Title
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Studies of the $N = 90$ shape transition region: the decay of ^{154}Eu to ^{154}Gd.

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The decay of ^{154}Eu $\rightarrow$ ^{154}Gd has been studied by γ-ray singles and $\gamma-\gamma$ coincidence spectroscopy using an array of 20 Compton-suppressed Ge detectors. The primary goal of the work was to confirm or refute a large nubmer of questionable features in the decay scheme: the outcome is the removal of 8 levels from the previously adopted scheme, with the result that a new type of collective band is revealed. Many weak decay branches for the decay are clarified. These results are critical for understanding the structure of ^{154}Gd and the $N = 90$ isotones; and the improved completeness of the decay scheme contributes to the use of ^{154}Eu as a metrological standard.

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I. INTRODUCTION

a. The structure of the $N = 90$ isotones in the vicinity of $Z = 64$ has been the focal point of a very large number of studies. The primary motivation for this is that these nuclei are located at the center of a region of rapid change in nuclear shape and consequently a rapid change in nuclear collectivity. Thus, these nuclei have been widely regarded as among the most challenging for models that aim to achieve a general description of nuclear collectivity.

b. Very recently, there has been renewed interest in this region due to the introduction of a completely new class of nuclear model called a "critical point symmetry"[1] which has been invoked as a new interpretation of the low-energy collective structure of the $N = 90$ nucleus ^{152}Sm[2]. A considerable body of literature[3] has ensued from this idea. However, there is controversy [4, 5] regarding these new ideas. Indeed, it would appear that it is not possible to easily choose between the wide variety[4] of collective models that vie to describe the $N = 90$ isotones based on currently available data.

c. The nucleus ^{154}Gd was selected as one of the nuclei in the present program[6] of study because it exhibits considerable similarities to ^{152}Sm, and also some apparent dramatic differences. The similarities and differences in the adopted level schemes of these isotones are illustrated in Fig. 1. Further, some of the differences have their origin in previously reported[7] studies of the radioactive decay of ^{154}Eu to ^{154}Gd. This, together with the suitability of the ^{154}Eu decay for further investigating low-lying low-spin states in ^{154}Gd, motivated the present study.

d. The β^--decaying isotope ^{154}Eu ($T_{\frac{1}{2}} = 8.6$ yr) has been widely studied, not only for nuclear structure reasons, but also for metrological reasons (it is an ex-

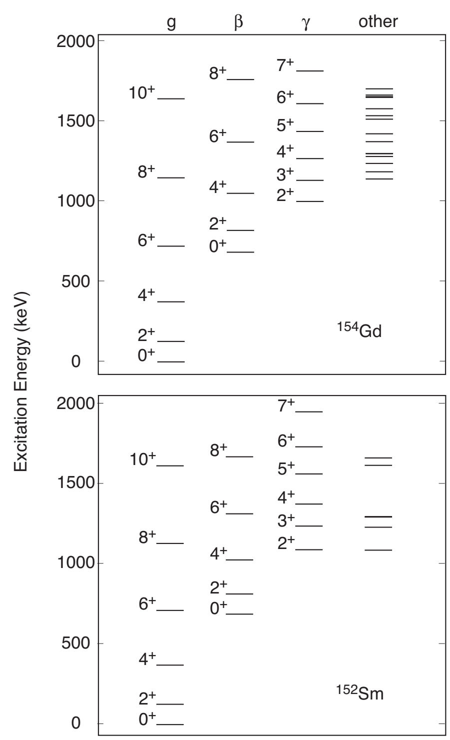

FIG. 1: A comparison of the low-lying positive-parity states in the isotones ^{152}Sm and ^{154}Gd based on the evaluated data presented in the *Nuclear Data Sheets* for these nuclei([8] and [7], respectively). Below 1.7 MeV excitation energy, ^{154}Gd has 29 positive-parity states and ^{152}Sm has 20 such states.

cellent secondary γ-ray standard for energy and photopeak efficiency calibrations). However, there are a large number of weak γ rays reported[9] and confirmed[10] for which there are either questionable assignments (cf. Fig. 1) or no assignments[7]. If the unassigned γ rays exist, they will define new levels in ^{154}Gd. The Q_β value for

^{154}Eu is 1968.5 keV, which means that these γ rays would impact the low-energy structure of ^{154}Gd. Thus, we undertake to resolve the issue of whether or not these weak γ rays exist.

II. EXPERIMENTAL PROCEDURE

e. A commercially produced[1] source of ^{154}Eu was used for these measurements. The source contained $16.8 \pm 0.2\%$ ^{155}Eu and $0.027 \pm 0.002\%$ ^{152}Eu (both determined in the present study), and had a strength of $\sim$5 μCi. The source had an active diameter of 3 mm and was mounted on 9 mg/cm^2 Kapton with a 0.254 mm aluminized Mylar cover and was in the form of evaporated metallic salts.

f. Gamma-ray singles and $\gamma - \gamma$ coincidence measurements were carried out using the "8π spectrometer"[11]. This spectrometer[2] is an array of 20 Compton-suppressed Ge(HP) detectors. The detectors had nominal active volumes of 115 cm^3, typical front-face diameters of 51.5 mm, and 0.3 μm Ge dead layers. The source-to-detector distances were 22.0 cm. Compton suppression was provided by BGO crystals. The 380 two-fold coincidence combinations for the array corresponded to angles of 41.8° (60 pairs), 70.5° (120 pairs), 109.5° (120 pairs), 138.2° (60 pairs), and 180.0° (20 pairs). This incurred an average angular correlation distortion for coincidence intensities, summed over the array, of $\pm$1%; and a maximum distortion (for a 0-2-0 spin-sequence cascade) of 7.6%. These numbers were calculated from Monte Carlo simulations of the detector "Q" factors averaged over the energy range studied and over the array: $Q_2 = 0.9925$, $Q_4 = 0.9753$.

g. In the presently described experiment the long-term energy resolution of singles spectra, summed over all 20 detectors, was 1.8 keV at 123 keV and 3.3 keV at 1597 keV. The peak-to-total ratios ranged from 0.77 (123 keV), 0.48 (677 keV), to 0.24 (1597 keV).

h. Besides the aforementioned ^{152}Eu and ^{155}Eu source contaminants, the only other activities present in the singles spectra were ^{40}K, ^{60}Co, ^{137}Cs, ^{207}Bi, ^{232}Th, and ^{238}U, from the room background. No absorbers were placed in front of the detectors and no shielding was used to attenuate room background. The low-energy "cut-off" was $\sim$30 keV (the Gd K X rays are at 42.8 and 48.8 keV).

i. Gamma-ray singles and $\gamma - \gamma$ coincidence events were recorded concurrently in a run lasting 240 hours. Single-detector events were scaled-down by rejecting 23 out of every 24 of these events in the trigger logic. This was done to reduce dead time in the data acquisition system so that coincidence information was maximized. Data were recorded event-by-event on magnetic tape and were subsequently scanned to provide γ-ray singles and $\gamma - \gamma$ coincidence spectra. The data sets obtained contained 1.00×10^8 $\gamma - \gamma$ coincidence events and 2.38×10^8 singles events.

j. Calibration for energies and intensities of lines in the ^{154}Eu decay was achieved "internally", i.e., use was made of the fact that the strong lines in this decay serve[7] as a secondary γ-ray energy and intensity calibration source. The energy calibration was made with a polynomial (containing terms up to cubic) describing keV/ch, fitted to the strongest 48 lines in the ^{154}Eu decay. The systematic error in the energy calibration is deduced to be $\pm$0.07 keV. The efficiency calibration was made with a polynomial (containing terms up to quartic) describing log(efficiency) versus log(energy), fitted to the 10 strong lines in the ^{154}Eu decay (123, 248, 592, 723, 757, 873, 996, 1005, 1275, and 1494 keV). These lines are reported[7] with intensity errors from $\pm$0.25% to $\pm$0.87%. With the fit achieved, the intensities of the next strongest 18 lines in the ^{154}Eu decay (188, 401, 445, 478, 558, 582, 625, 692, 716, 816, 845, 851, 893, 904, 1129, 1141, 1246, and 1597 keV) were calculated and compared with reported[7] values. The systematic error in the efficiency calibration is deduced to be $\pm$0.7%. Further details of the calibrations, especially the summing corrections applied to the data, are discussed in Section III. The peak:total ratio as a function of energy was determined using sources of ^{137}Cs, ^{60}Co, and coincidence-gated spectra from ^{154}Eu.

III. DATA ANALYSIS AND EXPERIMENTAL RESULTS

k. All γ-ray spectra and $\gamma - \gamma$ coincidence matrices were produced using the computer program `gtsort`[12]. The data for each of the 20 detectors in the array were matched in energy using a linear transformation and matched in time using an offset in order to correct for drifts in acquisition electronics. Random coincidences were removed by subtracting a delayed-time coincidence matrix from the prompt coincidence matrix.

l. The Radware software package[13] was used to analyze coincidence and singles data. A level scheme was constructed from the $\gamma - \gamma$ coincidence matrix using the program `escl8r`[14], however γ-ray intensity measurements were hindered by Compton artifacts from strong transitions in the decay. This was particularly limiting for weak transitions and transitions which coincided with a Compton feature, which required changing the background selection. Coincidence spectra were generated using the program `slice`[13] by selecting a peak gate of suitable channel width and subtracting a background gate (suitably normalized by a peak/background ratio) of equal width. Peaks in the resulting spectra were fitted with a skewed Gaussian shape using the program `gf3`[13].

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[1] The source was obtained from Isotope Products Laboratories, Burbank, CA.

[2] The spectrometer has been reconfigured and the detectors refurbished since the work described here was carried out.

m. The γ-ray singles spectrum obtained in this work is shown in Fig. 2. The γ-ray spectra in coincidence with the 123 keV ($2_1^+ \rightarrow 0_1^+$) and 248 keV ($4_1^+ \rightarrow 2_1^+$) transitions are shown in Figs. 3 and 4. The γ rays assigned to the decay of ^{154}Eu $\rightarrow$ ^{154}Gd, on the basis of the present work, are listed in Table I. All transition assignments are between adopted levels in the *Nuclear Data Sheets*[7] for ^{154}Gd and they have all been made on the basis of coincidence information obtained in the present work (our transition assignments are given in Table I). Further, all singles intensities were compared with coincidence intensities and weighted averages are adopted where appropriate. Intensities for closely-spaced doublets are from the coincidence spectra alone. The population of the levels at 1182, 1404 and 1433 keV has not been reported previously for the decay of ^{154}Eu. There are 23 transitions in ^{154}Gd identified in this work which are not in the *Nuclear Data Sheets*. However, the major outcome of the present work is the refutation of 8 excited states in ^{154}Gd below 1700 keV, shown in Table III, which were adopted in the *Nuclear Data Sheets*; and the refutation of 59 γ rays, shown in Table V, assigned to the decay of ^{154}Eu, which are almost entirely from two studies[9, 10]. Such an outcome in radioactive decay scheme spectroscopy is, to our knowledge, unprecedented. Further, the outcome is of critical concern for understanding the nuclear structure of ^{154}Gd and we reiterate the primary motivation of this investigation, illustrated in Fig. 1: there appear to be too many states in ^{154}Gd, compared to ^{152}Sm, below 1700 keV. We address the major points of our new assignments and our refutations below.

n. Figure 5 shows a selected energy range from the γ-ray singles spectrum and the same range from a selected coincidence gate, which is representative of the data quality in this study. Figure 6 shows the peak fitting to weak lines in a selected energy range of the γ-ray singles spectrum. The 349 keV line, which is assigned between established[7] levels at 1182 and 1531 keV, is the strongest new transition observed in this work. Further proof of this is presented in Fig. 7. The 344 keV line is the strongest contaminant line from ^{152}Eu, from which we deduce that the source used contained $0.027 \pm 0.002\%$ ^{152}Eu. This is lower than nearly all previous studies, which quote typically $\gtrsim$ 0.1%[15]. The only source reported[9] with less ^{152}Eu ("10^{-4} ") was evidently a very weak source which provided a 12 day singles spectrum (Fig. 1 in [9]) with ~1/100 the statistics reported here.

o. The study[9], which reported most of the weak γ-ray lines (that are a key focus of the present study), presents spectra with higher statistics (Fig. 2 in [9]) than the aforementioned very low statistics spectrum from a source reported to have 0.79% ^{152}Eu and 14% ^{155}Eu. From these spectra we deduce that in γ-ray singles we achieved ~2× the statistics with ~2× peak:background and in $\gamma-\gamma$ coincidences we achieved ~50× the statistics with ~5× peak:background reported (cf. our Figs. 2, 3, 4 with Figs. 2a, b, 3, 4 in [9]). (There are also strong random peaks in the coincidence spectra shown in[9], e.g., in the 123 γ-gated γ spectrum, the 123 peak is the strongest peak.) The other study[10], which reports confirmation of many of the weak lines given in [9], did not present any spectra or any information on the statistical quality of the data, e.g., source strength and counting times.

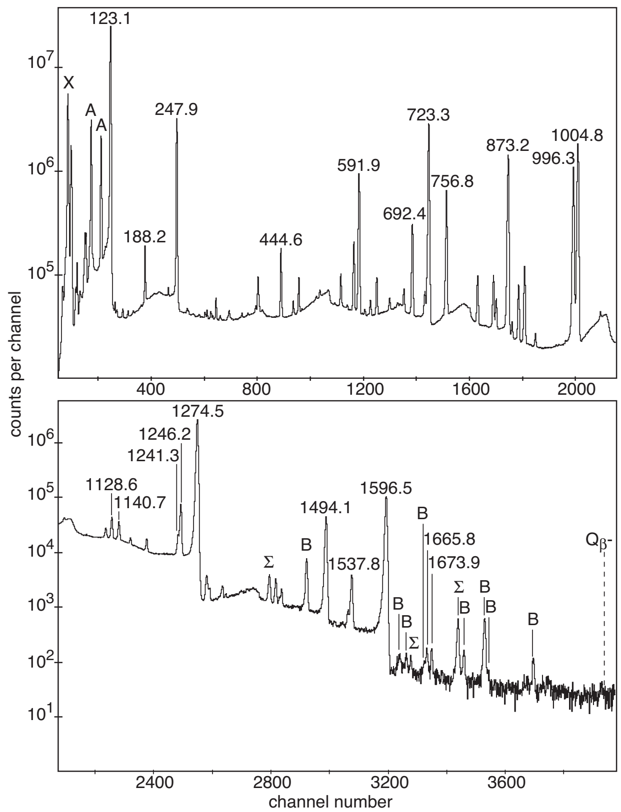

FIG. 2: The singles γ-ray spectrum for ^{154}Eu decay obtained in the present study. Peaks marked: X are X rays; A are the strong lines from the decay of ^{155}Eu at 86 and 105 keV; Σ are from coincidence summing; and B are from room background. Energies of selected lines are given in keV, and $Q_{\beta^-} = 1968.5$ keV is indicated.

p. The high statistical quality of our data allows us to set stringent upper limits on weak transitions using the method described by Currie[16]. For each claimed weak γ transition, regions of $n = \text{FWHM} + 1$ peak channels and $2m$ background channels with corresponding areas, G and S, are defined. If the net area, $A = G - B$ (where $B = \frac{nS}{2m}$ scales the background counts to the peak region), is less than a critical level, $L_c = 1.645[B(1+\frac{n}{2m})]^{\frac{1}{2}}$, then an upper limit, $L_u = A + 1.645[A + B(1+\frac{n}{2m})]^{\frac{1}{2}}$ may be set on the peak area (cf. Fig. 8). This corresponds to a 95% confidence limit on the maximum intensity of the transition in question.

q. Figure 9 shows our evidence for questioning the existence of a line at 1387 keV. This is the strongest line reported by Meyer[9] and Hammed *et al.*[10], that we are

TABLE I: Gamma rays assigned to the decay of ^{154}Eu, normalized such that $I_\gamma(1274) \equiv 100.0$. Multiply these relative I_γ by 0.3486(29) for intensity per 100 β decays of the parent (determined by requiring 100% feeding (I_γ+ce) to the ground state).

E_γ	I_γ	E_i	E_f	E_γ	I_γ	E_i	E_f
			Transitions assigned to ^{154}Gd.				
123.09 (7)	116.0 (10)	123.09	0.00	560.79 (19)	0.0018 (5)	1241.35	680.62
129.60 (13)	0.0045 (6)	1660.92	1531.33	569.50 (7)	0.040 (6)	1617.19	1047.65
131.56 (7)	0.0377 (12)	1127.85	996.28	581.97 (7)	2.563 (18)	1397.55	815.52
134.87 (7)	0.023 (3)	815.52	680.62	591.89 (7)	14.21 (10)	1719.61	1127.85
146.01 (7)	0.0205 (10)	1397.55	1251.68	598.30 (7)	0.030 (4)	1645.85	1047.65
156.28 (8)	0.0247 (25)	1397.55	1241.35	598.93 (7)	0.0008 (3)	1414.39	815.52
166.32 (10)	0.0030 (3)	1418.16	1251.68	602.68 (7)	0.084 (3)	1418.16	815.52
177.05 (20)	0.0020 (4)	1418.16	1241.35	613.24 (7)	0.2674 (29)	1660.92	1047.65
180.72 (7)	0.0150 (20)	996.28	815.52	621.6 (5)	0.012 (5)	1617.19	996.28
188.22 (7)	0.689 (5)	1719.61	1531.33	625.22 (7)	0.904 (7)	996.28	371.03
199.20 (8)	0.0021 (3)	1617.19	1418.16	649.52 (7)	0.251 (5)	1645.85	996.28
203.40 (29)	0.0018 (3)	1617.19	1414.39	664.74 (8)	0.0751 (29)	1660.92	996.28
213.06 (11)	0.0012 (2)	1617.19	1404.07	669.14 (8)	0.0460 (22)	1796.99	1127.85
218.71 (26)	0.0023 (4)	1617.19	1397.55	676.60 (7)	0.480 (4)	1047.65	371.03
228.28 (11)	0.0055 (11)	1660.92	1432.62	692.39 (7)	5.10 (4)	815.52	123.09
232.12 (7)	0.0627 (12)	1047.65	815.52	714.90 (16)	0.0026 (2)	1432.62	717.73
236.36 (8)	0.0066 (8)	1418.16	1182.02	715.76 (7)	0.537 (5)	1531.33	815.52
241.69 (9)	0.0036 (5)	1645.85	1404.07	723.29 (7)	57.6 (4)	1719.61	996.28
242.86 (6)	0.0117 (10)	1660.92	1418.16	737.69 (13)	0.0065 (6)	1418.16	680.62
245.07 (13)	0.0013 (2)	1241.35	996.28	740.91 (16)	0.0030 (5)	1788.91	1047.65
247.94 (7)	19.77 (14)	371.03	123.09	749.48 (9)	0.0215 (13)	1796.99	1047.65
255.80 (10)	0.0079 (26)	1251.68	996.28	756.81 (7)	12.98 (9)	1127.85	371.03
263.50 (16)	0.0029 (4)	1660.92	1397.55	800.61 (8)	0.061 (3)	1796.99	996.28
267.54 (7)	0.021 (4)	1263.82	996.28	801.69 (11)	0.0177 (17)	1617.19	815.52
267.55 (7)	0.0110 (3)	1531.33	1263.82	815.51 (7)	1.469 (11)	815.52	0.00
269.65 (8)	0.0330 (15)	1397.55	1127.85	830.42 (10)	0.0179 (16)	1645.85	815.52
279.65 (7)	0.0092 (3)	1531.33	1251.68	845.46 (7)	1.6252 (12)	1660.92	815.52
290.29 (11)	0.0041 (2)	1531.33	1241.35	850.67 (7)	0.697 (6)	1531.33	680.62
290.40 (8)	0.005 (2)	1418.16	1127.85	873.22 (7)	34.68 (24)	996.28	123.09
293.26 (22)	0.0010 (2)	1559.21	1263.82	880.65 (7)	0.241 (16)	1251.68	371.03
301.38 (7)	0.0355 (10)	1719.61	1418.16	892.80 (7)	1.492 (12)	1263.82	371.03
305.19 (7)	0.0593 (11)	1719.61	1414.39	904.10 (7)	2.549 (20)	1719.61	815.52
307.7 (3)	0.0011 (3)	1559.21	1251.68	924.57 (7)	0.1862 (25)	1047.65	123.09
312.32 (7)	0.0522 (10)	1127.85	815.52	928.21 (8)	0.0086 (5)	1645.85	717.73
315.64 (7)	0.0254 (3)	996.28	680.62	981.61 (9)	0.025 (4)	1796.99	815.52
322.07 (7)	0.1778 (17)	1719.61	1397.55	996.29 (7)	30.09 (21)	996.28	0.00
329.95 (7)	0.027 (3)	1047.65	717.73	1004.76 (7)	51.7 (4)	1127.85	123.09
346.70 (7)	0.0747 (12)	717.73	371.03	1034.59 (17)	0.0057 (7)	1404.07	371.03
349.23 (7)	0.0189 (22)	1531.33	1182.02	1047.18 (7)	0.161 (9)	1418.16	371.03
352.85 (20)	0.0038 (4)	1617.19	1263.82	1058.94 (10)	0.024 (4)	1182.02	123.09
365.47 (15)	0.0029 (4)	1617.19	1251.68	1061.58 (13)	0.0102 (30)	1432.62	371.03
366.49 (8)	0.0044 (10)	1182.02	815.52	1071.17 (24)	0.0007 (1)	1788.91	717.73
370.78 (8)	0.0121 (4)	1418.16	1047.65	1118.27 (7)	0.325 (11)	1241.35	123.09
378.90 (27)	0.0011 (3)	1796.99	1418.16	1128.56 (7)	0.856 (7)	1251.68	123.09
382.09 (8)	0.0272 (9)	1645.85	1263.82	1140.71 (7)	0.681 (9)	1263.82	123.09
382.46 (27)	0.0007 (2)	1796.99	1414.39	1160.31 (7)	0.1326 (13)	1531.33	371.03
397.07 (7)	0.0792 (18)	1660.92	1263.82	1188.14 (7)	0.2513 (29)	1559.21	371.03
401.26 (7)	0.541 (8)	1397.55	996.28	1241.34 (7)	0.352 (4)	1241.35	0.00
403.58 (7)	0.072 (7)	1531.33	1127.85	1246.16 (7)	2.469 (18)	1617.19	371.03
409.19 (8)	0.015 (5)	1660.92	1251.68	1274.51 (7)	100.0 (7)	1397.55	123.09
421.8 (8)	0.0038 (29)	1418.16	996.28	1275.22 (7)	obsc.	1645.85	371.03
426.00 (13)	0.0023 (4)	1241.35	815.52	1289.88 (11)	0.0603 (22)	1660.92	371.03
436.20 (11)	0.0090 (16)	1251.68	815.52	1291.25 (10)	0.068 (10)	1414.39	123.09
444.58 (7)	1.610 (12)	815.52	371.03	1294.99 (8)	0.0333 (17)	1418.16	123.09
448.45 (19)	0.0073 (11)	1263.82	815.52	1408.28 (7)	0.071 (3)	1531.33	123.09
467.92 (7)	0.1798 (21)	1719.61	1251.68	1414.44 (10)	0.0130 (14)	1414.39	0.00
478.24 (7)	0.646 (5)	1719.61	1241.35	1417.88 (9)	0.0152 (8)	1788.91	371.03
483.76 (7)	0.0263 (16)	1531.33	1047.65	1418.15 (9)	0.024 (3)	1418.16	0.00
511.60 (8)	0.0091 (7)	1559.21	1047.65	1426.03 (27)	0.0012 (2)	1796.99	371.03
517.98 (7)	0.143 (4)	1645.85	1127.85	1494.13 (7)	2.003 (18)	1617.19	123.09
533.03 (8)	0.0530 (29)	1660.92	1127.85	1522.19 (16)	0.0025 (5)	1645.85	123.09
533.11 (7)	0.0234 (14)	1796.99	1263.82	1531.40 (8)	0.0184 (6)	1531.33	0.00
534.88 (8)	0.110 (11)	1531.33	996.28	1537.81 (7)	0.1646 (29)	1660.92	123.09
545.20 (14)	0.0039 (5)	1796.99	1251.68	1596.49 (7)	5.16 (4)	1719.61	123.09
546.08 (7)	0.025 (4)	1263.82	717.73	1665.83 (12)	0.0058 (3)	1788.91	123.09
557.53 (7)	0.773 (6)	680.62	123.09	1673.93 (8)	0.0058 (3)	1796.99	123.09
			Transitions assigned to ^{154}Sm.				
81.78 (7)	obsc.	81.98	0	185.35 (9)	0.0148 (11)	266.79	81.98

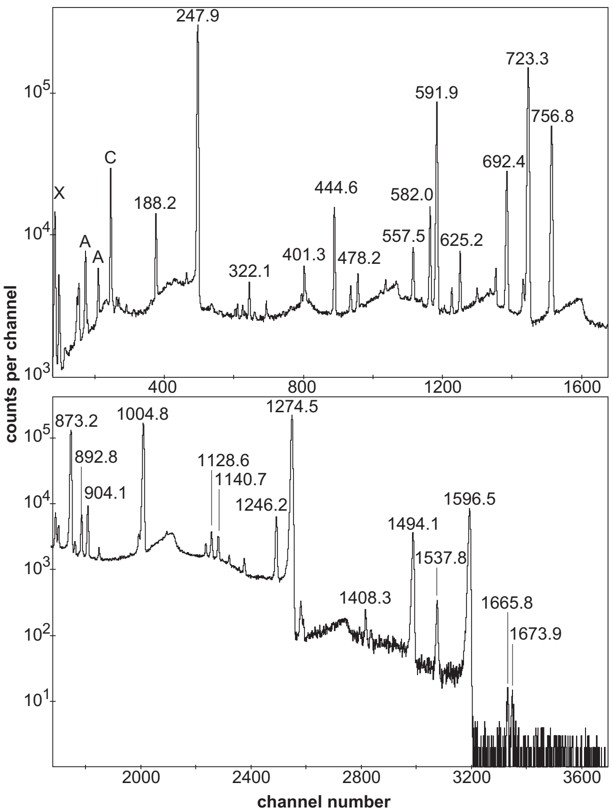

FIG. 3: The coincident γ-ray spectrum associated with the 123.1 keV ($2_1^+ \rightarrow 0_1^+$) transition. Peaks are marked as in Fig. 2 and chance coincidences are marked C.

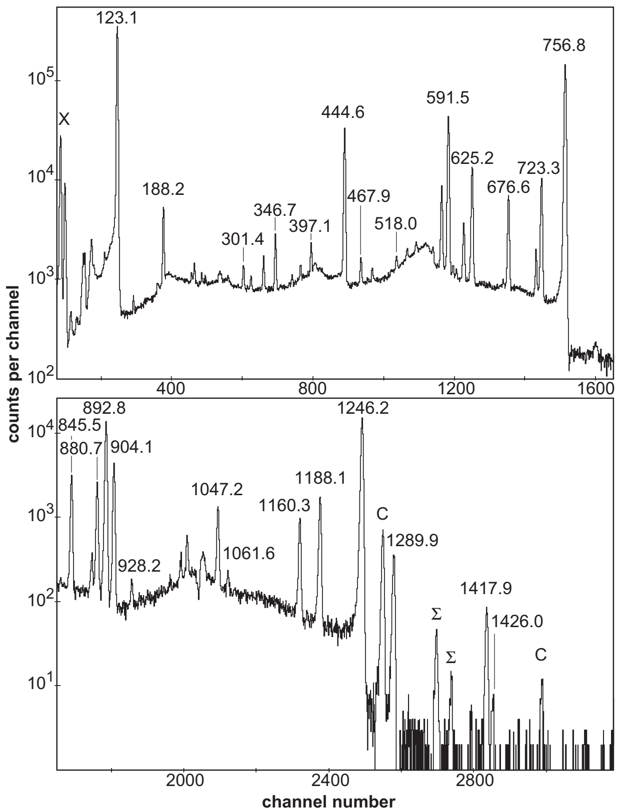

FIG. 4: The coincident γ-ray spectrum associated with the 247.9 keV ($4_1^+ \rightarrow 2_1^+$) transition. Peaks are marked as in Figs. 2 and 3.

unable to confirm. This γ ray should be visible in Meyer's published γ-ray singles spectrum (Fig. 2b in [9]); careful inspection of this figure suggests that it is not seen with the assigned intensity. The same observation applies to the 1510 keV line (cf. Fig. 9). It would appear that the assigned intensities for these lines: by Meyer[9] 0.056 ± 0.006 (1387) and 0.0141 ± 0.0028 (1510) (intensities normalized to 100 (1274.5)), are not typographical errors because confirmation by Hammed *et al.*[10] is implied, *viz.* 0.055 ± 0.005 (1387) and 0.013 ± 0.004 (1510). We note that, for comparison, the 1408.2 keV line is seen in the present study with an intensity of 0.071 ± 0.003, in good agreement with [9] 0.059 ± 0.008 and [10] 0.063 ± 0.008; and the 1531.5 keV line 0.0184 ± 0.0006 (present), 0.0172 ± 0.0011[9], 0.018 ± 0.002[10], also are all in good agreement. Our refutation of the 1387 and 1510 keV γ rays removes the evidence[7, 9] for a level in ^{154}Gd at 1510 keV. (We offer no explanation for the above inconsistencies.)

r. Figure 8 presents some of the data on the basis of which we refute a level in ^{154}Gd at 1294.17 keV[7, 9]. This level has played a critical role in the interpretation of the low-energy structure of ^{154}Gd because it has been assigned as the first excited rotational state built on the 0^+ state at 1182 keV (the resulting $0^+ - 2^+$ energy separation of 112 keV matches closely the $0_g^+ - 2_g^+$ spacing of 123 keV). Removal of the 1294 keV state completely changes the interpretation of the 0^+ state at 1182 keV. Prior to this work, the 0^+ states at 0, 681, and 1182 keV all appeared to be intrinsic structures with very similar deformations based on the assignment of rotational bands built on these states. As an outcome of this work, a completely new structure is suggested[17] for the 1182 keV 0^+ state. The removal of the 1294 keV level from the ^{154}Gd scheme[17] is not simply a matter of refuting the γ rays in the decay of ^{154}Eu which were used to define it; γ rays from the ^{153}Gd(n,γ) reaction[19] were also assigned to this level. We discuss this below.

s. The unpublished (n,γ) and (n,e^-) study[19] of ^{154}Gd has been incorporated into the most recent *Nuclear Data Sheets* evaluation[7] for $A = 154$. This study contains some useful information on levels and transitions in ^{154}Gd, relevant details of which are given here. Unfortunately, this study contains essentially equal spectroscopic contributions from neutron capture in ^{152}Gd and ^{153}Gd. While growth of line intensities with time was studied (the target was enriched ^{152}Gd, and ^{154}Gd was reached by double capture), no coincidence data were obtained. The resulting assignments on the basis of Ritz combinations for lines that appeared to be predominantly transitions in ^{154}Gd clearly has resulted in many errors for relative intensities of transitions out of individual lev-

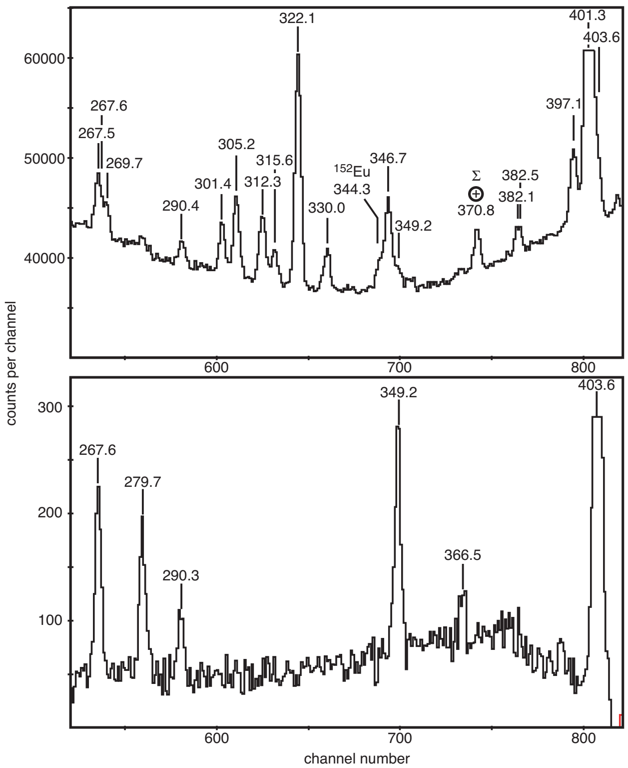

FIG. 5: A comparison of the singles γ-ray spectrum with a coincident γ-ray spectrum gated by the 188 keV (1719 $\rightarrow$ 1531 keV) transition for the energy range 260-410 keV. This reveals the existence of the 349.2 keV transition for the first time (see discussion in the text). It also reveals that the 267 and 290 peaks are doublets.

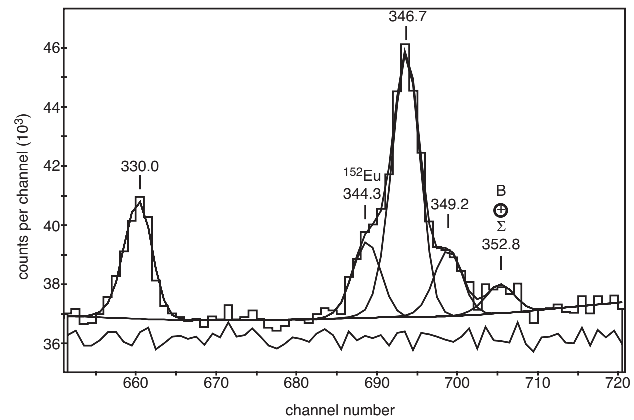

FIG. 6: An illustration of the quality of peak fitting for weak γ-ray lines, seen in this investigation. Some details of this figure are discussed in the text. The sum peak at 352.8 is the strongest random sum ($\Sigma 248 + 105$) in our spectrum.

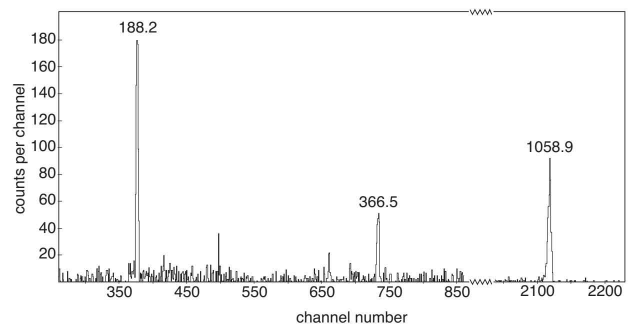

FIG. 7: The coincident γ-ray spectrum associated with the 349 keV (1531 $\rightarrow$ 1182 keV) transition. This establishes for the first time that the 0^+ 1182 keV level is populated (indirectly) in the decay of ^{154}Eu.

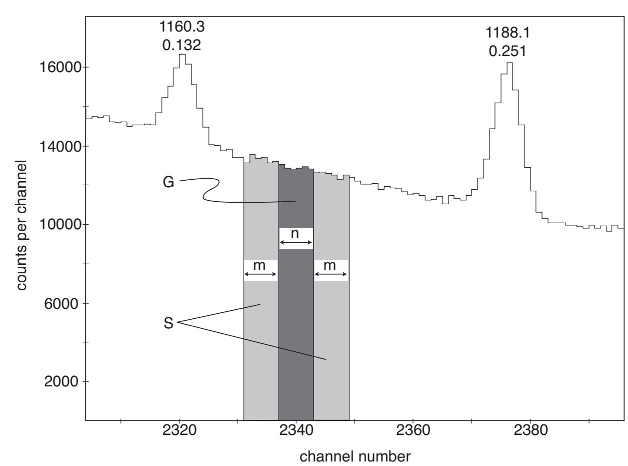

FIG. 8: An illustration of establishing an upper intensity limit for a γ-ray line by use of the method of Currie[16]. This figure is discussed further in the text.

els, as shown below. More seriously, the ambiguities in assignments, both by mass and by the Ritz method, enabled the authors to "confirm" all of the levels reported by Meyer[9]; but at the expense of noted[19] population anomalies and serious disagreements in relative transition intensities (out of individual levels). Unfortunately, some of these "weak confirmations" have been combined[7] into extensive sets of transitions de-exciting individual levels that give the impression of robust structural features in ^{154}Gd. We adopt the following criterion for refuting a level: if the strongest γ ray assigned as de-exciting a level reported by Meyer[9] is shown *not* to be so located in the ^{154}Gd level scheme on the basis of our coincidence data, or if such a γ ray is shown to have significantly weaker intensity (intensity upper limit) we reject all subsequent "confirmations" of the level.

t. In Table II we list the levels in ^{154}Gd observed to be populated in the decay of ^{154}Eu in the present study. We also give the γ-ray transitions de-exciting each level with their relative intensities. The relative intensities for these transitions as given in the *Nuclear Data Sheets* for $A = 154$[7] are also shown with the designation of the origin of the intensity, e.g., Eu decay, in-beam, neutron capture, or Tb decay. In a number of instances the relative intensities adopted[7], based (in part) on the neutron-

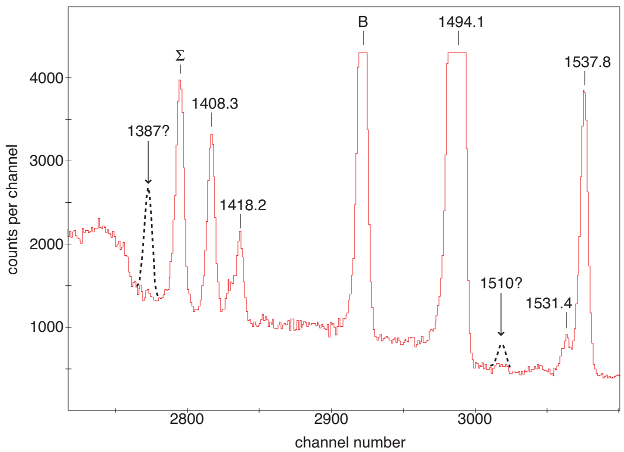

FIG. 9: Evidence from the γ-ray singles data that the lines reported[9, 10] at 1387 and 1510 keV are spurious. The spectrum also shows the strongest coincidence sum peak (at 1397.6 keV) in the spectrum and the strong room background peak (at 1460.8 keV) from ^{40}K

capture study[19], are clearly in disagreement with the Eu (and the Tb) decay values. Indeed, the authors of the neutron-capture study warn the reader that radioactive decay values must take precedence over their values because of the $A = 153$ "contamination".

u. In Table III we list the levels in ^{154}Gd that were reported by Meyer in his study[9] of ^{154}Eu decay, but which we refute in the present work. The refutation of the 1510 keV level has already been discussed. We do not observe the two γ rays, at 1387 and 1510 keV (cf. Fig. 9), which define[7, 9] the level. Upper intensity limits for these γ rays are given in Table V. Some discussion of the refutation of the 1294 keV level has also been made already, based on our non-observation of a γ ray at 1171 keV (cf. Fig. 8). A second strong decay branch of 1294 keV is assigned in the (n, γ) study[19], but not in the ^{154}Eu decay study[9]. This is a complex region of the spectra of both ^{154}Eu decay and neutron capture. Without coincidence information the neutron capture assignment is questionable. Our assignment of a line at 1294.9 keV is to the decay of the 1418 keV level, based on coincidence information. Since the 1294 keV level fails our criterion for acceptance (it originated in the ^{154}Eu decay study through the assignment of the 1171 keV γ ray as de-exciting the level) we assert that our data refute the existence of the level. Indeed, in the neutron capture study[19], while the table of levels and de-exciting transitions presents evidence for a level at 1294.185 keV with de-exciting transitions of 112.096, 923.08, 1171.24, and 1294.19 keV, in the text the authors express serious doubt about the existence of the level on the basis of the non-observation of a primary capture γ ray to this level. We are unclear as to what exactly the authors wished to communicate regarding the existence/non-existence of the 1294 keV level. All of these details for the 1294 level have been entered into the *Nuclear Data Sheets*[7] and a γ ray of 165.90 keV has also been added to the de-excitation of the level based on an assignment in a sole ^{154}Eu decay study[20]. We assign a 166.2 keV γ ray, on the basis of coincidence data, to the decay of the 1418 keV level. We note that the assignment in the *Nuclear Data Sheets* would result in a $B(E2)$ ratio for the 1294/166 transitions of $1 : 18,000$. We also note that the sum peak $\sum 123 + K_\alpha$ lies at 166 keV. We reiterate that the existence/non-existence of the 1294 keV level plays a critical role in understanding the structure of ^{154}Gd.

v. The levels in ^{154}Gd at 1135.96 and 1233.1 have only been reported in ^{154}Eu decays: the 1135.96 in[9, 21] and the 1233.1 in[9]. These claims are based upon extremely weak γ-ray peaks, making them very difficult to refute unequivocally. The strongest reported γ ray de-exciting the 1136 level (there are only two de-exciting transitions assigned) is an 1136 keV line with intensity 0.0211[9] and 0.042[21]. This energy places the claimed γ-ray peak on the tail of the 1140 keV line (intensity 0.68). We set an upper intensity limit for a line at 1136 of $\lesssim 0.003$. Where a second de-exciting γ-ray transition of 1012.8 keV ($1136 \rightarrow 123$) with an intensity of 0.008 has been assigned[9], we have no significant residual intensity and set an upper limit of $\lesssim 0.004$ due entirely to Poisson fluctuations in the background. The level at 1233.1 (indicated as tentative in [7]) depends on a single γ ray of 1110 keV observed in [9] with an intensity of 0.008; we set an upper limit of $<$0.005 for this transition. We also note that the ^{152}Eu impurity shows a line at 1112.1 keV and in the published[9] spectrum there was $\sim$34$\times$ as much ^{152}Eu as in our spectrum. We discuss the existence/non-existence of these levels in ^{154}Gd again when we address the systematics of level population, as a function of spin and excitation energy, in the ^{154}Eu $\rightarrow$ ^{154}Gd decay scheme.

w. The level at 1276.986 keV is based on γ rays of 905.99 keV (1277$\rightarrow$371) and 229.01 keV (1277$\rightarrow$1048). The 906 line is reported in both the (n, γ) study[19] and one of the ^{154}Eu decay studies[9]. In the (n, γ) study the line is noted to be a doublet with a $A = 153$ component. In the ^{154}Eu decay study it is reported[9] with an intensity of 0.0338. An impediment to proving/disproving the existence of this transition is that it feeds the 371 keV level which is also fed indirectly by a 904.1 keV γ ray with 75$\times$ the intensity: we set an upper intensity limit of 0.002. The 229.01 keV line has been reported in ^{154}Eu decay (only) with an intensity of 0.0056[9] and 0.0085[10]. It was only assigned in [20] and this is the assignment adopted[7]. We assign a 228.3 keV γ ray, intensity, $I_\gamma = 0.0055(11)$, on the basis of coincidence data shown in Fig. 10 as a 1661 $\rightarrow$ 1433 transition. We discuss the 1277 keV level again when we address population systematics.

x. The remaining levels, reported[7] as populated in the decay of ^{154}Eu, which we are unable to confirm are at 1698.501, 1770.182, 1838.597, 1861.546, and 1894.7, with a tentative level at 1878.3 keV. Of these, the lev-

TABLE II: Levels in ^{154}Gd populated in the decay of ^{154}Eu. Relative I_γ values from this study (8π) are compared with values from the evaluated[7] decay scheme (NDS). Where a transition has not been observed in this study, $<$ denotes an upper limit. The origins of the adopted[7] relative I_γ are labelled by: a ^{154}Eu decay; b (n,γ); c $(\alpha, 2n\gamma)$; d ^{154}Tb($J=3$) decay; e ^{154}Tb($J=7$) decay.

E_x (keV)	J^π	E_γ (keV)	8π	NDS	Source
0	0^+				
123.09 (7)	2^+	123.09 (7)	100	100	
371.03 (7)	4^+	247.94 (7)	100	100	
680.62 (7)	0^+	557.53 (7)	100.0 (8)	100.0 (9)	
		680.6	[2.1 (2)]	2.1 (2)	
717.73 (7)	6^+	346.70 (7)	100	100	a
815.52 (8)	2^+	134.87 (7)	0.45 (6)	0.400 (21)	a
		444.58 (7)	31.6 (3)	31.4 (3)	a
		692.39 (7)	100 (1)	100.0(3)	a
		815.51 (7)	28.8 (2)	28.65 (18)	a
996.28 (7)	2^+	180.72 (7)	0.043 (6)	0.033 (4)	a
		315.64 (7)	0.073 (1)	0.060 (11)	a
		625.22 (7)	2.61 (2)	2.61 (3)	a
		873.22 (7)	100.0 (7)	100.0 (3)	a,b
		996.29 (7)	86.8 (6)	89 (4)	a,b
1047.65 (7)	4^+	232.12 (7)	13.1 (3)	15.0 (6)	a
		329.95 (7)	5.6 (6)	6.1 (2)	a,b
		676.60 (7)	100.0 (8)	100 (2)	a,b
		924.57 (7)	38.8 (5)	38.2 (15)	b
1127.85 (7)	3^+	131.56 (7)	0.073 (2)	0.062 (3)	a
		312.32 (7)	0.101 (2)	0.104 (8)	a
		756.81 (7)	25.1 (2)	25.4 (3)	a,b
		1004.76 (7)	100.0 (8)	100.0 (3)	a,b
1182.02 (7)	0^+	366.49 (8)	18 (4)	18.1 (6)	b
		1058.94 (10)	100 (17)	100 (5)	b
1241.35 (7)	1^-	245.07 (13)	0.4 (1)		
		426.00 (13)	0.6 (1)	0.59 (6)	b
		560.79 (19)	0.5 (1)	1.2 (4)	b
		1118.27 (7)	92 (3)	81.3 (25)	b
		1241.34 (7)	100 (1)	100 (3)	b
1251.68 (7)	3^-	255.80 (10)	0.9 (3)		
		436.20 (11)	1.1 (2)		
		880.65 (7)	28 (2)	25.4 (10)	a
		1128.56 (7)	100.0 (8)	100.0 (11)	a,b
		1252.0	< 0.17	4.9 (8)	b
1263.82 (7)	4^+	267.54 (7)	1.4 (3)	≤ 2.8	
		448.45 (19)	0.5 (1)		
		546.08 (7)	1.7 (3)	2.8 (3)	a
		892.80 (7)	100.0 (8)	100.0 (7)	a
		1140.71 (7)	45.7 (6)	45.7 (4)	a
1397.55 (9)	2^-	146.01 (7)	0.020 (1)	0.074 (3)	a
		156.28 (8)	0.025 (3)	0.0280 (11)	a
		269.65 (8)	0.033 (1)	0.0205 (23)	a
		401.26 (7)	0.541 (8)	0.553 (6)	a,b
		581.97 (7)	2.56 (2)	2.54 (2)	a
		1274.51 (7)	100.0 (7)	100.0 (5)	a,b
1404.07 (17)	5^-	1034.59 (17)	100	100	
1414.44 (7)	1^-	598.93 (7)	1.1 (4)	3.52 (21)	b
		1291.35 (8)	100 (15)	100 (4)	b
		1414.44 (9)	19 (2)	28 (3)	b
1418.16 (8)	2^+	166.32 (10)	1.8 (2)	1.33 (9)	b
		177.05 (20)	1.2 (2)	1.24 (18)	b
		236.36 (8)	4.1 (5)	2.4 (3)	b
		290.40 (8)	3.1 (1)	1.77 (9)	b
		370.78 (8)	7.5 (2)	8.0 (5)	b
		421.80 (8)	2 (2)	2.1 (3)	b
		602.68 (7)	52 (2)	45.0 (9)	b
		737.69 (13)	4.0 (4)	2.0 (4)	b
		1047.18 (7)	100 (6)	100 (7)	a,b
		1294.99 (8)	21 (1)	18.4 (12)	a,b
		1418.15 (9)	15 (2)	24 (3)	a,b
1432.62 (7)	5^+	714.90 (16)	26 (2)	35 (2)	c
		1061.58 (13)	100 (29)	100 (4)	c
1531.32 (10)	2^+	116.868	< 0.15	1.0 (3)	b
		267.55 (7)	1.6 (1)	≤ 3.7	a,b
		279.65 (7)	1.32 (4)	1.23 (6)	a
		290.29 (11)	0.60 (3)	1.39 (7)	a
		349.23 (7)	2.7 (3)		
		403.58 (7)	10 (1)	10.0 (10)	a,b
		483.76 (7)	3.8 (2)	2.05 (12)	a
		534.88 (8)	16 (2)	< 5	a
		715.76 (7)	77 (1)	75 (3)	a,b
1531.32 (10)	2^+	850.67 (7)	100 (1)	100.0 (22)	a,b
		1160.31 (7)	19.0 (2)	18.1 (7)	a
		1408.28 (7)	10.3 (4)	9.5 (7)	a
		1531.33 (15)	2.6 (1)	2.47 (14)	a
1559.21 (8)	4^-	293.26 (22)	0.40 (8)	2.56 (15)	a
		307.7 (3)	0.4 (1)		
		511.60 (8)	3.6 (3)		
		1188.14 (7)	100 (1)	100 (3)	a
1617.19 (7)	3^-	199.20 (8)	0.12 (2)		
		203.40 (29)	0.07 (1)	3.2 (8)	a
		213.06 (11)	0.049 (8)		
		218.71 (26)	0.09 (2)	0.27 (6)	a
		352.85 (20)	0.15 (2)		
		365.47 (15)	0.12 (2)		
		569.50 (7)	1.6 (2)	1.16 (9)	a
		621.6 (5)	0.5 (2)	1.05 (6)	a
		801.69 (11)	0.72 (7)	1.4 (3)	a
		1246.16 (7)	100.0 (7)	100.0 (4)	a
		1494.13 (7)	81 (1)	81.0 (8)	a
1645.89 (9)	4^+	227.644	< 0.31	2.2 (7)	b
		241.20 (9)	1.4 (2)	≤ 5	b
		351.650	< 2.4	85	b
		382.09 (8)	10.9(4)	10.9 (16)	a,d
		394.217	< 0.16	4.8 (11)	b
		517.98 (7)	57 (2)	58 (3)	a,d
		598.30 (7)	12 (2)	10.5 (20)	a,d
		649.52 (7)	100 (2)	100 (4)	a,d
		830.42 (10)	7.1 (6)	6.2 (5)	d,e
		928.21 (8)	3.4(2)	3.1 (11)	d,e
		1275.22 (7)	*obsc.*	2.9 (11)	d
		1522.19 (16)	1.0 (2)	2.8 (12)	d
1660.92 (8)	3^+	129.60 (13)	0.28 (4)	2.3 (4)	a
		228.28 (11)	0.34 (7)		
		242.86 (7)	0.72 (6)		
		263.50 (16)	0.18 (2)		
		397.07 (7)	4.9 (1)	4.88 (18)	a
		409.19 (8)	0.9 (3)		
		533.03 (8)	3.3 (2)	1.2 (4)	a
		613.24 (7)	16.5 (2)	15.9 (5)	a
		664.74 (8)	4.6 (2)	4.88 (18)	a
		845.46 (7)	100.0 (7)	100.0 (6)	a
		1289.88 (11)	3.7 (1)	4.2 (4)	a
		1537.81 (7)	10.1 (2)	9.0 (3)	a
1719.61 (9)	2^-	159.555	< 0.002	0.67 (11)	b
		188.22 (7)	1.20 (1)	1.190 (21)	a
		301.38 (7)	0.062 (2)	0.0508 (17)	a
		305.19 (7)	0.103 (2)	0.087 (3)	a
		322.07 (7)	0.309 (3)	0.329 (9)	a
		467.92 (7)	0.312 (4)	0.301 (9)	a
		478.24 (7)	1.12 (1)	1.119 (9)	a
		591.89 (7)	24.7 (2)	24.68 (12)	a
		723.29 (7)	100.0 (7)	100.0 (4)	a,b
		904.10 (7)	4.42 (5)	4.440 (23)	a
		1596.49 (7)	8.96 (9)	8.89 (5)	a
1788.91 (7)	4^+	740.91 (16)	20 (3)		
		1071.17 (24)	4.8 (9)		
		1417.88 (9)	100 (5)	100 (5)	a
		1665.83 (12)	38 (3)	98 (12)	a
1797.00 (11)	3^-	378.90 (27)	1.8 (5)		
		382.46 (27)	1.2 (3)		
		392.862	< 0.17	19 (7)	b
		533.11 (7)	39 (3)	19 (4)	a,b
		545.20 (14)	6.4 (9)		
		555.684	< 0.76	11.6 (13)	b
		669.14 (8)	76 (5)	42 (5)	a
		749.48 (9)	36 (3)		
		800.61 (8)	100 (5)	100 (4)	a,b
		981.61 (9)	42 (7)	26 (4)	a
		1426.03 (27)	2.0 (4)	3.7 (15)	a
		1673.93 (8)	9.5 (5)	5.4 (7)	a
		1796.3	< 0.29	62 (4)	b

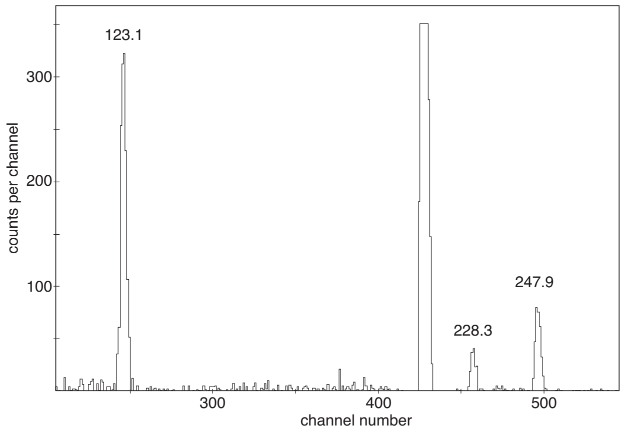

FIG. 10: The coincident γ-ray spectrum associated with the 1061.4 keV (1433 $\rightarrow$ 371 keV) transition which shows that the 228.3 keV transition is located between the 1661 and 1433 levels. This establishes for the first time that the 5^+ 1433 keV level is populated (indirectly) in the decay of ^{154}Eu. The events at 213 keV are due to Compton backscattering of 1274 keV γ rays.

TABLE III: Upper limits for population of levels in the adopted ^{154}Eu $\rightarrow$ ^{154}Gd decay scheme[7] which were not observed in this study. Total intensity (I_γ+ce, $I_\gamma(1274) \equiv 100.0$) out of each level is listed as an upper limit at the 95% confidence level and is compared with the value from [7]. Inclusion of the 0^+ level at 1295.467 keV in this comparison is discussed further in the text.

E_{level}	I_{limit}	I_{NDS}
1135.96	0.0073	0.0291
1233	0.0049	0.0080
1276.63	0.0039	0.0407
1293.59[a]	0.0051	0.0175
1294.17[a]	0.0083	
1295.467	0.0091	
1510.1	0.0086	0.0687
1698.2	0.0001	0.0289
1770.5	0.0045	0.0657
1838.3	0.0023	0.0532
1861.2	0.0008	0.0241
1879.0	0.0003	0.0122
1894.7	0.0017	0.0100

[a]Assumed to be the same level: see comment in [7].

els at 1698.501, 1770.182, 1838.597, and 1861.546 keV are also reported[7] as populated in the (n,γ) study[19]. The detailed decay information presented for all of these levels (except the 1878.3 keV level) suggests robustly established structure for ^{154}Gd. We concur that the level at 1770.182 is well established, based on a study[12] of the $J = 3, 7$ β-decaying isomers of ^{154}Tb. But we see no evidence for population of the 1770.182 keV level in ^{154}Eu decay. The strongest de-exciting transition of 774.4 keV (1770$\rightarrow$996, $[M3]$ multipolarity) is reported with an intensity of 0.028[9] and 0.022[10]. We set an upper limit of $\lesssim$ 0.002 for a 1770$\rightarrow$996 transition based on coincidences with the 996 keV γ ray. The level at 1698.501 is reported[7] to de-excite by six γ rays in the (n,γ) study[19], but only by one of the weaker decay branches in ^{154}Eu decay[9]: the 650.96 γ ray with an intensity of 0.028 to the 1048 keV level. We set an upper limit of $\lesssim$ 0.0005 for a 1698$\rightarrow$1048 transition based on coincidences with the 677 keV γ ray. Thus, we see no evidence for population of a level at 1698 keV in the ^{154}Eu decay. We direct the reader to Table III for the limits we set on the population of the levels above 1700 keV.

y. There are other levels below 1700 keV adopted[7] in ^{154}Gd with $E_x(J^\pi) = 1144$ (8^+), 1295 (0^+), 1366 (6^+), 1574 (0^+), 1607 (6^+), 1637 (10^+), and 1650 (0^+). The population of the states with $J \geq 6$ (excepting the 6^+ member of the ground-state band) in the decay of ^{154}Eu ($J^\pi = 3^-$) seems out of the question. However, the observed population of 0^+ states at 681 and 1182 keV in the decay of ^{154}Eu raises the question of observable population of, at least, the 1295 keV 0^+ state. We note that the decrease in population intensity of the 681 and 1182 keV 0^+ states, observed in the present study of ^{154}Eu, is such that the 1182 keV state is near the limit of observable population. Figure 11 shows the systematics of decay intensity for each level in ^{154}Gd observed in the present study, as a function of excitation energy and spin change in the β decay. We deduce that the total decay intensity out of a 0^+ state at 1295 keV, as populated in ^{154}Eu decay, would be $\sim$ 0.02. The 0^+ state at 1295 keV in ^{154}Gd has only been reported in the neutron capture study[19]. The strongest assigned de-exciting γ ray would be at 1172.55 keV (feeding the 2_1^+ state). As discussed earlier (cf. Fig. 8), we have set an upper limit of 0.003 on a γ ray at 1171 keV in the present experiment; using the same method, we can set a similar limit of 0.003 for a γ ray at 1172.6 keV. Thus, we can state that the population of this level in the decay of ^{154}Eu is $\lesssim$ 0.003. However, we seriously question the existence of this level on other grounds. A close inspection of the assigned[19] de-exciting radiations, namely γ rays of 299.24, 480.20, and 1172.55 keV and conversion electrons corresponding to a 1295.092 keV $E0$ transition reveals that the 299.24 line could be assigned entirely to $A = 153$, and the 480.20 and 1295.092 transitions give very poor Ritz combinations. Since the basis of the assignment in the neutron capture study[19] is good Ritz combinations, we call the existence of the 1295 keV 0^+ state in ^{154}Gd into question. Indeed, the authors of the neutron-capture study[19] caution the reader about the existence of this level because no primary capture γ ray was observed. Further, in a study[12] of the low-spin β-decaying isomer of ^{154}Tb ($J^\pi = 0^-$), no observable population of a 1295 keV state was discernable while excited 0^+ states at 1574, 1650, and 1836 keV were observed to be populated.

z. Our complete decay scheme for ^{154}Eu $\rightarrow$ ^{154}Gd is shown in Figs. 12-12. From this scheme, summing corrections were applied to the intensities of the γ rays

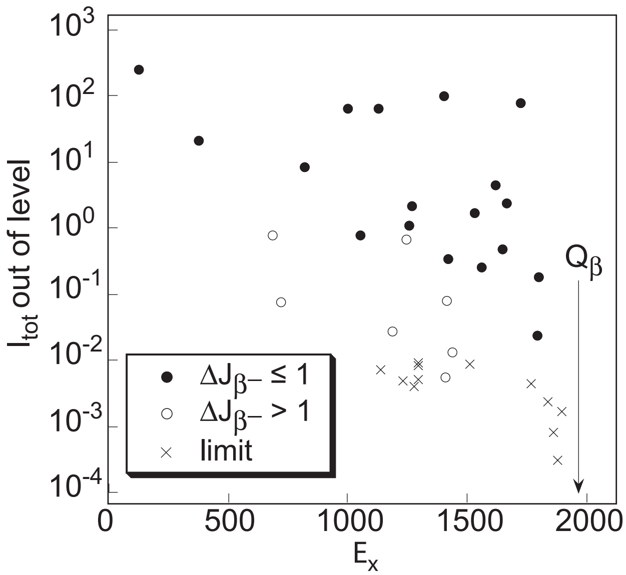

FIG. 11: Total decay intensity out of levels observed in ^{154}Gd through this work. $I_\gamma(1274) \equiv 100.0$.

TABLE IV: Transitions requiring the largest summing corrections ($\Delta I_\gamma > 1\%$). The most significant sources of the summing gains are listed; m denotes where other contributions are nearly equal to that of the cascade listed. The 557.53 keV line suffers from significant summing loss due to angular correlation effects in a ($J = 0 \rightarrow J = 2 \rightarrow J = 0$) cascade.

E_γ	Σ source	$\%\Sigma_{gain}$	$\%\Sigma_{loss}$
370.78	123+248	> 90	0.2
436.20	188+248	34.6	0.5
1522.19	649+873^m	15.4	0.2
830.42	582+248	7.9	0.4
880.65	757+123	7.6	0.6
1128.56	1005+123	5.4	0.3
737.69	613+123	4.6	0.3
569.50	445+123	4.5	0.5
715.76	592+123	3.8	0.5
845.46	723+123	2.7	0.5
426.00	301+123	2.7	0.4
1673.93	669+1005	2.6	0.2
1408.28	851+558	2.6	0.3
312.32	188+123	2.5	0.5
1414.44	1291+123^m	2.2	0.2
1531.40	716+816^m	2.2	0.2
378.90	243+135	1.9	0.3
1289.88	613+677	1.9	0.6
1291.25	846+445	1.9	0.7
1294.99	1047+248	1.7	0.3
800.61	677+123	1.5	0.4
801.69	677+123	1.5	0.2
1596.49	723+873	1.2	0.2
1537.81	845+692	1.2	0.2
322.07	188+135	1.0	0.4
557.53	$0 \rightarrow 2 \rightarrow 0$	0.0	1.5

assigned to the decay scheme. Details are given in Table IV. We discuss summing corrections in the ^{154}Eu $\rightarrow$ ^{154}Gd decay scheme in much greater detail elsewhere[18].

aa. There remain a large number of very weak γ rays reported in the decay of ^{154}Eu by Meyer[9], most of which were confirmed by Hammed *et al.*[10], which we do not confirm. These γ rays are listed in Table V, together with the upper limits that we can set for their intensities. We are puzzled by two particular features of these reported lines. First, we have searched the *Table of the Isotopes* list of γ rays from long-lived radioactive decaying species and cannot find any sensible explanation for these weak lines due to the presence of source impurities in the work of Meyer which were absent from our ^{154}Eu source. Second, Hammed *et al.*, confirm most of the very weak lines reported by Meyer with an intensity consistency that correlates far inside the standard deviations quoted. This makes no sense to us.

IV. DISCUSSION

bb. From the detailed assessments that we have made of decay data for ^{154}Eu (both the present work and that of others) and of other spectroscopic data from neutron capture, we arrive at the set of ^{154}Gd low-lying states shown in Fig. 13. Also shown in this figure are the low-lying states reported for ^{152}Sm. Compared to Fig. 1, which illustrated the primary motivation for this investigation, there are now seen to be similar structural/level density features.

cc. A fundamental requirement of any nuclear structure investigation is an assessment of completeness of the level scheme up to a specified excitation energy for a given spin and parity. In Fig. 11 we show the total decay intensity out of each of the excited states of ^{154}Gd observed in the present work, plotted versus excitation energy. Such a plot provides a useful, semi-quantitative guide to the population intensities that can be expected. In particular, it would be hard to justify the population of additional states, in ^{154}Gd from the β decay of ^{154}Eu, at 1136, 1233, 1277, 1294, and 1510 keV, cf. Table III, in view of the reported intensities of the de-exciting transitions. We caution that above the very strongly populated $J^\pi = 2^-$ state at 1719 keV, which decays directly or indirectly to many states, we only observe two weakly populated states. Thus we expect any systematic decay intensity pattern to deteriorate above the highest lying state (at 1531 keV) that is fed by the 1719 keV state, i.e., above an energy where no secondary feeding is observed.

dd. The most valuable independent view of the completeness of the present study is provided by the primary γ rays observed in the neutron-capture study[19]. The data reported are for a 1^- resonance populated in thermal neutron capture. This capture resonance is observed to decay directly to: 0^+ states at 0.0, 680.7, 1182.1, 1574.0, 1650.3, 1836.4, ... keV; 2^+ states at 123.1, 815.5, 996.3, 1418.2, 1531.3, 1716.0, 1775.4, ... keV; 1^-

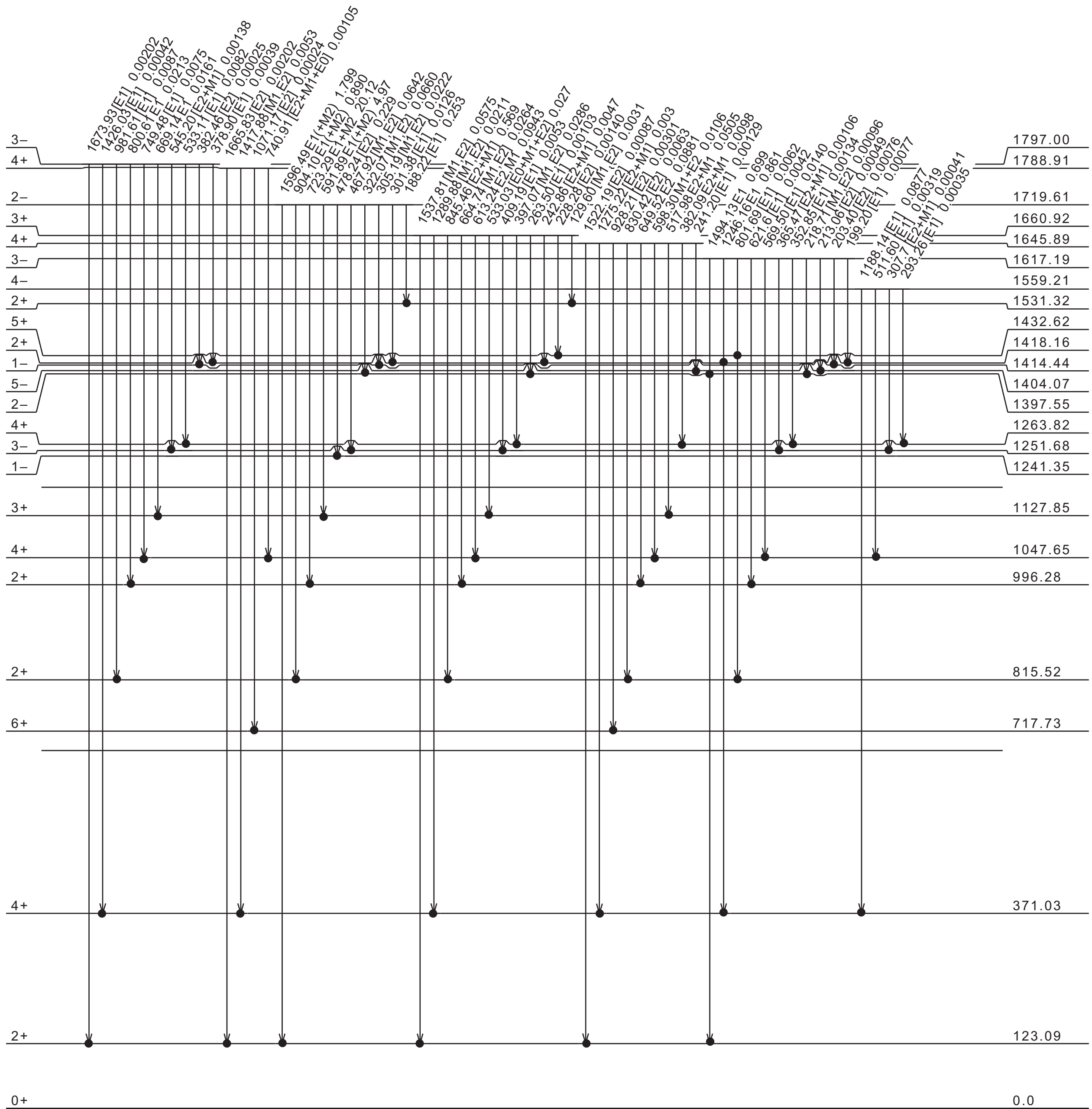

FIG. 12: The level scheme for ^{154}Gd populated in the decay of ^{154}Eu, as observed in the present work. Transitions are labeled by their energy, total (γ+ce) decay intensity (computed using conversion coefficient data in[7] where available or using [22]), and assigned[7] multipolarities. Dots denote that coincidence spectra confirm placement of a transition from above or below, as indicated. The intensities are normalized to 100 β decays of ^{154}Eu (cf. Table I).

states at 1241.3, 1414.4, …keV; 2^- states at 1397.6, …keV; and 3^- states at 1251.6, 1617.1, …keV. Other states populated directly from this capture resonance lie above 1900 keV and lack unique spin-parity assignments. The states at 1719.6 keV ($J^\pi = 2^-$) and 1796.9 keV ($J^\pi = 3^-$) are not reported to be directly populated from the capture resonance. From our non-observation of population of the 2^+ state at 1716.0 keV we deduce that, for states in ^{154}Gd that potentially can be populated in the decay of ^{154}Eu ($J^\pi = 3^-$), the present scheme is incomplete above an excitation energy somewhere between 1531 and 1716 keV.

ee. The spin-parity selection rules for β decay forbid strong direct population from the decay of ^{154}Eu to the states observed in ^{154}Gd with 0^+, 1^-, 5^+, 5^-, 6^+. Intensity balances for the states with J^π (E_x(keV))

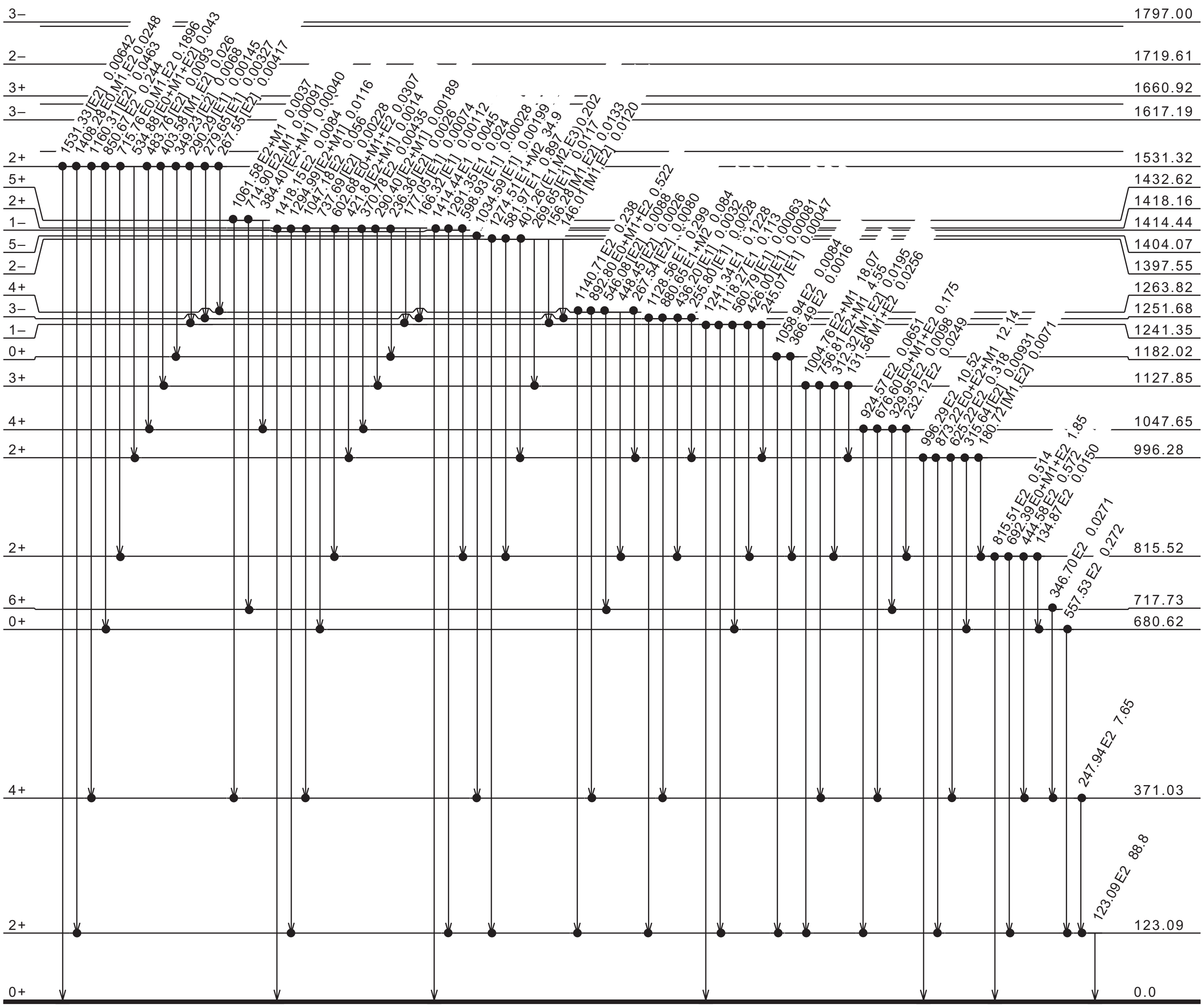

FIG. 12: Level scheme continued.

$= 0^+$ (680.7, 1182.1), 1^- (1241.3, 1414.4), 5^+ (1432.6), 5^- (1404.1), 6^+ (717.7) are given in Table VI.

V. CONCLUSIONS

ff. The primary outcome from this study is manifested in the comparison of Figs. 1 and 13. The previously available data for ^{154}Gd[7] erroneously implied that this nucleus has a very different structure than the neighboring isotone ^{152}Sm above an excitation energy of 1.1 MeV. To achieve this required that γ-ray spectroscopy following radioactive decay be carried out in unprecedented detail. The resulting emergence[17] of a coexisting collective structure (the band based on the 0^+ 1182 keV state) was not anticipated. Further, the large number of changes in the weakly-populated decay branches of ^{154}Eu $\rightarrow$ ^{154}Gd (cf. Table II) was not expected. We find this especially suprising since this decay has been the subject of many investigations.

gg. A further important outcome from the study is implicit in Table V. The study of Meyer reported many weak γ rays, which the work of Hammed *et al.* appeared to confirm, but which were unassigned in the ^{154}Eu $\rightarrow$ ^{154}Gd decay scheme. We have assigned some of these γ rays; and the remainder we have refuted at the intensity levels shown in Table V. Noting that the Q_{β^-} value for the decay is 1968.5 keV emphasizes that the existence or non-existence of these γ rays has a critical impact on the implied low-energy structure of ^{154}Gd: the γ rays must be located somewhere in the scheme. The number of lines refuted is very large and had they been confirmed, would

TABLE V: Upper limits for reported[7] γ rays in the decay of ^{154}Eu which were not observed in this study. Gamma-ray intensities ($I_\gamma(1274) \equiv 100.0$) are listed as upper limits at the 95% confidence level and are compared with the reported values.

E_γ	$I_\gamma^{\rm limit}$	$I_\gamma^{\rm NDS}$	E_γ	$I_\gamma^{\rm limit}$	$I_\gamma^{\rm NDS}$	E_γ	$I_\gamma^{\rm limit}$	$I_\gamma^{\rm NDS}$
125.39	0.0053	0.020	480.2	0.0032	[a]	1072.2	0.0039	0.0100
159.9	0.0011	0.0030	480.6	0.0032	0.0138	1110.0	0.0049	0.0080
162.09	0.0010	0.0031	484.64	[b]	0.0113	1124.2	0.0197	0.0123
165.9	0.0021	0.0071	488.26	0.0027	0.020	1136.1	0.0030	0.0211
195.5	0.0014	0.0060	506.5	0.0007	0.0180	1153.1	0.0033	0.0310
197	0.0014	0.0045	510.6	0.0217	0.017	1170.0	0.0031	0.0104
209.4	0.0042	0.0071	563.4	0.0031	0.008	1171.2	0.0030	[c]
229.0	0.0016	0.0069	597.5	0.0006	0.0158	1172.6	0.0030	[a]
237.7	0.0006	0.0180	642.4	0.0010	0.0130	1216.8	0.0042	0.0096
260.2	0.0015	0.0062	650.6	0.0005	0.0282	1232	0.0027	0.0230
274.0	0.0024	0.0111	774.4	0.0025	0.0240	1316.4	0.0391	0.0500
296	0.0041	0.0040	790.1	0.0009	0.0300	1387.0	0.0056	0.0550
299.2	0.0028	[a]	898.4	0.0007	0.0056	1400.0	0.0002	0.0090
308.2	0.0016	0.0068	906.1	0.0023	0.0338	1490.2	0.0002	0.0082
320	0.0023	0.0028	919.24	0.0032	0.0350	1510.0	0.0030	0.0137
368.21	0.0022	0.0085	923.1	0.0032	[c]	1522.0	0.0002	0.0017
375.2	0.0020	0.0056	984.5	0.0036	0.027	1554	0.0011	0.0032
414.30	0.0161	0.0142	1012.8	0.0043	0.0080	1716.9	0.0004	0.0017
419.4	0.0021	0.010	1023.0	0.0004	0.0190	1773.0	0.0006	0.0009
463.9	0.0003	0.0122	1049.4	0.0042	0.0493	1838.0	0.0007	0.0024
						1895.0	0.0002	0.0018

[a]Transition from the adopted $(2)^+$level at 1294.174 keV. The evaluator has assumed this is the same level as the 1293.59 keV reported in the decay scheme for ^{154}Eu[7].

[b]Our coincidence data support assignment of only one transition, 483.76 (7), between the levels at 1531.33 and 1047.65. keV.

[c]Transition reported from the adopted 0^+ level at 1295.467 keV. This level should be populated indirectly in the decay of ^{154}Eu if the adopted[7] band structure is correct.

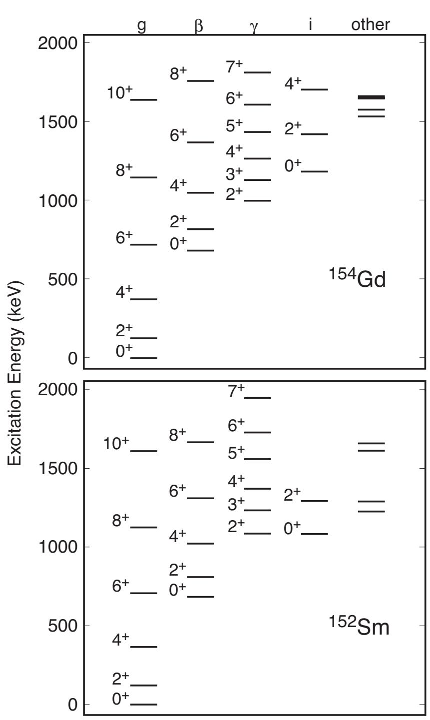

FIG. 13: The comparison of the low-lying positive-parity states in ^{152}Sm (data from [8]) and ^{154}Gd (from the present work), cf. Fig. 1.

have required many new levels (and excitation degrees of freedom) in ^{154}Gd. We are unable to offer an explanation for these reported lines. We re-emphasize the apparent confirmation of the lines reported by Meyer in the work of Hammed *et al.* at a remarkable level of precision that would, by standard statistical measure, be taken as a very robust confirmation and which in turn would demand invoking many new excited states in ^{154}Gd below 1968.5 keV.

hh. A major contributing factor to the present results was the use of an array of Compton-suppressed detectors. These arrays were developed for studying high-multiplicity events such as occur during in-beam γ-ray spectroscopy. Indeed, the spectrometer used in this investigation began its "career" as just such a device. The value of an array for studying low-multiplicity events is evident in the very high statistics achieved in the present study. More subtle benefits include the near-angular-correlation-free coincidence data obtainable from this array which permits accurate coincidence intensities to be obtained.

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TABLE VI: Intensity balances

E_x	$I_{\rm out}$	$I_{\rm in}$	$I_{\rm net}^{8\pi}$	$I_{\rm net}^{\rm NDS}$
123.09	254.9(22)	224.4(16)	30.5(27)[a]	30.6
371.03	21.96(15)	21.04(23)	0.92(27)[b]	0.936
680.62	0.796(6)	0.778(14)	0.0180(15)	0.0351
717.73	0.0776(12)	0.065(8)	0.013(8)	0.0176
815.52	8.50(7)	7.62(8)	0.88(11)	0.850
996.28	65.9(5)	58.9(5)	7.0(7)	7.40
1047.65	0.792(12)	0.411(17)	0.381(21)	0.292
1127.85	65.0(5)	14.61(10)	50.4(5)	50.0
1182.02	0.029(5)	0.027(3)	0.002(6)	
1241.35	0.683(15)	0.701(10)	−0.018(18)	−0.0329
1251.68	1.115(27)	0.254(11)	0.861(29)	0.83
1263.82	2.235(29)	0.149(5)	2.086(29)	2.02
1397.55	103.3(7)	0.1951(27)	103.1(7)	103.2
1404.07	0.0057(7)	0.0051(7)	0.0006(10)	
1414.44	0.082(11)	0.0664(20)	0.016(11)	−0.1138
1418.16	0.348(24)	0.0537(30)	0.294(24)	0.31
1432.62	0.0128(32)	0.0063(12)	0.0065(34)	
1531.32	1.72(4)	0.735(10)	0.99(4)	0.82
1559.21	0.263(4)		0.263(4)	0.286
1617.19	4.56(5)		4.56(5)	4.71
1645.89	0.50(7)		0.50(7)	0.42
1660.92	2.39(4)		2.38(4)	2.43
1719.61	81.5(6)		81.5(6)	81.3
1788.91	0.0248(17)		0.0248(17)	0.0111
1797.00	0.190(14)		0.190(14)	0.180

[a] Excess is $10.64 \pm 0.17\%$ (cf. from observation of direct β decay: $9.2 \pm 1.5\%$[23] and $10.8 \pm 1.2\%$[24]).
[b] Excess is $0.322 \pm 0.006\%$ (cf. from observation of direct β decay: $0.19 \pm 0.05\%$[23]).

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