (unpublished).

[42] R. Gunnink and J. B. Niday, Lawrence Livermore Laboratory Report UCRL-51061, 1971–72 (unpublished), Vols I–IV.

[43] Code written by J. W. Starner, H. A. Smith, Jr., and E. B. Shera, Los Alamos Scientific Laboratory (unpublished).

[44] S. V. Jackson, J. W. Starner, M. E. Bunker, and R. A. Meyer (unpublished).

[45] T. W. Burrows, Nucl. Data Sheets 12, 203 (1974).

[46] R. A. Meyer, S. V. Jackson, J. W. Starner, and M. E. Bunker (unpublished).

[47] K. E. Apt, Ph.D. thesis, Massachusetts Institute of Technology, 1971 (unpublished).

[48] Codes GEOSEF, TRUDY, and ADAM, written by J. W. Starner, E. B. Shera, and S. V. Jackson, Los Alamos Scientific Laboratory (unpublished).

[49] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[50] E. P. Steinberg, A. F. Stehney, C. Stearns, and I. Spaletto, Nucl. Phys. A113, 265 (1968).

[51] N. B. Gove and M. J. Martin, Nucl. Data A10, 205 (1971).

[52] K. E. Adelroth, H. Nyqvist, and A. Rosen, Phys. Scr. 2, 96 (1970).

[53] N. A. Golovkov, K. Y. Gromov, N. A. Lebedev, B. Makhmudov, A. S. Rudnev, and V. G. Chumin, Izv. Akad. Jauk SSSR, Ser. Fiz. 31, 1618 (1967) [Bull. Acad. Sci. USSR, Phys. Ser. 31, 1657 (1968)].

B. Harmatz, Nucl. Data Sheets 19, 33 (1976).

[55] M. E. Bunker, S. V. Jackson, J. W. Starner, W. R. Daniels, B. J. Dropesky, C. W. Reich, and R. G. Helmer, Bull. Am. Phys. Soc. 22, 614 (1977).

[56] J. W. Starner, S. V. Jackson, M. E. Bunker, C. W. Reich, and R. G. Helmer (unpublished).

[57] E. Hammaren, P. Puhakka, A. Siivola, and T. Tuurnala, Z. Phys. A272, 341 (1975).

[58] V. G. Chumin, Z. T. Zhelev, K. Y. Gromov, B. Makhmudov, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 146 (1967) [Bull. Acad. Sci. USSR, Phys. Ser. 31, 138 (1968)].

[59] V. G. Chumin, Z. T. Zhelev, K. Y. Gromov, and B. Makhmudov, in *Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee,* 1966, edited by R. L. Beeker, C. D. Goodman, P. H. Stelson, and A. Zuker (Academic Press, New York, 1968).

[60] S. Raman and N. B. Gove, Phys. Rev. C 7, 1995 (1973).

[61] L. A. Sliv and I. M. Band, Tables of Internal Conversion Coefficients, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, p. 1639.

[62] C. Ekström, S. Ingelman, D. Olsmats, and B. Wannberg, Phys. Scr. 6, 181 (1972).

[63] H. W. Taylor, B. Singh, F. S. Prato, and R. McPherson, Nucl. Data A9, 1 (1971).

[64] Y. Vavryschhuk, W. Zuk, E. Krupa, V. V. Kuznetsov, V. A. Morozov, H. Fuya, and A. B. Khalikulov, Izv. Akad. Nauk SSSR, Ser. Fiz. 36, 757 (1972) [Bull. Acad. Sci. USSR, Phys. Ser. 36, 685 (1973)].

[65] K. S. Krane, At. Data Nucl. Data Tables 19, 363 (1977).

[66] W. B. Ewbank, M. J. Martin, and S. Raman, Nucl. Data B2, 4 (1967).

[67] Z. Haratym, J. Kownacki, J. Ludziejewski, Z. Sujkowski, L.-E. De Geer, A. Kerek, and H. Ryde, Nucl. Phys. A276, 299 (1977).

[68] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (Wiley, New York, 1955).

[69] M. A. Preston and R. K. Bhaduri, *Structure of the Nucleus* (Addison-Wesley, Reading Mass., 1975), p. 222.

[70] A. de Shalit and H. Feshbach, *Theoretical Nuclear Physics* (Wiley, New York, 1974), Vol. I, p. 44.

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

[72] S. G. Nilsson, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 29, No. 16 (1955).

[73] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

[74] M. D. Devous, Sr. and T. T. Sugihara, Phys. Rev. C 15, 740 (1977).

[75] E. Newman, K. S. Toth, R. L. Auble, R. M. Gaedke, M. F. Roche, and B. H. Wildenthal, Phys. Rev. C 1, 1118 (1970).

[76] Y. Y. Chu, E. M. Franz, and G. Friedlander, Phys. Rev. 187, 1529 (1969).

[77] V. P. Afanas'ev, I. I. Gromova, G. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, and N. A. Lebedev, Izv. Akad. Nauk SSSR, Ser. Fiz. 35, 719 (1971) [Bull. Acad. Sci. USSR, Phys. Ser. 35, 659 (1971)].

[78] E. Newman, K. S. Toth, D. C. Hensley, and W.-D Schmidt-Ott, Phys. Rev. C 9, 674 (1974).

[79] S. Liran and N. Zeldes, Nucl. Phys. A136, 190 (1969).

[80] S. Maripuu, At. Data Nucl. Data Tables 17, 411 (1976).

[81] B. R. Mottelson and S. G. Nilsson, K. Dan. Vidensk. Selsk. Mat.-Fys. Skr. 1, No. 8 (1959).

[82] B. S. Nielsen and M. E. Bunker, Nucl. Phys. A245, 376 (1975).

[83] T. W. Burrows, Nucl. Data Sheets 14, 413 (1975).

[84] B. Harmatz and J. R. Shepard, Nucl. Data Sheets 20, 373 (1977).

[85] C. M. Baglin, Nucl. Data Sheets 18, 223 (1976).

[86] D. R. Zolnowski, E. G. Funk, and J. W. Mihelich, Nucl. Phys. A177, 513 (1971).

[87] T. W. Burrows and R.L. Auble, Nucl. Data Sheets 16, 231 (1975).

[88] C. Garrett, J. R. Leigh, and G. D. Dracoulis, Nucl. Phys. A262, 137 (1976).

[89] P. Kleinheinz, A. K. Sheline, M. R. Maier, R. M. Diamond, and F. S. Stephens, Phys. Rev. Lett. 32, 68 (1974).

[90] P. Kleinheinz, A. M. Stefanini, M. R. Maier, R. K. Sheline, R. M. Diamond, and F. S. Stephens, Nucl. Phys. A283, 189 (1977).

[91] G. Løvhoiden and D. G. Burke, Can. J. Phys. 53, 1182 (1975).

[92] O. Straume and D. G. Burke, Can. J. Phys. (to be published).