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$N=90$ region: The decay of ^{154}Eu to ^{154}Gd

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The decay of $^{154}\text{Eu} \rightarrow {}^{154}\text{Gd}$ 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 investigate the structure of ^{154}Gd above 1 MeV: The outcome is the removal of 11 levels from the previously adopted ^{154}Eu decay scheme, the addition of 40 new γ-ray assignments, and upper limits set on 75 γ-ray transitions which had been previously assigned to the ^{154}Gd level scheme. The current results, combined with data from other spectroscopic techniques, indicate that states which were previously interpreted as "two-phonon" excitations are either spurious or are shown to be of a different nature. These results provide a deeper understanding of the structure of ^{154}Gd and the $N=90$ isotones.

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I. INTRODUCTION

The structure of the $N=90$ isotones in the vicinity of $Z=64$ has been the focal point of a very large number of experimental and theoretical 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 regarded as among the most challenging for models that aim to achieve a general description of nuclear collectivity.

Despite detailed experimental data on the strikingly similar bands built upon the 0_1^+, 0_2^+, and 2_3^+ states of the $N=90$ nuclei, ^{152}Sm and ^{154}Gd (cf. Fig. 1), there has been recent controversy [3–5] regarding which nuclear models best describe the structure of these nuclei and other $N=90$ isotones. We have initiated a program [6] of detailed spectroscopy to provide additional data which might better discriminate between the various models (see [3–5] and references therein). In particular, we have focused on the other collective states above 1 MeV, where multiphonon excitations can be expected.

As illustrated in Fig. 1, besides the bands built on the 0_1^+, 0_2^+, and 2_3^+ levels, the adopted [2] level scheme for ^{154}Gd shows a wealth of collective states below 2 MeV (states labeled as "other"). Indeed, one study [7] of the radioactive decay of ^{154}Eu to ^{154}Gd suggests that several of these levels can be organized into two-phonon bands built upon the 0_2^+ ("β-vibrational") and 2_3^+ ("γ-vibrational") states. Because these states, and many of the other states in ^{154}Gd (cf. Fig. 1), have been reported [2] in the decay of ^{154}Eu ($T_{1/2}=8.6$ yr, $Q_\beta=1968.5$ keV), detailed spectroscopy of this decay held the most promise for investigation of excitations built on the underlying structure of the $N=90$ isotones.

*Deceased

II. EXPERIMENTAL PROCEDURE

A commercially produced source of ^{154}Eu obtained from Isotope Products Laboratories was used for these measurements. The source contained $(16.8\pm0.2)\%$ ^{155}Eu and $(0.027\pm0.002)\%$ ^{154g}Eu, determined as decay rates in this study, and had a strength of ~5 μCi. The source had an active diameter of 3mm 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.

Gamma-ray singles and $\gamma-\gamma$ coincidence measurements were carried out using the "8π spectrometer" [8]. This spectrometer is an array of 20 Compton-suppressed Ge (HP) detectors arranged such that the 380 twofold 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). 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. No absorbers were placed in front of the detectors and no shielding (other than that provided by the BGO crystals used for Compton suppression) was used to attenuate room background.

Gamma-ray singles and $\gamma-\gamma$ coincidence events were recorded concurrently in a run lasting 240 h. 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 obtained contained 1.00×10^8 $\gamma-\gamma$ coincidence events and 2.38×10^8 singles events.

Calibration for energies and intensities of lines in the ^{154}Eu decay was achieved "internally," i.e., use was made of

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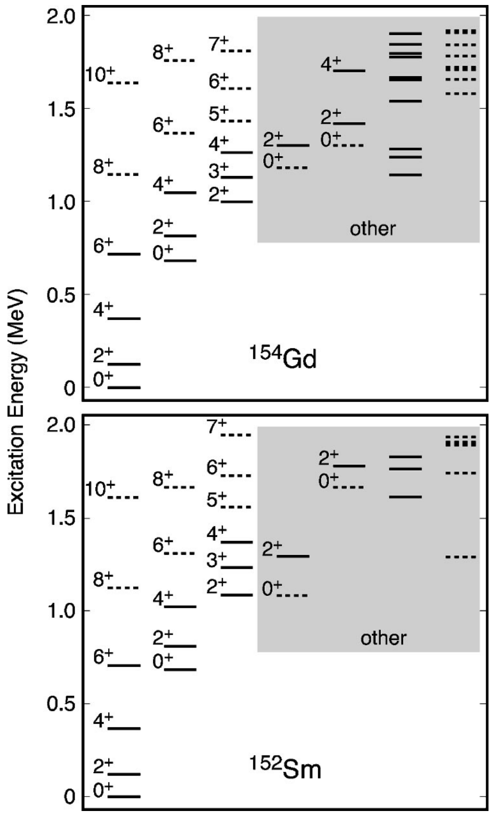

FIG. 1. A comparison of the positive-parity states below 2 MeV in the isotones ^{152}Sm and ^{154}Gd, based on the evaluated data presented in the Nuclear Data Sheets for these nuclei (Refs. [1] and [2], respectively). Below 2 MeV excitation energy, ^{154}Gd has 23 positive-parity states besides the bands built on the 0_1^+, 0_2^+, and 2_3^+ states, while ^{152}Sm has 13 such states. Bold lines indicate levels observed to be populated in ^{154}Eu or ^{152g}Eu decay, while dashed lines indicate levels observed through other methods.

the fact that the strong lines in this decay serve [2] 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 ±0.07 keV. The efficiency calibration was made with a polynomial (containing terms up to quartic) describing log(efficiency) versus log(energy), fitted to 10 strong lines in the ^{154}Eu decay (123, 248, 592, 723, 757, 873, 996, 1005, 1275, and 1494 keV). A systematic error of 0.7% in this efficiency curve was deduced by comparing the calculated intensities of 18 other strong 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) with the adopted [2] intensity values.

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 ratio as a function of energy was determined using sources of ^{137}Cs, ^{60}Co, and coincidence-gated spectra from ^{154}Eu. Peak-to-total ratios ranged from 0.77 (123 keV), 0.48 (677 keV), to 0.24 (1597 keV).

III. DATA ANALYSIS AND EXPERIMENTAL RESULTS

All γ-ray spectra and $\gamma-\gamma$ coincidence matrices were produced using the computer program GTSORT [9]. 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. The RADWARE software package [10] was used to analyze coincidence and singles data.

The γ-ray singles spectrum obtained in this work is shown in Fig. 2. Peaks in the singles spectrum were fitted with a skewed Gaussian shape using the program GF3 [10]. Corrections in peak areas were made to account for coincidence summing, angular correlation effects, and the presence of background radiation. Besides the aforementioned ^{152g}Eu and ^{155}Eu source contaminants, only peaks from room background (^{40}K, ^{60}Co, ^{137}Cs, ^{207}Bi, and the ^{232}Th and ^{238}U decay series) were present in the singles spectrum. The low-energy "cutoff" was ~30 keV (the Gd K x rays are at 42.8 and 48.8 keV).

A $\gamma-\gamma$ coincidence matrix was constructed by setting a 48 ns time gate for prompt $\gamma-\gamma$ coincidences, then subtracting a delayed-time coincidence matrix (with a time gate of the same width) from the prompt coincidence matrix in order to remove random coincidences. Using the program ESCL8R [11], peaks with multiple components were identified and a level scheme was constructed from the $\gamma-\gamma$ coincidence matrix. Compton artifacts from strong transitions in the decay hindered γ-ray intensity measurements using ESCL8R, however, because this required changing the background spectrum often. Coincidence spectra were therefore generated using the program SLICE [10] by selecting a peak gate of appropriate 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 [10].

Three methods were used to determine γ-ray energies and intensities. Only the singles measurements were used for the (previously listed) efficiency curve calibration peaks and for peaks selected for intensity normalization in coincidence gates. An average of singles and coincidence measurements, weighted by the uncertainty of each value, was used for transitions observed in the singles spectrum and in coincidence spectra. Coincidence measurements alone determined the energy and intensity of closely spaced doublets (unresolved in the singles spectrum), peaks obscured by Compton features, and peaks too weak to fit in the singles spectrum. An illustration of situations where each method was employed is provided in Fig. 3.

Figure 3 shows a selected energy range from the γ-ray singles spectrum and the same range from the 188 keV coincidence gate. The intensity of the 349 keV transition ($1531 \rightarrow 1182$) is used for intensity normalization in the coincidence spectrum to obtain the intensity of the 236 keV line (the only other transition feeding the 1182 keV level in this work), thus the singles measurement alone is used for the intensity of the 349 keV γ ray. The intensities of the 280, 404, and 484 keV transitions are determined using a weighted average of singles and coincidence data. The peaks at 268 and 290 keV in the singles spectrum are doublets

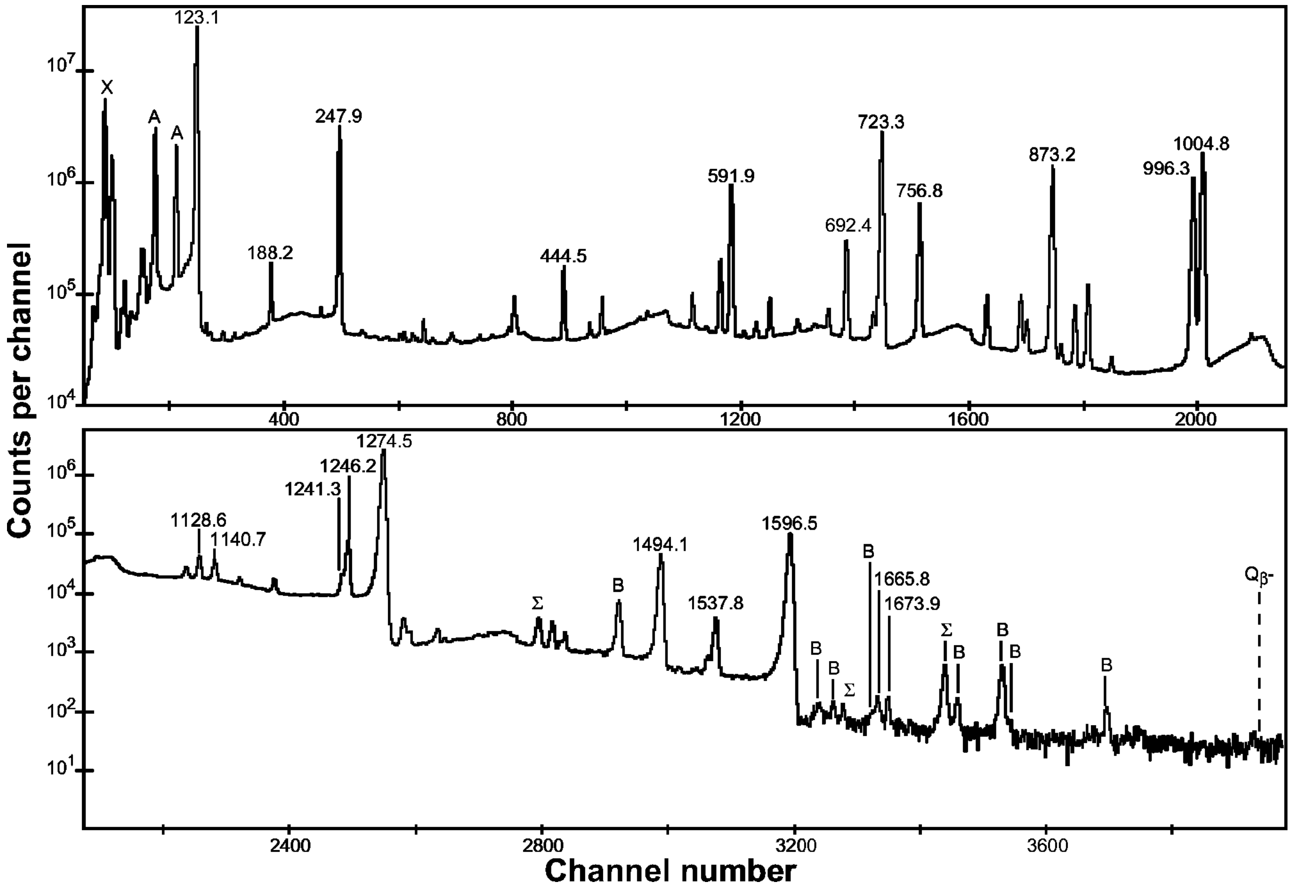

FIG. 2. The singles γ-ray spectrum for ^{154}Eu decay obtained in the present study. Peaks marked X are x rays; A are the strong lines from the decay of ^{155}Eu at 86 and 105 keV; Σ are from coincidence summing; and B are from room background. Energies of selected lines are given in keV, and Q_{β^-}=1968.5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

which have (unresolved) intensities of 0.034 and 0.015, respectively. Coincidence intensities of $I_\gamma(267.6)=0.0110(3)$ and $I_\gamma(290.3)=0.0041(2)$ based on the peaks in the 188 keV coincidence-gated spectrum and gates on γ rays below these transitions disentangle the components of these γ rays which deexcite the 2^+ level at 1531 keV.

A. Transitions assigned to the decay of ^{154}Eu

Measured energies and intensities for γ rays assigned to the decay of ^{154}Eu are listed in Table I. All of these assignments have been made on the basis of coincidence spectroscopy and are between adopted [2] levels in ^{154}Gd and ^{154}Sm. A total of 134 γ rays are assigned to the decay of ^{154}Eu, of which 40 transitions are newly placed in the ^{154}Gd decay scheme.

New assignments in the decay of ^{154}Eu are due to observation of new γ rays, resolution of peaks with multiple components, and moving transitions previously assigned elsewhere in the ^{154}Gd scheme to new locations based upon coincidence data. The strongest new γ ray identified (I_γ =0.0189) is the 349.2 keV ($1531\rightarrow1182$) transition. Doublet components of transitions at 267.5, 290.0, 382.00, 545.60, 715.76, and 1274.436 keV (as listed in the adopted ^{154}Eu $\rightarrow$ ^{154}Gd decay scheme [2]) are resolved using coincidence data. The 1275.7 keV ($1646\rightarrow371$) transition, for example, although well-established through the decay of ^{154}Tb [2,9], is very weak in comparison with the 1274.5 keV ($1398\rightarrow123$) in the decay of ^{154}Eu and is apparent in coincidence with the 248 keV γ ray only after removing the residue of accidental coincidences with the 1274 keV γ ray by subtracting a scaled 123 keV γ-gated spectrum from the 248 keV γ-gated spectrum. Transitions moved from one location in the ^{154}Gd decay scheme to another include the 228.3 keV transition, which is assigned using coincidence spectroscopy between the levels at 1661 and 1433 keV but was previously assigned [2] between levels at 1277 and 1048 keV.

B. Upper limits on unobserved γ rays

There remain a number of very weak γ rays adopted [2] in the decay of ^{154}Eu$\rightarrow$^{154}Gd which we do not observe in our spectra with the reported intensities. In addition to these lines, we find no evidence for some transitions listed in the "Adopted Levels and Gammas" [2] which were based (in part) on the neutron-capture study [12]. The high statistical quality of our data allows us to set stringent upper limits (UL) on unobserved weak transitions; these values are listed in Table II.

We have used the method described by Currie [13] to set upper limits on γ-ray transitions. This is illustrated in Fig. 4

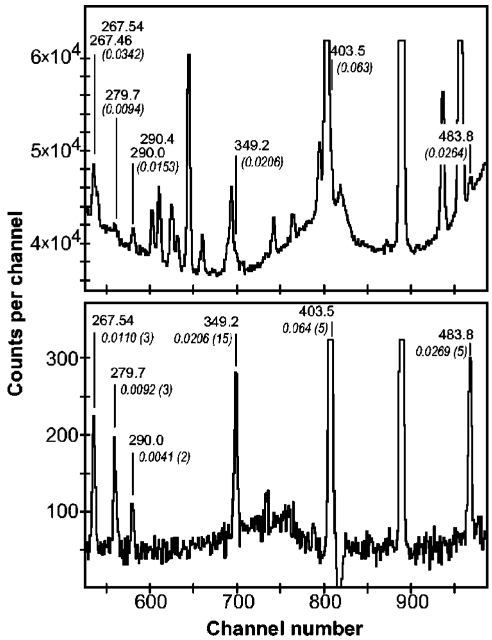

FIG. 3. A comparison of the singles γ-ray spectrum (top) with a coincident γ-ray spectrum gated by the 188 keV $(1719 \rightarrow 1531)$ transition (bottom) for the energy range 260–492 keV. Singles intensities (in parenthesis in the upper spectrum) and the measured intensities determined in this study (in the bottom spectrum) are presented in italics below the γ-ray energy for transitions out of the 1531 keV level. All intensities are normalized such that $I_\gamma(1274) \equiv 100.0$. The coincidence spectrum reveals for the first time the 349 keV transition $(1531 \rightarrow 1182)$ and separates the components of the 267 and 290 keV doublets (see discussion in the text).

using a portion of the singles spectrum from this experiment. For a possible weak γ ray, regions of $n = \text{FWHM} + 1$ peak channels and $2m$ background channels with corresponding areas, G and S, are defined as shown in Fig. 4. If the net area, $A = G - B$ (where $B = nS/2m$ scales the background counts to the peak region), is less than a critical level, $L_c = 1.645[B(1 + n/2m)]^{1/2}$, then an upper limit, $\text{UL} = A + 1.645[A + B(1 + n/2m)]^{1/2}$ may be set on the peak area. This value, UL, corresponds to a 95% confidence limit on the maximum possible intensity of the transition in question.

Some of the UL values in Table II have not been corrected for probable contaminants, e.g., the 296 keV line will have some contribution from the $248 + K_\beta = 296.6$ keV coincidence sum. An upper limit for the 123.7 keV transition listed in the adopted [2] ^{154}Gd scheme is not included because the 123.1 keV $(123 \rightarrow 0)$ γ ray dominates this region of the spectrum both in singles and in coincidence gates from above. Gamma rays at 82.1 and 184.7 keV listed in the evaluated [2] $^{154}\text{Eu} \rightarrow {}^{154}\text{Gd}$ decay scheme are not given in Table II because we conclude these lines have been mistakenly included with ^{154}Gd data (the intensity values for these γ rays in ^{154}Sm were reported by Ref. [14], tabulated by Ref. [15] for the decay of ^{154}Eu, but included with the data for ^{154}Gd in Ref. [2]).

A recent paper [16] also reported several new lines which we do not observe with the published intensities. Most of these lines can be attributed to $\gamma - \gamma$ sum peaks. The strongest of these new lines that does not coincide with a known $\gamma - \gamma$ coincidence sum peak is a 765.1 keV transition reported to feed the 4^+ level at 371 keV with $I_\gamma = 0.463(134)$ [16]; we set an upper limit on this transition of 0.0014 and suggest that this peak may have resulted from a coincidence sum of the 723 keV γ-ray transition and a 40 keV K_α x ray in Gd due to internal conversion. Because of the high incidence of summing in the spectra presented in [16], we do not set upper limits on any of the peaks reported in this work with intensities less than that suggested for the 765.1 keV γ ray; nor do we set upper limits on peaks reported in this work known to have coincidence summing contributions.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

The addition of 40 new γ-ray assignments and the removal of 75 previously placed transitions has dramatic ramifications for the level scheme of ^{154}Gd. Our data confirm the existence of three levels in ^{154}Gd which had not been previously observed in the decay of ^{154}Eu and suggest the removal of at least 11 levels from ^{154}Gd. These changes are discussed below.

A. Level additions

Levels at 1182, 1404, and 1433 keV have been added to the $^{154}\text{Eu} \rightarrow {}^{154}\text{Gd}$ decay scheme. These levels are well-established through other methods of spectroscopy but have not been reported previously in the decay of ^{154}Eu. Each of these levels has a spin assignment which is at least two units different from that of the $(J^\pi = 3^-)$ ^{154}Eu parent. The intensity balance for each level, calculated as the difference between total intensity ($\text{TI} = I_\gamma +$ conversion electron intensity), is consistent with the expectation that these levels are populated only through indirect feeding from levels higher in the ^{154}Gd excitation spectrum.

1. 0^+ level at 1182 keV

Coincidence gates on transitions feeding the levels at 1418 and 1531 keV indicate that γ rays of 236.4 and 349.2 keV, respectively, feed this level. Only two γ rays, at 366.5 and 1058.9 keV, are observed (see Fig. 5) to depopulate the level. The intensities of the two populating transitions indicate a $\text{TI} = 0.027(3)$ feeding into the level, and a TI out (based on the two observed γ rays) of 0.029(5). The intensity balance of 0.002(6) is consistent with exclusively indirect feeding of the 1182 keV level from the decay of ^{154}Eu.

2. (5^-) level at 1404 keV

A γ ray of 1033.7 keV, seen in coincidence with the 248 keV$(371 \rightarrow 123$ keV$)$ transition, is the only transition observed from the level at 1404 keV. The 1034 keV γ-gated spectrum reveals only two γ rays feeding the 1404 level: a new 213.1 keV transition from the 3^- level at 1617 keV and a 241.2 keV transition from the 4^+ level at 1646 keV. There is a slightly positive net intensity of 0.0028(13) for the 1404 level: the 1034 keV transition out of the level has a $\text{TI} = 0.0079(11)$ and the 213 and 241 γ rays into the level have

TABLE I. Gamma rays assigned to the decay of ^{154}Eu, normalized such that $I_\gamma(1274)\equiv 100.0$. To obtain intensity per 100 β decays of the parent [determined by requiring 100% feeding (I_γ+ce) to the ground state] multiply the relative I_γ by 0.3486(29). Measured E_γ and I_γ values are determined by a weighted average of singles and coincidence data, except where indicated by a superscript 1, where singles data only have been used or indicated by a superscript 2, where coincidence data only have been used. Transitions with a star (*) are newly assigned to the decay scheme.

E_γ	I_γ	E_i	E_f	E_γ	I_γ	E_i	E_f
Transitions assigned to ^{154}Gd							
123.09(7)[1]	116.0 (10)	123	0	*560.79(19)[2]	0.0018 (5)	1241	681
129.60(13)[2]	0.0045 (6)	1661	1531	569.50 (7)	0.040 (6)	1617	1048
131.56(7)[2]	0.0377 (12)	1128	996	581.97(7)[1]	2.563 (18)	1398	816
134.87 (7)	0.023 (3)	816	681	591.89(7)[1]	14.21 (10)	1720	1128
146.01(7)[2]	0.0205 (10)	1398	1252	598.30 (7)	0.030 (4)	1646	1048
156.28 (8)	0.0247 (25)	1398	1241	598.93(7)[2]	0.0010 (3)	1414	816
*166.32(10)[2]	0.0030 (3)	1418	1252	602.68 (7)	0.084 (3)	1418	816
*177.05(20)[2]	0.0020 (4)	1418	1241	613.24(7)[1]	0.2674 (29)	1661	1048
180.72 (7)	0.0150 (20)	996	816	621.6(5)[2]	0.012 (5)	1617	996
188.22(7)[1]	0.689 (5)	1720	1531	625.22 (7)	0.906 (9)	996	371
*199.20(8)[2]	0.0029 (4)	1617	1418	649.52 (7)	0.251 (5)	1646	996
203.40(29)[2]	0.0015 (2)	1617	1414	664.74 (8)	0.0751 (29)	1661	996
*213.06(11)[2]	0.0012 (2)	1617	1404	669.14(8)[2]	0.0460 (22)	1797	1128
218.71(26)[2]	0.0023 (4)	1617	1398	676.60(7)[1]	0.480 (4)	1048	371
*228.23(9)	0.0059 (4)	1661	1433	692.39(7)[1]	5.10 (4)	816	123
232.12 (7)	0.0627 (12)	1048	816	*714.90(16)[2]	0.0026 (2)	1433	718
*236.36(8)[2]	0.0050 (9)	1418	1182	715.76 (7)	0.536 (15)	1531	816
*241.20(9)[2]	0.0036 (5)	1646	1404	723.29(7)[1]	57.6 (4)	1720	996
*242.86(6)[2]	0.0117 (10)	1661	1418	*737.69(13)[2]	0.0065 (6)	1418	681
*245.07(13)[2]	0.0013 (2)	1241	996	*740.91(16)[2]	0.0030 (5)	1789	1048
247.94(7)[1]	19.77 (14)	371	123	*749.48(9)[2]	0.0215 (13)	1797	1048
*255.80(10)[2]	0.0079 (26)	1252	996	756.81(7)[1]	12.98 (9)	1128	371
*263.50(16)[2]	0.0029 (4)	1661	1398	800.61(8)[2]	0.061 (3)	1797	996
267.46(15)[2]	0.021 (4)	1264	996	801.69(11)[2]	0.0177 (17)	1617	816
267.54(8)[2]	0.0110 (3)	1531	1264	815.51 (7)	1.467 (11)	816	0
269.65(8)[2]	0.0330 (15)	1398	1128	*830.42(10)	0.0179 (16)	1646	816
279.65 (7)	0.0092 (3)	1531	1252	845.46 (7)	1.628 (31)	1661	816
289.99(22)[2]	0.0041 (2)	1531	1241	850.67(7)[1]	0.697 (6)	1531	681
*290.38(11)[2]	0.0050 (2)	1418	1128	873.22(7)[1]	34.68 (24)	996	123
293.26(22)[2]	0.0010 (2)	1559	1264	880.65 (7)	0.241 (16)	1252	371
301.38(7)[1]	0.0355 (10)	1720	1418	892.80(7)[1]	1.497 (12)	1264	371
305.19(7)[1]	0.0588 (11)	1720	1414	904.10 (7)	2.551 (20)	1720	816
*307.7(3)[2]	0.0011 (3)	1559	1252	924.57 (7)	0.1862 (25)	1048	123
312.32 (7)	0.0522 (10)	1128	816	*928.21(8)[2]	0.0086 (5)	1646	718
315.64 (7)	0.0254 (3)	996	681	981.61 (9)	0.025 (4)	1797	816
322.07(7)[1]	0.1778 (17)	1720	1398	996.29(7)[1]	30.09 (21)	996	0
329.95 (7)	0.027 (3)	1048	718	1004.76(7)[1]	51.7 (4)	1128	123
346.70 (7)	0.0747 (12)	718	371	*1033.72(21)[2]	0.0079 (11)	1404	371
*349.24(7)[1]	0.0206 (15)	1531	1182	1047.18(7)[1]	0.176 (4)	1418	371
*352.85(20)[2]	0.0038 (4)	1617	1264	*1058.94(10)[2]	0.021 (4)	1182	123
*365.47(15)[2]	0.0029 (4)	1617	1252	*1061.67(8)[2]	0.0102 (30)	1433	371
*366.49(8)[2]	0.0044 (10)	1182	816	*1071.17(24)[2]	0.0007 (1)	1789	718
370.78(8)[2]	0.0121 (4)	1418	1048	1118.27 (7)	0.325 (11)	1241	123
*378.90(27)[2]	0.0011 (3)	1797	1418	1128.56(7)[1]	0.86 (1)	1252	123

TABLE I. (*Continued.*)

E_γ	I_γ	E_i	E_f	E_γ	I_γ	E_i	E_f
382.09(8)^2	0.0272 (9)	1646	1264	1140.71 (7)	0.681 (9)	1264	123
*382.46(27)	0.0006 (2)	1797	1414	1160.31 (7)	0.1326 (13)	1531	371
397.07(7)^1	0.0792 (18)	1661	1264	1188.14 (7)	0.2515 (18)	1559	371
401.26 (7)	0.541 (8)	1398	996	1241.34(7)^1	0.352 (4)	1241	0
403.49 (7)	0.064 (5)	1531	1128	1246.16 (7)	2.456 (25)	1617	371
*409.19(8)^2	0.015 (5)	1661	1252	1274.51(7)^1	100.0 (7)	1398	123
*421.8(8)^2	0.0038 (29)	1418	996	*1275.66(12)^2	0.0050(49)	1646	371
*426.00(13)^2	0.0023 (4)	1241	816	1289.88(11)^2	0.0603 (22)	1661	371
*436.20(11)	0.0090 (16)	1252	816	1291.36 (8)	0.063 (22)	1414	123
444.51 (7)	1.570 (14)	816	371	1294.99 (8)	0.0333 (17)	1418	123
*448.45(19)^2	0.0073 (11)	1264	816	1408.28 (7)	0.071 (3)	1531	123
467.92(7)^1	0.1798 (21)	1720	1252	1414.44(10)^1	0.0148 (9)	1414	0
478.24(7)^1	0.646 (5)	1720	1241	1417.88(9)^2	0.0152 (8)	1789	371
483.76 (7)	0.0269 (5)	1531	1048	1418.15(9)^2	0.024 (3)	1418	0
*511.60(8)^2	0.0091 (7)	1559	1048	1426.03(27)^2	0.0012 (2)	1797	371
517.98 (7)	0.143 (4)	1646	1128	1494.13(7)^1	2.003 (18)	1617	123
533.03(8)^2	0.0530 (29)	1661	1128	*1522.19(16)	0.0025 (4)	1646	123
533.11(7)^2	0.0234 (14)	1797	1264	1531.33(15)^2	0.0184 (6)	1531	0
*534.86(7)^2	0.049 (18)	1531	996	1537.81 (7)	0.1646 (29)	1661	123
*545.20(14)^2	0.0039 (5)	1797	1252	1596.49 (7)	5.16 (6)	1720	123
546.08(7)^1	0.025 (4)	1264	718	1665.83 (12)	0.0058 (3)	1789	123
557.53 (7)	0.773 (7)	681	123	1673.93 (8)	0.0058 (3)	1797	123
Transitions assigned to ^{154}Sm							
81.78 (7)	obscured	81.98	0	185.35(9)^1	0.0148 (11)	266.79	81.98

a combined TI = 0.0051(7). While we discount a reported [12] 393 keV γ ray feeding this level (cf. Table II), this level is at the limits of our observation and other unobserved, weak indirect feeding of the 1404 level is possible.

3. 5^+ level at 1433 keV

We observe two known transitions out of the 1433 level, the 714.9 and 1061.6 keV γ rays, and determine a TI = 0.0128(32) out of this level. The level is fed only by a 228.3 keV ($1661 \rightarrow 1433$) transition with TI = 0.0063(12), which is observed in the 1062 keV γ-gated coincidence spectrum. These assignments indicate a positive intensity balance of 0.0065(34), but unobserved γ rays may feed the level from above, e.g., a Compton feature at 213 keV in the 1062 gate would obscure a transition from the 4^+ level at 1646 keV (although there is no evidence of such a transition in a gate on the weaker 715 keV γ ray).

B. Level deletions

The consequences of removing a large number of previously reported γ rays from the ^{154}Gd scheme, based upon the upper limits we have set, are profound. Many states in ^{154}Gd, originally proposed as populated in the decay of ^{154}Eu, are found to be unsupported by our data. We adopt the following criterion for refuting the existence of a previously adopted level: if the strongest γ ray assigned as deexciting a level reported [2] 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.

1. Levels reported only in ^{154}Eu decay studies

Only studies of ^{154}Eu decay have reported γ rays associated with proposed levels in ^{154}Gd at 1136 [14,16,17], 1233 [14], 1510 [14,15,18], 1879 [14,15], and 1895 keV [14,15]. The 1387 keV γ ray is the strongest of the transitions associated with these levels, and (with the 1510.0 keV γ ray, the other transition which defines the 1510 keV level) should be visible in our singles spectrum. As Fig. 6 demonstrates, these lines are not present with the reported [14,15] intensities. Indeed, we find no evidence to support any of these proposed levels or their associated transitions and list UL values in Table II for γ rays which feed or deexcite levels at 1136, 1233, 1510, 1879, and 1895 keV in the adopted [2] ^{154}Gd level scheme.

2. Levels only reported in ^{154}Gd decay and (n,γ) studies

Levels in ^{154}Gd at 1277, 1839, and 1861 keV were first proposed [14] in a ^{154}Eu decay study and were reported to be

TABLE II. Intensity upper limits, UL, for γ rays listed in the evaluated [2] data for ^{154}Gd which were not observed in this study. These limits may be compared with intensities, $I_\gamma^{\rm NDS}$, from: A: the evaluated [2] γ-ray intensity for ^{154}Eu decay; B: the intensity calculated from the evaluated [2] relative intensity (RI) and intensity of the strongest observed γ out of the level (reference transition is listed by E_γ); and C: intensity calculated from the evaluated [2] RI's and the intensity of the ~1170 keV γ rays. Upper limits are set at the 95% confidence level using the method of Currie [13] (cf. Fig. 4 and discussion in the text). Intensities are normalized such that $I_\gamma(1274)\equiv 100.0$.

E_γ	UL	$I_\gamma^{\rm NDS}$	Source	E_γ	UL	$I_\gamma^{\rm NDS}$	Source	E_γ	UL	$I_\gamma^{\rm NDS}$	Source
112.1	0.0003	0.004	C	375.2	0.0020	0.0056	A	1023.0	0.0004	0.0190	A
116.9	0.0010	0.007	B (851)	392.9	0.0001	0.17	B (801)	1049.4	0.0042	0.0493	A
120.2	0.0002	0.0002	B (1291)	394.2	0.0004	0.011	B (650)	1072.2	0.0039	0.0100	A
122.7	0.0014	0.002	B (1047)	414.3	0.0161	0.0142	A	1110.0	0.0049	0.0080	A
124.0	0.0020	0.002	B (1047)	419.4	0.0021	0.010	A	1124.2	0.0123	0.0197	A
125.4	0.0020	0.020	A	463.9	0.0003	0.0122	A	1136.1	0.0030	0.0211	A
159.6	0.0013	0.38	B (723)	480.2	0.0024	0.001	C	1153.1	0.0033	0.0310	A
159.9	0.0011	0.0030	A	480.6	0.0032	0.0138	A	1170.0	0.0031	0.0104	A
162.1	0.0010	0.0031	A	484.6	0.0026	0.0113	A	1171.2	0.0030	0.0104	C
165.9	0.0021	0.0071	A	488.3	0.0027	0.020	A	1172.6	0.0030	0.0104	C
195.5	0.0014	0.0060	A	506.5	0.0007	0.0180	A	1216.8	0.0042	0.0096	A
197	0.0014	0.0045	A	510.6	0.0217	0.017	A	1232	0.0027	0.0230	A
209.4	0.0042	0.0071	A	555.7	0.0005	0.11	B (801)	1252.0	0.0015	0.0446	B (1129)
227.6	0.0008	0.005	B (650)	563.4	0.0031	0.008	A	1316.4	0.0391	0.0500	A
229.0	0.0016	0.0069	A	597.5	0.0006	0.0158	A	1387.0	0.0056	0.0550	A
237.7	0.0006	0.0180	A	642.4	0.0010	0.0130	A	1400.0	0.0002	0.0090	A
260.2	0.0015	0.0062	A	650.6	0.0005	0.0282	A	1490.2	0.0002	0.0082	A
274.0	0.0024	0.0111	A	774.4	0.0025	0.0240	A	1510.0	0.0030	0.0137	A
283.0	0.0017	0.0173	B (1189)	790.1	0.0009	0.0300	A	1522.0	0.0002	0.0017	A
296	0.0041	0.0040	A	898.4	0.0007	0.0056	A	1554	0.0011	0.0032	A
299.2	0.0028	0.0030	C	906.1	0.0023	0.0338	A	1716.9	0.0004	0.0017	A
308.2	0.0016	0.0068	A	919.2	0.0032	0.0350	A	1773.0	0.0006	0.0009	A
320	0.0023	0.0028	A	923.1	0.0032	0.0078	C	1796.3	0.0002	0.056	B (801)
351.7	0.0060	0.19	B (650)	984.5	0.0036	0.027	A	1838.0	0.0007	0.0024	A
368.2	0.0022	0.0085	A	1012.8	0.0043	0.0080	A	1895.0	0.0002	0.0018	A

confirmed based upon Ritz combinations in an (n,γ) study [12] (although no primary capture γ rays are reported to these levels). Other confirmations have come from reports of transitions associated with the levels at 1277 [15,19], 1839 [15], and 1861 keV [15]. The work by [15] includes a detailed comparison of γ rays emitted in ^{154}Eu decay which lists also that 1717 and 1838 keV transitions were observed [17] associated with the 1839 keV level. However, Table 1 in Ref. [17] and the statement, "no γ ray associated with [levels adopted [2] at 1277, 1510, 1699, 1839, and 1895 keV] was observed in our measurements," indicates that this listing is in error. Based upon coincidence data, we have placed transitions associated with these levels elsewhere in the decay scheme (cf. γ rays at 228, 367, and 904 keV in Table I) and have set UL values (cf. Table II) for transitions that we do not observe. We find no evidence in our data to support the 1277, 1839, and 1861 keV levels.

3. Levels at 1293.59, 1294.17, and 1295.467 keV

The entangled history of a level(s) at ~1294 keV with $J^\pi=0^+$ or 2^+ complicates any separate discussion of the levels adopted [2] at 1293.59, 1294.17, and 1292.7 keV. The first work [14] to suggest such a state proposed a 0^+ state at 1292.7 keV based on assigned 612 and 1170 keV transitions out of the level and γ rays of 126 and 237 keV feeding the level. A subsequent study of the decay of ^{154}Tb [20] disputed the placement of this 0^+ state, suggesting instead an energy of 1295.8 keV based upon assignment of a 615.1 keV $E0$ from the level. Another study of ^{154}Gd decay [21] rejected the 615.1 keV $E0$ assigned in [20], suggesting instead a level at 1295.1 keV based upon K conversion electrons associated with 1172.1 and 1295.1 keV transitions (although [21] considers the possibility that the 1295 K e^- may be associated exclusively with the 1418→123 transition). The lack of primary capture γ rays feeding any level at ~1294 keV is cited as a reason for expressing "considerable doubt" about these levels in an (n,γ) study [12]. However, it is suggested [12] that if one assumes a 0^+ band based on levels at 1295 and 1418 keV, then a 2^+ at ~1300 keV might be expected as the 2^+ member of a band built on the 0^+ level at 1182 keV, and this study presents a probable decay pattern for a 2^+ level at 1294.2 (based on γ rays of 112.1, 923.1, 1171.2, and 1274.2 keV) and a 0^+ level at 1295.5 (based on transitions of

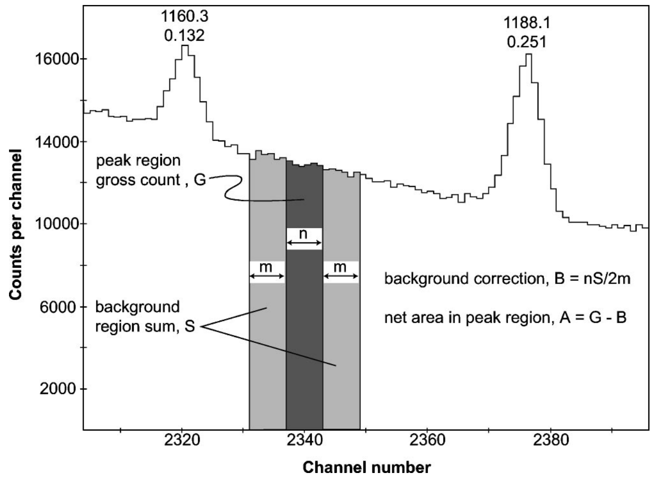

FIG. 4. An illustration of the data used to establish an upper intensity limit for a γ-ray line by use of the method of Currie [13]. This figure is discussed further in the text.

247.9, 299.2, 480.2, 1172.6, and 1295.1 keV).

The level scheme adopted [2] for ^{154}Gd includes a $(2)^+$ level at 1294.174 keV [assumed to be the same as the $(2)^+$ 1293.59 level listed in the scheme adopted for the decay of ^{154}Eu in the evaluation] and a 0^+ level at 1295.467 keV. Gamma rays of 112.1, 165.9 (165.9), 923.1, 1171.2 (1170.0), and 1294.2 keV are assigned from the 1294.2 (1293.6) state. The 1295.5 level has assigned γ rays of 299.2, 480.2, and 1172.55 keV (as well as a 1295 keV $E0$ transition with a smaller branching fraction than that assigned by [21]).

We find no evidence in our data to support any level(s) at ~1294 keV. Each of the proposed levels at this energy has an assigned [2] ~1170 keV γ ray with a relative intensity of 100 out of the level; an illustration of the limits set on the population of these levels is found in Fig. 4. This is the region selected to illustrate the method used to set UL values. Upper intensity limits for the ~1170 keV γ rays and the other transitions (at 112, 165.9 ($\sim 1294 \rightarrow 1128$), 299.2, 480.2, and 238 keV) which define these levels are listed in Table II.

The adopted ^{154}Gd level [2] scheme lists γ rays at 120.2, 122.7, 124.0 (125.4), 237.7, 351.7, 404.3, and 407.8 keV feeding levels at ~1294 keV from states at 1414, 1418, 1531, 1646, 1699, and 1702 keV. Table II lists UL values for all of those transitions except the 404.3 and 407.8 γ rays which will be discussed in Sec. IV B 4. Upper limits for the ~123 keV lines were calculated from background fluctuations in coincidence gates on the 301 and 305 keV transitions feeding the 1414 and 1418 keV states. We find no evidence of doublet structure in these gates (except a very small 122 keV line in the 243 keV gate from the $2_1^+ \rightarrow 0_1^+$ transition in ^{152}Sm) and we determine that the intensity of the 123 keV γ ray is consistent with that expected for secondary coincidences with the $123 \rightarrow 0$ transition in the ground state band.

The adopted [2] 0^+ state at 1295.467 keV is a result of the (n,γ) study [12]; however, this level should be populated in β decay if the next state in the presumed band (i.e., the 1418 keV level) is populated or if higher 0^+ states are observed to be populated. The 1418 keV level is populated in this work, but none of the γ rays associated with the 1295 keV state are observed (cf. Table II). Similarly, the 1418 keV state is observed to be populated in a study of the $(J=3)$ β-decaying isomer of 1295 keV [9,22], but there is no evidence of transitions associated with a state at ~1294 keV. Furthermore, in a study [9,22] of the low-spin β-decaying isomer of ^{154}Tb ($J^{\pi}=0^-$), no observable population of the 1295 keV state is discernable, while excited 0^+ states at 1574, 1650, and 1836 keV are observed to be populated. This lack of evidence for β decay feeding of a 0^+ state at 1295 keV and a 2^+ state at 1294 keV, when combined with the absence of primary capture γ rays feeding these low-spin states in the (n,γ) study [12], indicates that there are no 0^+ or 2^+ states at ~1294 keV in ^{154}Gd.

4. Levels at 1698.2 and 1702.0 keV

Inelastic deuteron scattering [23] first revealed a level at ~1700 keV, but this state (like the ~1294 keV levels) has had a complicated past. Citing the (d,d') results, a study [14] of ^{154}Eu decay tentatively proposed a (4^+) level at

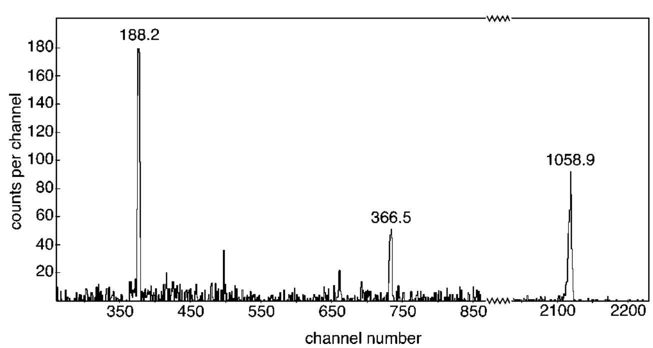

FIG. 5. The coincident γ-ray spectrum associated with the 349 keV ($1531 \rightarrow 1182$) transition. This establishes for the first time that the 0^+ 1182 keV level is populated (indirectly) in the decay of ^{154}Eu.

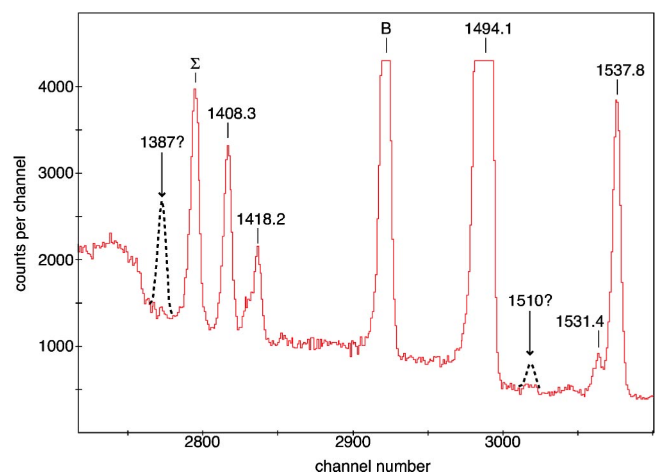

FIG. 6. (Color online) Evidence from the γ-ray singles data that lines adopted [2] at 1387 and 1510 keV are spurious; dashed lines indicate the reported intensities of these transitions. The spectrum also shows the strongest coincidence sum peak (at 1397.6 1397.6 $=\Sigma 123+1274$ keV) in the spectrum and the strong room background peak (at 1460.8 keV) from ^{40}K.

TABLE III. Relative intensities for γ rays assigned to levels at ~1700 keV. The refutation of the 1294 keV level is discussed in Sec. IV B 3, but assignments by others to this level are included for comparison. Level energies are expressed in keV.

E_x	1701.3	1698.9	1702.0
E_f	[9,22]	[25]	[2]
1646			70
1418	20	12	
1294		17	72
1252	4		
1128	9		
1048	100	20	
816	10	43	
718	91		100
371	65	100	
123	12	59	

1698.3 keV based upon the assignment of γ rays at 650.6 (fitted as a weak component of the 649.5 keV transition), 981.3 (placed without an intensity), and 1327 keV (assigned only as an intensity upper limit). A level at 1704 or 1705 keV was later suggested [24] based upon (d,t) and $(^3\mathrm{He},\alpha)$ reaction studies. Levels at 1698 and 1702 keV were then assigned γ rays of 280.4, 404.3, 651.0, 883.2, 1327.9, and 1575.1 keV and γ rays of 407.8 and 984.5 keV, respectively, in the (n,γ) study [12] using Ritz combinations. In a study [9,22] of ^{154}Tb decay, we have placed a 4^+ level at 1701.3 keV.

The deduced spin of the adopted [2] states, (4^+) for the 1698.5 keV level and $(3,4)^+$ for the 1702.0 keV level, preclude feeding from a primary capture γ ray in the (n,γ) study [12]; thus there is no direct evidence of two levels at ~1700 keV. Coincidence spectroscopy data in the ^{154}Tb decay study [9,22] indicate only one 4^+ level at 1701.3 keV and show no evidence for a 1701→1294 transition which would correspond to the 404.3 and 407.8 keV transitions assigned [12] through Ritz combinations to support levels at 1998.5 and 1702.0 keV. We suggest that the assignments [12] for the 404.3 and 407.8 keV γ rays are in error, and therefore these assignments should not be considered as additional evidence in support of the ~1294 keV levels (cf. Sec. IV B 3).

We find no evidence that a level(s) at ~1700 keV has been populated in this work. However, as shown in Table III, the relative intensities for γ rays out of a level at this energy disagree and the energy of the strongest line out of the 1700 keV level could be disputed. Only a 650.96 γ ray (1699→1048) with an intensity of 0.0282 has been adopted [2] in the decay of ^{154}Eu, and we set an upper limit of <0.0005 for this transition based on coincidences with the 677 keV γ ray. The 1702 keV level is not in the evaluated [2] ^{154}Eu decay scheme; however, an unassigned line at 984.5 keV (I_γ=0.027) in the evaluated [2] ^{154}Eu decay data set is at the same energy as the strongest γ ray assigned [12] to this level (1702→718); we present an intensity UL for this transition based upon our singles spectrum in Table I. Our results [9,22] from the decay of ^{154}Tb indicate the strongest line out of the 1701.3 keV level should be a 1701→1048 transition at 653.7 keV, and we determine an UL of <0.001 in the 677 keV gate for this γ ray.

5. 1770.5 keV level

While the adopted [2] 5^+ level at 1770.182 in ^{154}Gd is well established (our study [9] of the J=3,7 β-decaying isomers of ^{154}Tb decay populates this level), we find no evidence for its population in ^{154}Eu decay. The 506.5, 642.4, and 1400.0 keV γ rays out of this level have been observed in other methods, and reported [14,15,17,19] in the decay of ^{154}Eu. We do not observe any of these transitions in this study (cf. Table II). The strongest deexciting transition of 774.4 keV (1770→996, [$M3$] multipolarity) is reported only in the decay of ^{154}Eu [14,15,19] and has an adopted [2] intensity of 0.024; we calculate an intensity UL of <0.0043 from our singles spectrum and determine an UL value of <0.0025 for a 1770→996 transition based on coincidences with the 996 keV γ ray (cf. Table II).

C. Population systematics

Detailed reasons for questioning the population (and in some instances, the existence) of levels at 1136, 1233, 1277, 1294, 1295, 1510, 1698, 1702, 1770, 1838, 1861, 1879, and 1895 keV have been presented in Sec. IV B. Intensity upper limits presented in Table II, when summed over the transitions assigned out of each level and compared with the expected population of these levels based on adopted [2] intensities and internal conversion coefficients, provide compelling evidence that these levels are not populated in the decay of ^{154}Eu. In Table IV we present the results of such a comparison for levels which have γ rays assigned in the adopted [2] ^{154}Eu decay data (the 1295 level is included due to the possibility that the state could be fed through γ rays assigned to other levels in the decay scheme).

The upper limit population intensities presented in Table IV are presented graphically, with the population intensity of all levels observed in this study, in Fig. 7. States adopted [2] at 1136, 1294, 1699, 1838, 1861, and 1895 keV which would have a spin change of 1 or less from the β-decaying parent ^{154}Eu are shown to have population intensities (upper limits) that are 1 to 2 orders of magnitude smaller than the observed states that would be classified as allowed and first-forbidden β decays. With the exception of the level at 1770 keV [a state well-established from the decay of ^{154}Tb and from $(\alpha,2n\gamma)$ studies], the results presented in Table IV and Fig. 7 argue for the removal of the levels listed in Table IV from the ^{154}Gd level scheme. Based upon the arguments presented in Sec. IV B 4, it is recommended that the adopted [2] 1702 keV level should also be stricken from the ^{154}Gd scheme.

D. ^{154}Eu→^{154}Gd decay scheme

Based upon the γ ray intensities listed in Table I and conversion coefficient data (values listed in [2] are used where available or computed using HSICC [26]), the intensity

TABLE IV. Upper limits (UL) for population of levels in the adopted ^{154}Eu$\rightarrow$^{154}Gd decay scheme [2] which were not observed in this study. Total intensity $[I_\gamma + \mathrm{ce}, I_\gamma(1274) \equiv 100.0]$ out of each level is listed as an upper limit at the 95% confidence level and is compared with a value, I_{NDS}, calculated using the evaluated [2] ^{154}Eu decay data. Inclusion of the 0^+ level at 1295.467 keV in this comparison is discussed further in the text.

E_{level}	UL	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	0.0006	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 [2].

balance for the 123 keV level indicates an excess of $(10.6 \pm 0.9)\%$ (cf. from observation of direct β decay: $9.2 \pm 1.5\%$ [27] and $10.8 \pm 1.2\%$ [28]). The 371 keV level has an excess of $0.19 \pm 0.05\%$ (cf. from observation of direct β decay: 95% [27]). From this we deduce that the states at 123 and 371 keV primarily are populated indirectly by γ rays from levels higher in the decay scheme. This is illustrated in Fig. 8, where the spectra gated by the 123.1 keV $(2_1^+ \rightarrow 0_1^+)$ and 247.9 keV $(4_1^+ \rightarrow 2_1^+)$ γ rays are presented. These two gated spectra together provide positive evidence of all 25 levels observed in this decay through γ rays which decay directly to the levels at 123 and 371 keV (although population of the 1182 and 1646 keV levels are more readily apparent in other gates, e.g., population of the 1182 keV level is illustrated in Fig. 5).

An internal check of "completeness" in our decay scheme is determined through the intensity balances for states observed in ^{154}Gd with $J^\pi = 0^+$, 1^-, 5^+, 5^-, or 6^+. Spin-parity selection rules for β decay forbid strong direct population of these states from the $J^\pi = 3^-$ parent, ^{154}Eu, thus only a small intensity excess may be expected. Balances for the states with J^π (E_x, in keV) $=0^+$ (680.7, 1182.1), 1^-(1241.3, 1414.4), 5^+(1432.6), (5^-)(1404.1), and 6^+(717.7) are given in Table V. We conclude from these values that the γ ray intensities and assignments determined in this study leave little room for additional levels below $\sim$1.5 MeV as states lower than these should have greater probability of both direct and indirect population in ^{154}Eu decay.

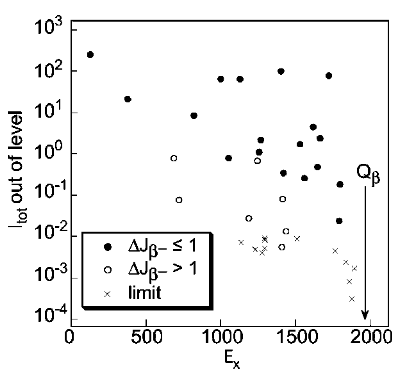

FIG. 7. Total decay intensity (I_γ + ce) out of levels observed in ^{154}Gd through this work. $I_\gamma(1274) \equiv 100.0$.

All levels and transitions placed in the ^{154}Eu$\rightarrow$^{154}Gd decay scheme presented in Fig. 9 are based upon $\gamma-\gamma$ coincidence spectroscopy. Transitions from all states included in the scheme have been observed in γ ray coincidence gates below the deexciting level. States up to 1531 keV have been observed through coincidence gates set on γ rays feeding the states from above. No γ rays were observed to feed states above 1531 keV and we conclude that these states are populated almost exclusively through direct feeding in the β decay of ^{154}Eu.

The most valuable independent view of the completeness of the present study is provided by the primary capture γ rays observed in the neutron-capture study [12]. 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^- 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 nonobservation 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.

V. DISCUSSION OF BAND STRUCTURES IN ^{154}Gd ABOVE 1 MeV

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 available spectroscopic data for ^{154}Gd, we arrive at the set of ^{154}Gd low-lying states shown in Fig. 10. Compared to Fig. 1, where a wealth of collective states in ^{154}Gd between 1 and 2 MeV held the promise of distinguishing between multiple models vying to describe the $N=90$ isotones, we find instead a structure much more similar to that reported for ^{152}Sm. While this result does not immediately present a solution to the controversy surrounding these nuclei, it does reinforce the need for a theory which has general application for the $N=90$ isotones.

The change in the structure of ^{154}Gd, as illustrated in the differences between Figs. 1 and 10, also serves as a warning to use caution when searching for a specific kind of structure, or when relying on a single kind of data [e.g., $B(E2)$ ratios]

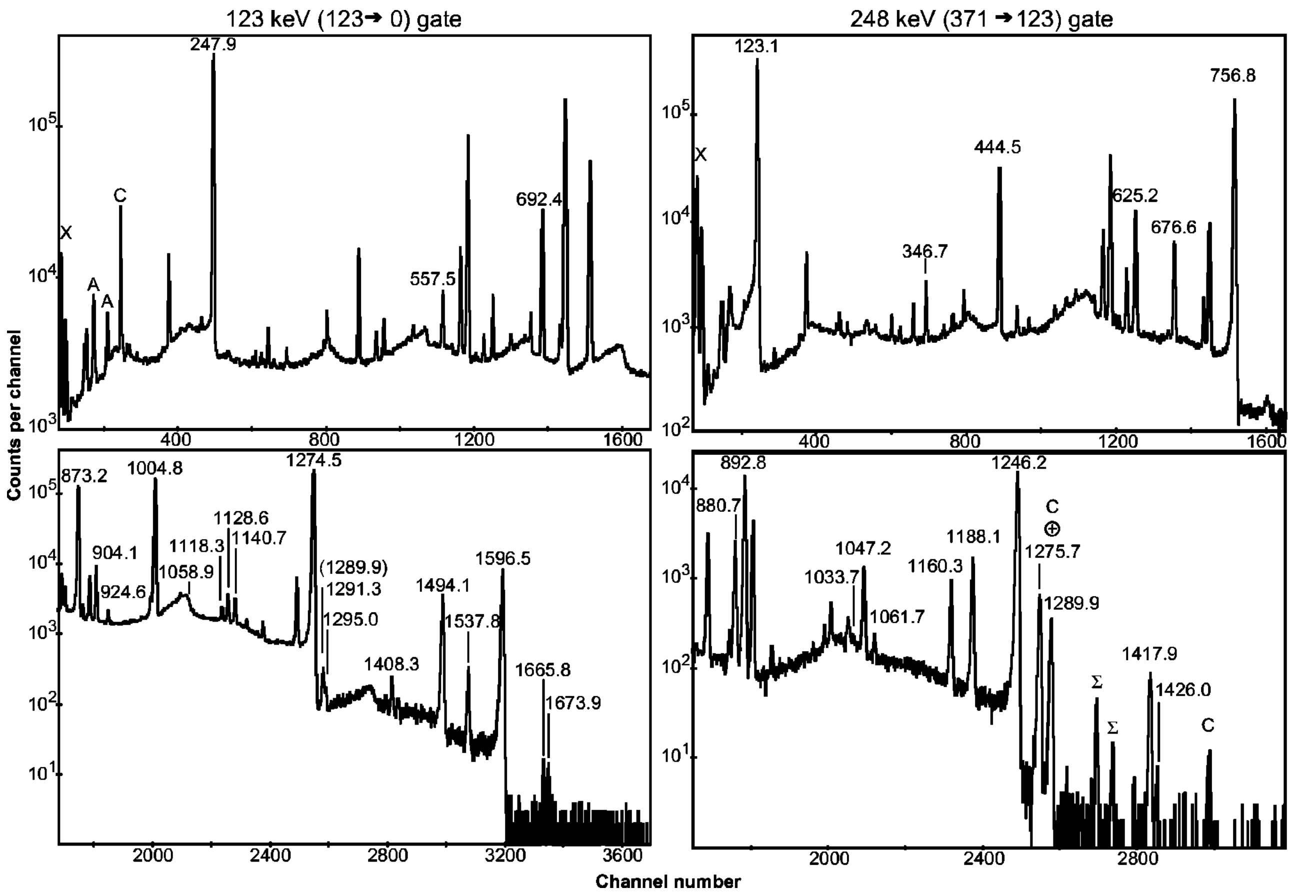

FIG. 8. The coincident γ-ray spectrum associated with the 123.1 keV$(2_1^+ \rightarrow 0_1^+)$ and 247.9 keV$(4_1^+ \rightarrow 2_1^+)$ transitions. Gamma rays which directly feed the levels at 123 and 371 keV, respectively, are marked by energy (in keV), other peaks are marked as in Fig. 2, and chance coincidences are marked C.

to interpret nuclear structure. The early study of ^{154}Gd through the decay of ^{154}Eu by [14] not only provided most of the comparison data in Table II, but also shaped the interpretation of the structure of ^{154}Gd for decades. Much of the discussion in [14] and in the follow-up paper, [7], uses $B(E2)$ ratios and excitation energy to argue for the "two-phonon" nature of band structures in ^{154}Gd built upon states at 1294 ("$\beta\beta$"), 1531("$\beta\gamma$"), 1646, and 1838 keV ("$\gamma\gamma$"). Controversy (over the band-head energy of the "$\beta\beta$" band in [12,20,29,30] and the nature of the "$\gamma\gamma$" bands in [20,30–33]) has surrounded these structures since that initial interpretation. We discuss the nature of these "multiphonon" bands individually below.

TABLE V. Total decay intensity (γ+ce) into and out of levels in ^{154}Gd which are not expected to be strongly populated by the ^{154}Eu(J^π=3$^-$) parent in β decay due to spin-parity selection rules. Only a small excess in the observed intensity balance, $I_{\text{net}}=I_{\text{out}}-I_{\text{in}}$, may be expected for these states.

E_x(keV)	J^π	I_{out}	I_{in}	I_{net}
680.62(7)	0^+	0.796(6)	0.778(14)	0.018(15)
717.73(7)	6^+	0.0776(12)	0.065(8)	0.013(8)
1182.02(7)	0^+	0.029(5)	0.027(3)	0.002(6)
1241.35(7)	1^-	0.683(15)	0.701(10)	−0.018(18)
1404.07(21)	(5^-)	0.0079(11)	0.0051(7)	0.0028(13)
1414.44(7)	1^-	0.082(11)	0.0664(20)	0.016(11)
1432.62(7)	5^+	0.0128(32)	0.0063(12)	0.0065(34)

A. "$0^+_{\beta\beta}$" band

If the band built upon the 0_2^+ 681 keV state is considered a β vibration (the review by Garrett [34] suggests that this is one of the rare candidate states which is consistent with the definition of such excitations), then the $\beta\beta$ band head is expected to be at 1362 keV. The search for this state (discussed in detail in Sec. IV B 3) led to the controversy over levels at $\sim$1294 keV. This controversy and the continued search for a "$\beta\beta$" band failed to correctly interpret the structure of the 0_3^+ band because the emergence [22] of a new type of coexisting collective structure (the band based on the 0_3^+ 1182 keV state) could not have been anticipated.

Shahabuddin *et al.* [29] first proposed that the 1182 and 1418 keV states were the 0^+ and 2^+ members of a new excited band, based upon analysis of the transfer cross sections to these levels from the (t,p) reaction. The strong population of these levels in two-nucleon transfer reactions precludes interpretation of these states as members of a multiphonon band [29] (indeed, this is a key datum for the pairing isomer interpretation of the structure built upon the 0^+ state at

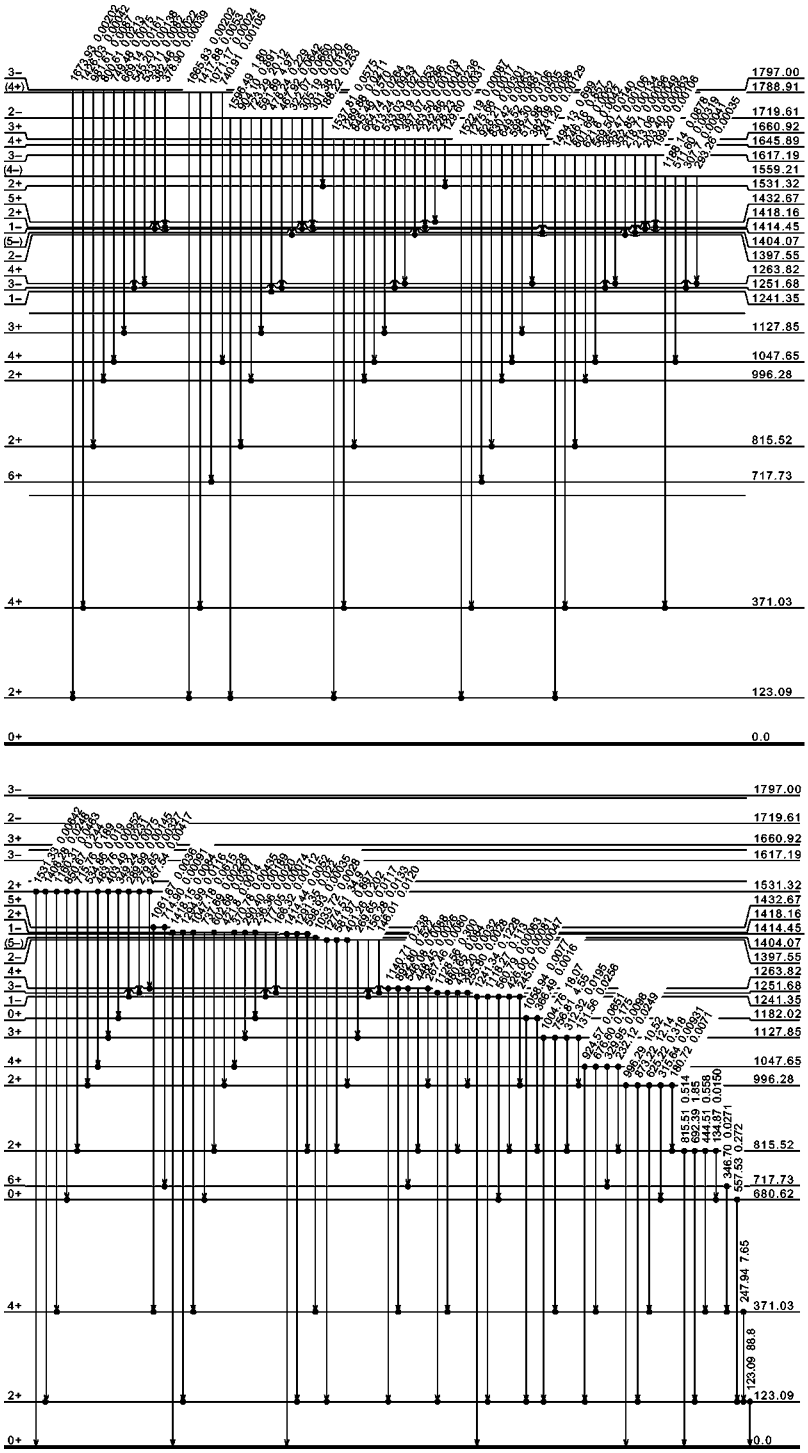

FIG. 9. The level scheme for ^{154}Gd populated in the decay of ^{154}Eu, as observed in the present work. Level and transition energies and decay intensities are determined in this work, spins and parities are from [2]. Transitions are labeled by energy and total (γ+ce) decay intensity (computed using conversion coefficient data in [2] where available or using HSICC [26]). 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).

1182 keV [22]). Our coincidence spectra positively identify the 238 keV γ ray as the $1418 \rightarrow 1182$ intraband transition and the upper limits on the transitions associated with the levels proposed at $\sim$1294 keV indicate that this is the only $K^{\pi}=0^{+}$ band between 1.0 and 1.5 MeV.

The next 0^{+} states (possible "$\beta\beta$" band head candidates) in the adopted [2] ^{154}Gd scheme are at 1574 and 1650 keV. Shahabuddin *et al.* [29] report a 1576 keV state which received 10% of the ground state transfer strength. This population strength is indicative (based upon the conservative estimate of Garrett [34]) of a 0^{+} state which has significant quasiparticle pair configurations and is, therefore, not a good candidate for a multiphonon state. Thus the first possible multiphonon $K^{\pi}=0^{+}$ state is the 1650 state, which has been reported only in the (n,γ) study by Spits [12] and in the ^{154}Tb $(J^{\pi}=0^{-})\beta$ decay study by Kulp [9].

B. "$2^{+}_{\beta\gamma}$" band

A two-phonon $\beta\gamma$ band resulting from the coupling of one-phonon β-vibrational and γ-vibrational states should decay with equal strength to the one-phonon bands and should

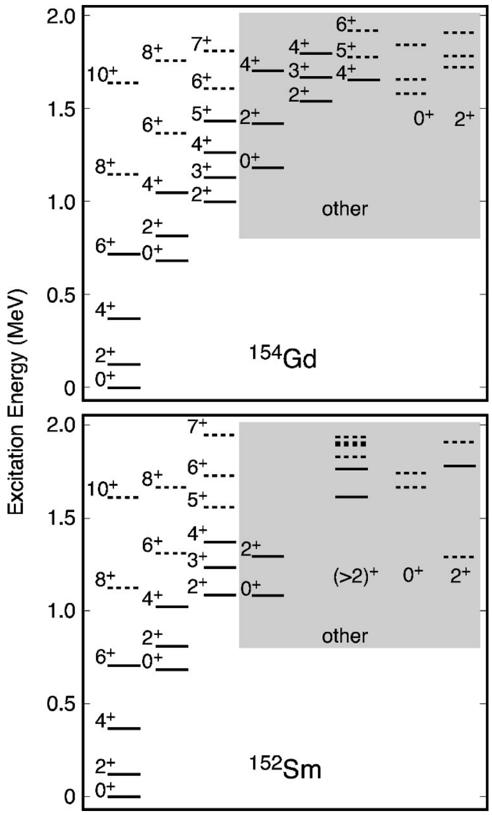

FIG. 10. Comparison of the low-lying positive-parity states in ^{152}Sm (bold lines indicate states populated in the decay of ^{152g}Eu and dashed lines indicate levels observed through other methods of spectroscopy; data from [1]) and ^{154}Gd (bold lines from the present work and dashed lines from [2]), cf. Fig. 1.

decay with significantly reduced strength to the ground-state band. Assuming the bands built on the 0_2^+ (681 keV) and the 2_3^+ (996 keV) states are of one-phonon β-vibrational and γ-vibrational nature, respectively, the band head of the $\beta\gamma$ band is expected at an energy of 1677 keV. The best candidate for such a band is the $K^\pi=2^+$ band based upon the 2^+ state at 1531 keV.

In Table VI, we present relative $B(E2)$ values divided by the squares of the appropriate Clebsch-Gordan coefficient for transitions out of the 1531, 1661, and 1788 keV levels. We have assumed pure $E2$ transitions for the purposes of this discussion. Dividing the relative $B(E2)$ value of each transition by the square of the Clebsch-Gordan coefficient connecting the two states removes the J and K dependence, thus allowing a straightforward comparison of interband transitions. The "reduced" values presented in Table VI show, e.g., that transitions from the 2^+ 1531 keV level to the 2_2^+ "β-vibrational" and 2_3^+ "γ-vibrational" states are approximately the same strength while the transition to the 2_g^+ is much weaker. Transitions between the 1531 keV level and $J^\pi=4^+$ states below follow the same trend, but these relative $B(E2)$ values are much stronger than those for transitions to $J^\pi=2^+$ states which indicates a departure from simple Alaga rules and is evidence of strong mixing between bands.

Meyer [7] suggests that the odd-even J dependence in band-mixing calculations for the states at 1531, 1661, and

TABLE VI. The systematic increase with spin, J_f, in relative $B(E2)$ values divided by Clebsch-Gordan coefficients for transitions out of the states at 1531, 1661, 1788, and 1646 keV suggests that the transition quadrupole moment from these states to lower bands increases with the spin of the final level.

J_f	1531	1661	1788	1646
0_1^+	0.0349 (11)			
2_1^+	0.144 (6)	0.0438 (8)	1.41 (8)	
4_1^+	14.11 (13)	0.097 (4)	2.78 (15)	
6_1^+			6.2 (11)	
0_2^+	25.00 (22)			
2_2^+	31.9 (9)	8.63 (16)		
4_2^+	227 (4)	17.65 (19)		
2_3^+	12.6 (30)	1.32 (5)		1.168 (23)
3_1^+	38.1 (29)			3.68 (12)
4_3^+	120 (4)	19.1 (4)		9.17 (29)
5_1^+		26.2 (16)		

1788 keV may be indicative of mixed (prolate-spherical-oblate) character. Such mixing has been described by Kumar in the dynamic pairing plus quadrupole model (DPPQ) [35]. Results from Kumar's [36] extensive DPPQ calculations for ^{154}Gd are compared with our experimental results in Table VII. While there are notable discrepancies for transitions out of the $J^\pi=2^+$ and 4^+ states, the agreement between experimental and calculated values is within a factor of ~ 2 for transitions out of the $J^\pi=3^+$ state.

Kumar's calculations [36] do not assume the presence of β and γ vibrations in an axially symmetric nucleus; thus the good agreement (cf. Table VII) with some experimental val-

TABLE VII. Comparison of relative $B(E2)$ ratios from this work (8π) with Kumar's DPPQ calculations [36].

J_i	$J_f/J_{f'}$	8π	DPPQ [36]
2	$0_1/2_1$	0.17 (1)	0.013
	$4_1/2_1$	4.89 (22)	0.09
	$0_2/2_2$	0.55 (2)	1
	$4_2/2_2$	0.36 (1)	1.6
	$3_1/4_3$	0.74 (6)	0.95
	$0_2/0_1$	717 (23)	550
	$2_2/2_1$	221 (11)	7.1
3	$4_1/2_1$	0.88 (4)	1.9
	$4_2/2_2$	0.818 (18)	0.7
	$2_2/2_1$	197 (5)	375
	$4_2/4_1$	183 (7)	134
	$4_3/2_3$	13.9 (6)	13
	$4_3/4_1$	475 (21)	350
	$4_2/4_3$	0.384 (10)	0.38
	$2_2/2_3$	6.52 (28)	7.25
	$2_3/2_1$	30.2 (13)	51
4	$2_1/4_1$	0.172 (14)	0.3
	$6_1/4_1$	0.19 (4)	0.8

ues does not provide a clear indication of the nature of the $K^{\pi}=2_2^+$ band, but rather shows a need to examine more data. While a true coupled-phonon $\beta\gamma$ excitation could explain the presence of electric monopole $(E0)$ components for the 533 keV $(1661\rightarrow1128)$ and 535 keV $(1531\rightarrow996)$ transitions [12,37], these $E0$ components are alternatively [38] indicative of shape coexistence and mixing between the $K^{\pi}=2_1^+$ and $K^{\pi}=2_2^+$ bands. Further experimental studies (e.g., measurement of the lifetime of the 1531 and 1661 keV states, determination of the $E2/M1$ mixing ratios for transitions out of the band, and new measurements of the $E0$ transitions) would provide insight and constraints for any interpretation of this structure. As Fig. 11 indicates, however, the 533 and 535 keV transitions are weak and will require exacting experimental work to obtain precise data for comparison.

It is apparent that the present results and available data from other studies cannot conclusively rule out a $\beta\gamma$ nature for the $K^{\pi}=2_2^+$ band at this time. However, the lack of an expected $\beta\beta$ two-phonon excitation below the 1531 keV level casts doubt upon an interpretation of this band as coupled-phonon excitation and a new interpretation is warranted. The experimental evidence, i.e., $E0$ transitions between $K^{\pi}=2^+$ bands and the systematic increase in transition quadrupole moments (cf. Table VI), indicate the presence of shape coexistence and mixing. If the 1531 keV state is not a two-phonon state, but rather an analog for the 681 keV 0^+ state as the 996 keV state is to the ground state, then the structure of ^{154}Gd could be described as the coexistence of two similar rotational structures (bands built on the 0_1^+ ground state and the 0_2^+ 681 keV level). Such similar structures very close in excitation energy would mix strongly, and the same argument would apply for $K^{\pi}=2^+$ excitations. This would imply mixing for even-J states which includes four or more bands (the less-deformed band built on the 1182 keV [22] state would also mix due to its proximity to the other $K^{\pi}=0^+$ bands). Such an interpretation is consistent with our results; but additional data, e.g., absolute $E2$ and $E0$ transition strengths from lifetime measurements, would be useful to constrain band-mixing calculations.

C. "$\gamma\gamma$" bands

Bands associated with two-phonon $\gamma\gamma$ vibrational structure are expected at an energy of $\sim$1992 keV (assuming the 2^+ level at 996 keV is the one-phonon γ vibrational state). Parallel and antiparallel combinations of γ-vibrational quanta $(K=2)$ would produce $K^{\pi}=4^+$ and $K^{\pi}=0^+$ bands, respectively. While a previous study of ^{154}Eu decay [7,14] argues that such structures have been observed in ^{154}Gd, and a study of ^{152}Sm$(\alpha,2n\gamma)^{154}$Gd [33] supports the assignment of the $K^{\pi}=4^+$ (parallel) $\gamma\gamma$ band, available data do not support these claims.

We refute the population (cf. Sec. IV B) of a level at 1839 keV through the decay of ^{154}Eu. This level had been suggested [7,14] as the 2^+ member of the $K^{\pi}=0^+$ band. No other levels have been suggested as members of the $K^{\pi}=0^+$ (antiparallel) band, thus the deletion of the 1839 keV state removes any evidence of this kind of two-phonon $\gamma\gamma$ band in ^{154}Gd.

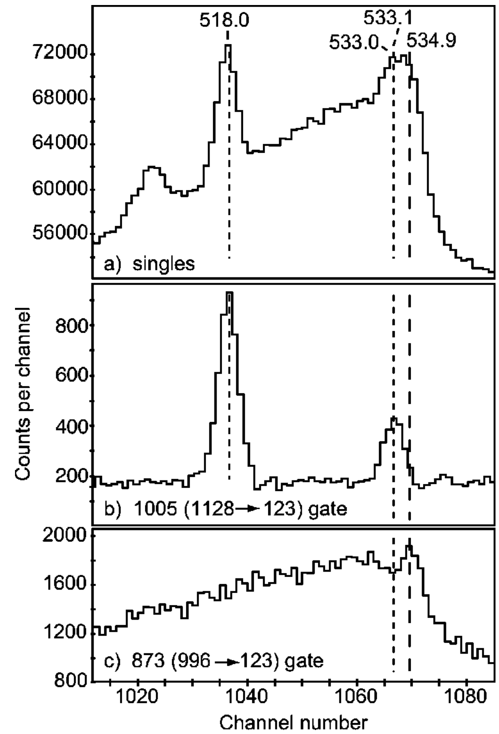

FIG. 11. The weak 533 keV $(1661\rightarrow1128)$ and 535 keV $(1531\rightarrow996)$ transitions coincide with a Compton artifact in (a) the γ-ray singles spectrum, but are measured through (b) the 1005 keV and (c) the 873 keV coincidence spectra.

The 4^+ level at 1646 keV populated in ^{154}Eu decay is considered a candidate for a two-phonon state due to the weak relative $B(E2)$ values for transitions to the ground-state band [14]. A study of ^{152}Sm$(\alpha,2n\gamma)^{154}$Gd [33] argues that the $B(E2)$ strength to the $K^{\pi}=2^+$ band built upon the 996 keV level from states in the band built upon the 4^+ level at 1646 keV is proof that this is the $K^{\pi}=4^+$ two-phonon $\gamma\gamma$ excitation in ^{154}Gd. However, $\Delta K=4$ transitions are expected to be weak, and should only occur as a result of mixing. The relative $B(E2)$ values divided by Clebsch-Gordan coefficients for $\Delta K=2$ transitions, presented in Table VI, suggest that mixing is indeed present because of the spin-dependent increase in the transition quadrupole moment. Single-particle transfer data studies [31,32] indicate that the 4^+ 1646 keV state has primarily a $\frac{3}{2}^+[411\uparrow]+\frac{5}{2}^+[413\downarrow]$ two quasiproton (i.e., one-phonon) nature. This configuration for the 1646 keV level is supported by the ^{154}Tb decay studies of Sousa *et al.*, who also suggest that there is significant mixing with the $K^{\pi}=2^+$ band at 996 keV.

VI. SUMMARY

We have studied excited states in ^{154}Gd populated in the decay of ^{154}Eu. New assignments and/or intensities for 40 γ rays and the population of three states in ^{154}Gd, which had not been previously observed in the decay of ^{154}Eu, provide sensitive measurements with which to probe the collective structure of ^{154}Gd. Stringent upper limits set on the intensities of 75 γ-ray transitions suggest the removal of at least 11 states assigned [2] to ^{154}Gd below 2 MeV, significantly changing the possible interpretations of collective structures above 1 MeV.

The resultant changes in the structure of ^{154}Gd above 1 MeV due to our experimental results contradicts the previous interpretation of robust multiphonon band structures. The search for a two-phonon structure in ^{154}Gd led to the introduction of states which we have shown to be spuriously assigned. Previous two-phonon interpretations of structures in ^{154}Gd, which we observe to be populated in the decay of ^{154}Eu, relied upon ratios of $B(E2)$ values and approximate agreement with expected excitation energies. Such an approach has been found to be misleading in light of the complementary data from other spectroscopic methods.

Multiple types of nuclear data have been used to discuss the structure of excited bands in ^{154}Gd populated in this study of the decay of ^{154}Eu. Two-nucleon transfer data [29] provided the key data for a new interpretation of the 0_3^+ band as a pairing isomer [22]. Single-nucleon transfer data [3,32] established the two-quasiparticle nature of the $K^\pi=4^+$ band at 1646 keV. Electric monopole components [12,37] of transitions out of the $K^\pi=2^+$ band at 1531 keV provided the first indication of band mixing which is supported by the systematic increases in transition electric quadrupole moments for $E2$ transitions out of the band.

A review of all available data at this time shows that only the $K^\pi=2_2^+$ band built on the 1531 keV state remains a possible multiphonon band. The ratios of relative $B(E2)$ values and $\rho^2(E0)$ values for γ rays to the "β" and "γ" bands below indicate that decay to these bands is somewhat preferred and the excitation energy is somewhat close to the expected energy of 1677 keV. This weak support for a multiphonon interpretation, however, does not prove that the 1531 keV level is indeed a coupled $\beta\gamma$ band. Measurement of absolute $B(E2)$ values for transitions out of this band (e.g., from lifetime measurements or extracted from multi-Coulex yields) would help determine whether or not this is a two-phonon excitation; but care must be exercised to consider the effects of shape coexistence and mixing indicated by the presence of $E0$ transitions and changes in transition quadrupole moments between bands.

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