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LEVEL STRUCTURE OF ^{154}Gd

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The decay of ^{154}Eu to ^{154}Gd has been studied using H. P. Ge and H. P. Ge-NaI(Tl) spectrometers in coincidence measurements. 141 gamma transitions have been observed. One of these transitions is found to be new and has an energy of 202.5 keV. The 165.9, 202.5, 229.8 and 484.6 keV transitions are placed correctly in the decay scheme of ^{154}Eu. The levels from this and previous work are compared with those calculated by means of the unified model.

1. Introduction

The decay of ^{154}Eu to ^{154}Gd has been studied early by Meyer [1]. Electron capture intensities to the excited states of ^{154}Sm were estimated using the log ft values of beta transitions to the corresponding states of ^{154}Gd. Hansen et al [2] and Ng et al [3] obtained the branching ratio of beta decay to the excited states of ^{154}Gd by beta ray measurements. The relative intensities of gamma rays in the decay of ^{154}Eu were measured by Yoshizawa [4]. Intensities of the 618 and 692 keV E0 transitions measured by Yamada et al [5] and the multipole mixing ratios of the 692.873 and 1005.0 keV transitions by Gupta et al [6] were used in the internal conversion and gamma ray intensity measurements by Iwata et al [7]. Angular correlation experiments were performed by Varnell et al [8] to determine the multipole mixing ratios of some transitions and several new gamma transitions were observed in ^{154}Gd. An experiment to measure the triple gamma ray directional correlation is employed to study the 723–873–123 cascade following the beta decay of ^{154}Eu by Lewis [9].

Although there is general agreement between the results of these authors, still there are some weak intensity transitions not known and/or not placed in the decay scheme of ^{154}Eu as well as doubted spin-parity assignments to some energy levels as reported by Helmer [10] in a recent publication of accumulated results. Accordingly, it was felt worthwhile to reinvestigate the gamma spectrum of ^{154}Gd following the beta decay of ^{154}Eu using a detector with better resolution (= 1.8 keV at 1.33 MeV). In addition, contributions due to gamma background spectra are highly eliminated since a complete quantitative analysis of gamma background radiations is available [11]. Another goal was to extend the comparison of the experimentally observed energy levels to those predicted by the unified model.

2. Experimental procedure

Several sources from different manufacturers have been used (ORTEC, USA, Isotope Products, Canada and French Atomic Energy Commission, France).

In the present work, successive gamma singles spectra have been investigated over a period of two years using different sources of activities ranging from 50 μC to 1 mC placed at different distances from the detector.

The gamma ray spectra over the range 80–2000 keV have been studied using an ORTEC p-type hyper pure Ge-detector. The detector active volume is 56.6 cc while its energy resolution is $\simeq$ 1.8 keV at 1.33 MeV. The obtained spectra were analysed using a NORLAND 4096 multi-channel analyzer (MCA) model 5400 with data processor, model 5430, and an IBM-XT personal computer equipped with a Nucleus 8192 MCA plug-in card.

The system was calibrated for energy and photopeak efficiency using well-known standard sources (^{22}Na, ^{60}Co, ^{133}Ba, ^{137}Cs and ^{266}Ra).

The gamma–gamma coincidence measurements were performed using a 3″×3″ NaI(Tl)-Ge fast-slow coincidence spectrometer. The time resolution of the fast coincidence pulse was about 20 ns. A triple slow coincidence pulse (time resolution 0.5 μs), was used to gate the MCA to obtain the coincidence spectra.

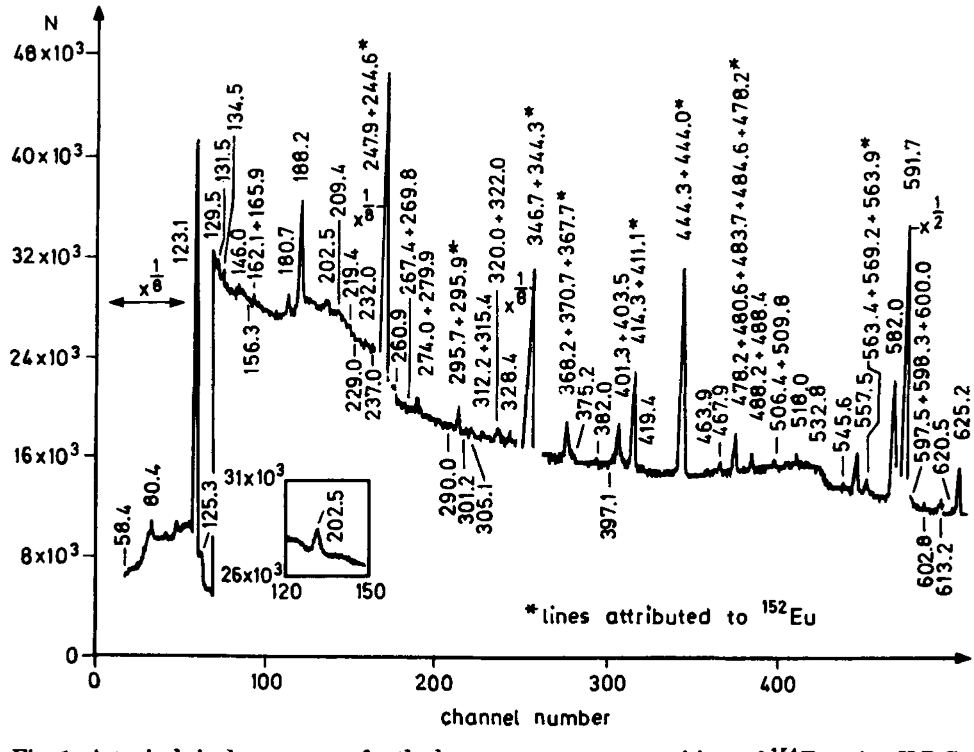

Fig. 1. A typical singles spectrum for the low energy gamma transitions of ^{154}Eu using H.P.Ge-detector where the source activity was 50 μC, source-to-detector distance was 15 cm and the measuring time was 20 h

3. Gamma-ray singles spectra

The analysis of the gamma ray spectra observed in our measurements has revealed the existence of 141 gamma transitions attributed to the decay of ^{154}Eu. Their energies and intensities, together with the previous data [7,10] are listed in Table I. The intensities were normalized to 100 for the 1247 keV gamma ray. Successive measurements were undertaken within two years to differentiate between lines of different origins. One of the gamma transitions at energy 202.5 keV is found to be new and the reduction rate of its intensity is similar to the activity decay rate of ^{154}Eu. The intensities of the 563.4, 680.0 and 801.2 keV transitions which were not known previously are estimated in the present work as shown in Table I. A typical gamma-singles spectrum of the low energy transitions is shown in Fig. 1 where the 202.5 keV gamma transition is clearly visible.

4. Gamma–gamma coincidence measurements

Gamma–gamma coincidence measurements have been performed using several window sets; only the results from three window sets are considered. These windows are: 125–185, 200–270 and 560–625 keV. There are fourteen gamma transitions not placed in the level scheme of ^{154}Gd [10]. Three of these at energies 165.9, 229.8 and 484.6 keV are placed correctly in the level scheme by means of our measurements.

To confirm the placement of the 165.9 keV transition between the 1293.3 and 1127.8 keV levels, the 131.5 keV transition depopulating the 1127.8 keV level was selected as gating transition because of two reasons worth mentioning. First, the 125–185 gate is pure from any contributions due to ^{152}Eu. Furthermore, the most intense 756.8 and 1004.7 keV transitions depopulating the 1127.8 keV level are not suitable as gating transitions because they are very close to other γ-transitions attributed to ^{152}Eu decay. The obtained spectra confirm the presence of the 165.9 keV transition as is obvious in Fig. 2.

The 229.8 and 484.6 keV transitions were proposed to populate the 1047.5 keV level. The 232.0 keV transition depopulating the 1047.5 keV level was chosen as a gating transition. Fig. 2 shows a typical coincidence spectrum gated by the energy window 200–270 keV. The analysis of the obtained spectra confirms the existence of these two transitions populating the 1047.5 keV level.

The new observed 202.5 keV transition was proposed to populate the 1415.0 keV level. The most intense lines depopulating the 1415.0 keV level are the 600.0 and 1292.0 keV transitions. The 1292.0 keV transition is close to the high intense 1299.1 keV transition attributed to ^{152}Eu decay, hence, the 600.0 keV transition was chosen as a gating transition (gate 560–625 keV). Fig. 2 shows an example of the obtained spectra which confirms the position of the 202.5 keV transition between the 1617.1 and 1415.0 keV levels.

Table I
Energy and intensity values for gamma transitions in ^{154}Gd following β^--decay of ^{154}Eu

Present work				Helmer [10]				Iwata [7]		
E_γ		I_γ		E_γ		I_γ		E_γ	I_γ	
58.40	10	0.012	10	58.4		0.0113	11	–	–	
80.40	12	0.010	6	80.4		0.008	4	–	–	
123.10	8	117.54	30	123.068	3	117.5	8	123.1	118.5	12
125.35	16	0.02	1	125.39		0.020	6	–	–	
129.52	13	0.04	1	129.5		0.039	5	–	–	
131.5	1	0.03	1	131.573	29	0.0310	11	–	–	
134.56	20	0.02	1	134.84		0.0203	11	–	–	
146.04	10	0.070	16	146.036	22	0.0733	28	–	–	
156.3	1	0.032	12	136.31	10	0.0282	11	–	–	
162.11	18	0.003	1	162.09		0.0028	14	–	–	
165.90	21	0.007	1	165.91		0.0065	14	–	–	
180.75	11	0.015	6	180.73		0.0127	28	–	–	
188.22	15	0.668	8	188.246	13	0.676	22	–	–	
202.50	16	0.08	2	–		–		–	–	
209.42	12	0.007	1	209.4	4	0.0068	23	–	–	
219.4	1	0.007	1	219.4		0.0065	25	–	–	
229.01	13	0.006	2	229.0		0.0056	22	–	–	
231.03	6	0.071	9	232.01	5	0.0677	28	–	–	
237.0	3	0.020	7	237.0		0.017	11	–	–	
247.95	17	19.9	1	247.932	15	19.87	9	248.0	19.91	13
260.92	12	0.006	1	260.9		0.0056	25	–	–	
267.41	11	0.04	1	267.44		0.0395	17	–	–	
269.82	16	0.020	6	269.8		0.0197	28	–	–	
274.0	4	0.013	5	274.0	5	0.0113	6	–	–	
279.91	21	0.009	2	279.9		0.0085	6	–	–	
290.0	3	0.011	3	290.0		0.0096	6	–	–	
295.72	12	0.007	1	295.7		0.0068	6	–	–	
301.2	2	0.035	15	301.25		0.0282	11	–	–	
305.12	13	0.05	1	305.12		0.0496	20	–	–	
312.23	18	0.042	10	312.28		0.0415	17	–	–	
315.42	15	0.015	8	314.42		0.0130	6	–	–	
320.0	1	0.003	1	320.0	1	0.0028	20	–	–	
322.02	11	0.19	1	322.01	5	0.189	8	–	–	
328.4	3	0.026	9	322.48		0.0259	14	–	–	
346.71	14	0.085	10	346.72	5	0.085	3	–	–	
368.20	11	0.010	9	368.21		0.0085	6	–	–	
370.72	8	0.015	4	370.71		0.015	4	–	–	
375.20	9	0.005	2	375.2	5	0.0051	28	–	–	
382.02	15	0.03	1	382.00	5	0.0285	11	–	–	
397.12	23	0.09	2	397.14		0.085	3	–	–	
401.36	22	0.61	8	401.30	5	0.56	3	–	–	
403.57	9	0.071	11	403.55	5	0.076	3	–	–	
414.32	8	0.015	8	414.30		0.0141	8	–	–	
419.4	1	0.015	6	419.4		0.011	6	–	–	
444.38	7	1.62	5	444.39	4	1.60	3	444.5	1.63	3
463.93	19	0.014	5	463.9		0.0121	6	–	–	

Table I (cont.)

Present work				Helmer [10]				Iwata [7]		
E_γ		I_γ		E_γ		I_γ		E_γ	I_γ	
467.90	12	0.165	9	467.92		0.161	6	–	–	
478.25	7	0.625	27	478.26	5	0.612	14	478.3	0.626	27
480.62	12	0.015	4	480.61		0.0138	6	–	–	
483.75	15	0.016	3	483.74		0.0141	8	–	–	
484.63	9	0.012	4	484.64		0.0113	6	–	–	
488.40	11	0.021	6	488.26		0.020	8	–	–	
506.4	2	0.019	4	506.4		0.017	6	–	–	
509.9	2	0.11	3	509.88		0.103	4	–	–	
518.0	1	0.135	4	518.00	5	0.132	5	–	–	
532.88	10	0.04	1	532.84		0.031	6	–	–	
545.6	1	0.05	1	545.6		0.047	6	–	–	
557.5	2	0.75	2	557.56	5	0.741	17	557.6	0.758	24
563.40	7	0.008	2	563.4		–		–	–	
569.20	7	0.03	1	569.23		0.0282	11	–	–	
582.0	1	2.62	2	582.00	5	2.60	3	582.0	2.61	3
591.70	11	14.30	18	591.76	3	14.29	6	591.7	14.35	6
597.5	1	0.020	6	597.5		0.0158	8	–	–	
598.30	9	0.015	4	598.31		0.0172	8	–	–	
600.0	1	0.017	2	600.0		0.017	11	–	–	
602.8	2	0.10	3	602.81	5	0.096	4	–	–	
613.22	16	0.281	12	613.26	5	0.267	10	–	–	
620.5	1	0.031	2	625.22	5	0.925	21	625.2	0.927	21
642.41	8	0.012	3	642.4		0.011	6	–	–	
649.4	1	0.22	2	649.44	5	0.214	8	–	–	
650.62	9	0.030	4	650.6		0.0282	11	–	–	
664.63	10	0.08	2	664.68	5	0.082	3	–	–	
668.9	2	0.035	4	668.9		0.034	4	–	–	
676.52	9	0.440	5	676.59	5	0.395	12	676.5	0.47	5
680.0	2	0.010	3	680.0		–		–	–	
692.41	7	5.183	17	692.42	4	5.182	25	692.4	5.182	25
715.76	3	0.49	1	715.76	5	0.494	15	–	–	
722.30	5	55.10	5	722.30		55.09	21	723.2	58.19	21
756.83	6	13.11	5	756.86	3	13.09	9	756.8	13.18	7
774.41	5	0.03	1	774.4		0.028	14	–	–	
790.13	4	0.032	6	790.12		0.031	8	–	–	
800.2	1	0.10	2	800.2		0.092	14	–	–	
801.21	4	0.035	7	801.2		–		–	–	
815.56	8	1.45	2	815.55	5	1.46	7	815.5	1.51	5
845.35	5	1.70	6	845.39	5	1.687	21	845.4	1.687	21
850.66	4	0.657	6	850.64	5	0.668	15	850.7	0.692	23
873.2	1	35.15	9	873.20	3	35.14	10	873.1	35.18	12
880.60	5	0.25	3	880.61	5	0.231	9	–	–	
892.73	5	1.45	3	892.73	5	1.44	4	892.8	1.497	26
898.3	1	0.006	2	898.37		0.0056	14	–	–	
904.05	5	2.46	4	904.05	5	2.47	9	904.1	2.62	3
906.15	7	0.035	5	906.1		0.0338	14	–	–	
919.25	6	0.031	7	919.24		0.0352	14	–	–	
924.5	1	0.17	2	924.49	5	0.166	7	–	–	

Table I (cont.)

Present work				Helmer [10]				Iwata [7]			
E_γ		I_γ		E_γ		I_γ		E_γ		I_γ	
981.36	5	0.02	1	981.3		0.022	6	–		–	
984.5	2	0.020	4	984.5		0.0180	34	–		–	
996.35	7	30.10	3	996.30	3	30.07	12	996.2	12	30.09	12
1004.75	9	52.1	1	1004.76	3	52.03	19	1004.7		52.04	19
1012.8	2	0.008	2	1012.8	2	0.0082	34	–		–	
1023.0	2	0.021	4	1023.0	10	0.020	8	–		–	
1033.07	9	0.034	3	1033.4		0.0338	14	–		–	
1047.43	12	0.15	3	1047.4	1	0.141	6	–		–	
1049.40	8	0.05	2	1049.4	1	0.0493	20	–		–	
1110.0	2	0.010	6	1110.0		0.008	6	–		–	
1118.52	14	0.30	3	1118.5	1	0.290	9	–		–	
1124.22	18	0.020	6	1124.2		0.0197	28	–		–	
1128.44	8	0.85	5	1128.4	1	0.85	6	1128.5		0.90	4
1136.15	7	0.022	4	1136.1		0.0211	28	–		–	
1140.92	6	0.64	3	1140.9	1	0.638	20	1140.7		0.671	14
1153.14	11	0.04	1	1153.1	5	0.039	11	–		–	
1160.6	2	0.125	12	1160.6		0.124	5	–		–	
1170.0	5	0.015	6	1170.0	5	0.012	6	–		–	
1188.63	8	0.26	5	1188.6		0.251	20	–		–	
1232.11	14	0.03	1	1232.1	5	0.026	17	–		–	
1241.65	12	0.40	3	1241.6	2	0.366	11	1241.4		0.38	5
1246.60	11	2.35	7	1246.6	2	2.33	15	1246.2		2.49	4
1274.55	10	100.00	3	1274.51	7	100.0	5	1274.4		100.00	3
1290.0	1	0.03	1	1290.0	2	0.0324	14	–		–	
1292.06	8	0.04	1	1290.0	2	0.0369	14	–		–	
1295.58	30	0.029	11	1295.5	2	0.0254	28	–		–	
1387.07	11	0.06	2	1387.0	5	0.056	6	–		–	
1400.0	3	0.00	2	1400.0		0.0084	28	–		–	
1408.44	12	0.06	2	1408.4	2	0.059	8	–		–	
1415.03	7	0.015	6	1415.0	5	0.0113	6	–		–	
1418.6	2	0.024	7	1418.6	2	0.0208	11	–		–	
1419.06	12	0.006	2	1419.0		0.0056	3	–		–	
1425.66	20	0.004	1	1425.6	6	0.0036	22	–		–	
1490.26	15	0.007	2	1490.2		0.0084	14	–		–	
1494.0	2	2.10	11	1494.08	7	2.058	16	1494.4		2.058	16
1510.0	2	0.015	4	1510.0	5	0.0141	28	–		–	
1522.1	2	0.002	1	1522.0	10	0.0017	8	–		–	
1531.44	12	0.020	7	1531.4		0.0172	11	–		–	
1537.85	15	0.15	3	1537.8		0.141	6	–		–	
1596.50	6	5.25	2	1596.45	7	5.247	26	1596.7		5.247	26
1667.33	12	0.006	2	1667.3		0.0056	8	–		–	
1673.17	21	0.004	1	1673.6		0.0039	11	–		–	
1716.9	2	0.002	1	1716.9		0.0017	10	–		–	
1773.13	23	0.0010	4	1773.0	10	0.0008	6	–		–	
1838.0	2	0.003	1	1838.0	5	0.0022	6	–		–	
1895.18	13	0.0020	6	1895.0	10	0.0017	6	–		–	

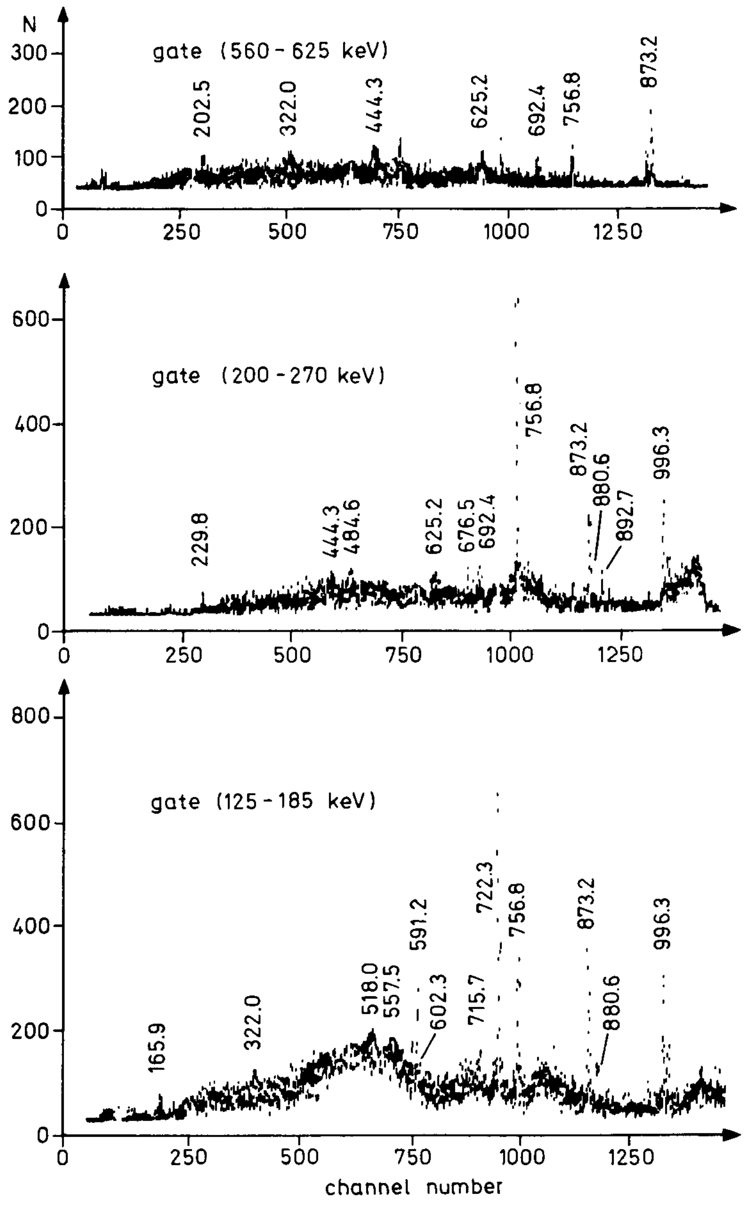

Fig. 2. **Gamma–gamma coincidence spectra using NaI(Tl)-Ge detectors**

The results of the present work have been used to construct a partial level scheme of ^{154}Gd as shown in Fig. 3.

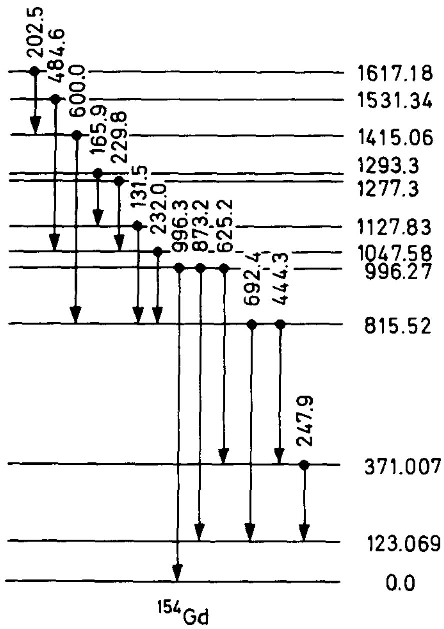

Fig. 3. Partial level scheme of ^{154}Gd

5. Analysis of the ^{154}Gd energy bands

The analysis of the spectra of strongly deformed nuclei is based on the collective model [12]. In lowest order the energy spacing in a rotational band is predicted to follow an $I(I+1)$ progression. First order corrections are attributed to Coriolis interaction, non-axial symmetry of the deformed rotor, or rotation–vibration interaction. A systematic deviation from the rotational spectrum [13] is noted. This deviation can be explained by adding correction terms to the energy representing different modes of coupling. This coupling contributes to a change in the energy given by last terms in the energy relation

$$E_{I,K} = E_k + AI(I+1) + BI^2(I+1)^2 + \ldots \\ + (-1)^{I+k}\frac{(I+k)!}{(I-k)!}[(A_{2k} + B_{2k}I(I+1) + \ldots].$$

The energy spectra for ten bands are calculated and the set of parameters which yielded the best fit to the data by means of the foregoing energy relation are adopted for every band.

5.1. Positive parity bands

A. The $k^{\pi} = 0^{+}$ ground state, $k^{\pi} = 0^{+}$ β-vibrational, $k^{\pi} = 2^{+}\gamma$-vibrational bands

The regular spacing of energy levels of these bands indicates that they are rotational bands with fitting parameters $E_k = 58.0427$, $A = 15.14$ and $B = -0.01$ for the ground state band, $E_k = 747.7$, $A = 11.328$ and $B = -0.0045$ for the β-vibrational band, $E_k = 897.766$, $A = 19.583$, $B = -0.0615$ and $A_{2k} = -0.00295$ for the γ-vibrational band.

B. The $k^{\pi} = 0^{+}$ band

This band was proposed to consist of levels at (0^+)1294.93, (2^+)1418.35, (4^+)1698.0 keV. The fitting parameters are $E_k = 1294.93$, $A = 20.74$ and $B = -0.02975$. The observed level spacings indicate extreme agreement with our calculation. The calculated energy of the 6^+ member of this band is 2113.888 keV which corresponds to the 2101.0 keV level observed in (d, d') reaction and/or the 2117.1 keV level observed in ^{154}Sm$(\alpha, 4n\gamma)$ and ^{152}Sm$(\alpha, 2n\gamma)$ reactions [14].

C. The $k^{\pi} = 2^{+}$ band

The energy levels (2^+)1531.318, (3^+)1660.9, (4^+)1790.2 keV were proposed members of this band. The level spacing in this band can now be described by the parameters $E_k = 1531.3$, $A = 28.6$ and $B = -0.39$. The 5^+ member of this band is found to have an energy of 2038.3 keV. This may correspond to the 2040.5 keV level observed in (α, α') reaction [14].

D. The $k^{\pi} = 4^{+}$ band

This band is used on the configuration ((π3/2 [411]) (π5/2 [413])) and was proposed to consist of levels at 1645.8, 1770.19, 1911.54, 2073.2 and 2253.99 keV with spin sequence 4–8. The observed level spacings indicate excellent agreement with our calculations where the fitting parameters are $E_k = 1405.855$, $A = 12.4064$, $B = -0.008728$ and $A_{2k} = 0.6 \times 10^{-8}$. The calculated energy of the 10^+ member of this band is 2665.6778 keV which may correspond to the 2668.3 keV level observed in nuclear reactions [14].

5.2 Negative parity bands

A. The $k^{\pi} = 0^{-}, 2^{-}, 7^{-}$ bands

The 0^- octupole-vibrational band was proposed to consist of levels at 1241.31, 1251.75, 1404.2, 1674.6, 2040.5 and 2482.2 keV with spin sequence 1–11. The 2^- octupole-vibrational band was proposed to consist of (2^-)1719.565, (3^-)1796.45, (4^-)1861 keV levels while the 7^- band consists of (7^-)2137.49, (8^-)2309.47 and (9^-)2474.1 keV levels. Calculations of energy levels using the foregoing formula were done for these three negative bands. All the experimental levels attributed to each band were considered. It is noticed that this formula failed to determine the expected energy values for these bands. This may be due to the vibrational nature of these bands.

B. The $k^{\pi} = 1^-$ band

The (2^-)1347.559, (1^-)1414.6, (4^-)1560.09 and (3^-)1617.14 keV levels were proposed to be the members of this band. The calculated energy levels are in excellent agreement with the experimental values where the fitting parameters are $E_k = 1385.639$, $A = 6.308$, $B = 0.4811$ and $A_{2k} = 7.209$. The large value of A_{2k} is due to the strength of the Coriolis coupling.

6. Conclusion

In this work an attempt has been made making use of good resolution detectors to study the energy spectra of ^{154}Eu–β^- decay. A new transition is observed and placed correctly in the decay scheme. Also, the 165.9, 229.8 and 484.6 keV transitions are placed in the decay scheme by means of our $\gamma - \gamma$ coincidence measurements for the first time. Furthermore, the unified model calculations were applied to ten energy bands attributed to the ^{154}Gd level scheme. A good agreement is noticed between experimental and theoretical calculations for positive parity states giving a correct prediction for the already adopted levels and assigning the spin–parity character of some higher levels. Contrary to that, a disagreement is found between experimental and theoretical calculations for the negative parity bands (expect the $k = 1^-$ band) and the applied model is not suitable because of the vibrational nature of these bands.

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