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DECAY OF ^{159}Gd

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Abstract

The gamma-ray spectrum of ^{159}Tb following the β^--decay of ^{159}Gd has been studied through gamma spectroscopy. A new branch in the ^{159}Gd decay has been evidenced through the observation of two new gamma transitions with 273.6 keV and 753.8 keV attributed to ^{159}Tb. A level with 891.3 keV belonging to ^{159}Tb has been observed for the first time by following the ^{159}Gd decay. Four gamma transitions previously attributed to this decay were not confirmed.

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I. INTRODUCTION

In the 60's and earlier 70's several experiments were performed to obtain a comprehension of the low-energy excited states of the deformed nucleus ^{159}Tb. Studies were carried out on the ^{159}Gd β^--decay [1–4], ^{159}Dy β^+-decay [5], proton-transfer reactions [6,7], two-neutrons capture reactions [8], Coulomb excitation [9], Mössbauer effect [10,11] and paramagnetic resonance [12]. In the 80's the interest in the behavior of nuclei at high angular momentum motivated studies of the ^{159}Tb high spin states which were populated in Coulomb excitation [13–15]. Also in the 80's Janabi et al. [16] and Darwish et al. [17] performed experiments of neutron inelastic scattering on ^{159}Tb and β^--decay of ^{159}Gd, respectively. In the recent

review of Lee [18] the changes in the decay of ^{159}Gd suggested by Darwish et al. [17] have not been included.

A carefull analysis of the published data shows discrepancies in the assignments of some of the low-energy excited levels of ^{159}Tb. The interest in solving these discrepancies motivated us to employ the facilities of our laboratory to perform a reinvestigation of the ^{159}Gd decay using methods of gamma spectroscopy.

II. EXPERIMENTAL PROCEDURE

The ^{159}Gd sources were prepared in the reactor of the *Instituto de Pesquisas Energéticas e Nucleares* (IPEN - São Paulo) by irradiating samples of metallic gadolinium enriched to 97.8% in ^{158}Gd in a flux of 10^{13} neutrons·cm^{-2}·s^{-1}. Single and gamma-gamma coincidence spectra were taken in off-line measurements.

The single spectra were taken using a HPGe coaxial detector with active volume of 59 cm^3 (resolution of 1.35 keV for the 662 keV transition of ^{137}Cs) and a 572-ORTEC amplifier in pile-up rejection mode. The background radiation was diminished by employing the same iron shield described by Vanin et al. [19] A multi-step procedure for the energy calibration was employed to obtain high accuracy in the energy determination (see Appendix).

Two experiments of gamma-gamma coincidence were carried out with the same detector used in the single experiment. In the first one, the other detector was a 61 cm^3 coaxial Ge(Li) and the time resolution obtained in the energy range from 100 keV to 1 MeV was 10 ns. In the second experiment we used a 40 cm^3 coaxial HPGe with Berillium window (ORTEC LOAX-serie) and the time resolution was 25 ns in the energy range from 30 keV to 1 MeV. In both experiments the detectors were placed at 90° and each of them was shielded with 1 cm lead to avoid coincidence events due to Compton scattered gamma-rays. Two time windows were chosen in a conventional fast-slow coincidence circuit, one for "true" and the other for random coincidences. Three parameters (energies of both detectors and type of coincidence) were recorded on magnetic tape. The method of analysis was the same a described by Brown et al. [4]

III. MEASUREMENTS AND RESULTS

A. Single spectra

The single spectra of four sources of ^{159}Gd were recorded during 96 hours of live counting time. The spectrum is shown in Fig. 1. Twenty one transitions were attributed to the decay of ^{159}Gd. Their energies and intensities compared with the values publicated by Darwish et al. [17] and Brown et al. [4] are listed in Table I. Very precise energy values were obtained using the least squares method, taking into account all data covariances, as described in the Appendix.

Two transitions with energies 273.6 keV and 753.8 keV were observed for the first time belonging to the ^{159}Gd decay. Four transitions with energies 246.5 keV, 269.0 keV, 371.0 keV and 429.1 keV which were attributed to this decay by Darwish et al. [17] were not confirmed, although the present experiment has achieved better observation limits. The upper limits for intensities were calculated following Helene's prescription [20] for a 95% confidence level.

The peak at 274 keV, presented as a singlet in previous works, is in fact a doublet. To prove this we adjusted the squared FWHM as a linear function of the energy using five singlets in the energy range from 226 keV to 348 keV (see Fig. 2). The FWHM of the 274 keV peak fitted as a singlet was greater than three times the standard deviations from the expected value, allowing us to reject the hypotheses that this peak is a singlet. Fitting the 274 peak as a doublet, constraining the width according to the linear function showed in Fig. 2, the energies obtained were 273.62(12) keV and 274.164(18) keV.

The transition with 753.8 keV together with the one with 273.6 keV could be ordered in the accepted level scheme of ^{159}Tb. The energy values permitted us to interpret them as transitions that depopulate a level with 891.3 keV, as we will see forward.

A transition with 479.85(6) keV and half-life of 16(5) hours is present in our spectra but couldn't be interpreted as belonging to contaminants or background. We tried to assign it as a transition between the 617.6 keV and 137.5 keV levels, but the difference of 0.26 keV (four standard deviations) discarded this interpretation. We nevertheless include it as a ^{159}Tb transition in Table I since it occurs in coincidence with Tb X-rays (see below).

B. Gamma-gamma coincidence spectra

The counting time for the gamma-gamma coincidence experiments were 240 hours with the first detector combination and 140 hours with the second one. A summary of the coincidences for several gates is shown in the Table II. The existence of the three new transitions observed in the single spectra was confirmed in the coincidence measurements. None of the four new transitions observed by Darwish et al. [17] was present in our coincidence spectra.

Figures 3(a) and 3(b) show the gamma spectra in coincidence with gates at 581 keV and 559 keV, respectively. The 274.2 keV transition appears in coincidence with the 581 keV transition only, while the gate at 559 keV reveals coincidences with the 237.3 keV transition and with the new one at 273.6 keV.

The gates at 618 keV and 274 keV are consistent with the ones shown in Figs. 3(a) and 3(b), as one can see in Table II. These results reinforce the suggestion of a new feeding of the 618 keV level through the 273.6 keV transition, as shown in the previous section.

The new transitions with 753.8 keV and 479.8 keV didn't appear in coincidence with the gates at 58 keV and 80 keV due to their low intensity. Though we found them in coincidence with the X-ray of Tb, whose main contributions come from the 58 keV and 80 keV electron conversion (the internal conversion coefficients are 11.0 and 4.37, respectively [18]).

IV. ^{159}GD DECAY SCHEME

The ^{159}Gd decay scheme proposed in this work is shown in Fig. 4. The *logft* values were evaluated using the tables of Gove and Martin [21]. The intensity of the beta feeding to the ground state - 62(9)% - and the Q-value - 970.8(12) keV - were extracted from Lee

[18]. The energies of the levels were obtained through a least square fit using the twenty transitions that could be ordered in the scheme.

The observation of new transitions with 273.6 keV and 753.8 keV in the single and coincidence spectra permitted us to place a level with 891.3 keV in the ^{159}Tb level scheme. These two transitions depopulate the new level to known levels with 617.6 keV and 137.5 keV. According to the obtained $logft = 8.0$, the classification for the β^--transition is allowed hindered or first forbidden. The ground state of ^{159}Gd has spin 3/2, fact that limits the possible spins for the 891.3 keV level to 1/2, 3/2, 5/2 or 7/2. A $J\pi = 7/2-$ assignment is not probable since it would imply in a second forbidden beta-transition. The observation of gamma-transitions from this level to levels with $J\pi = 3/2+$ and $7/2+$ discards the $J\pi = 3/2-$ assignment because it would imply in an improbable competition between E1 and M2 transitions, and the spin 1/2. The remaining possibilities of $J\pi$ assignment for the new level are 3/2+, 5/2+, 7/2+ and 5/2−.

Most of the ^{159}Tb levels observed in the ^{159}Gd decay are already classified and complete discussions about them can be found in the works of Hill and Wiedenbeck [3] and Tippett and Burke [7], for instance. Besides the new level, there is only the level with 855.0 keV which has uncertain classification [18], but probably has spin 1/2.

Assuming the most probable assignment for the spin of the 855.0 keV level as J= 1/2 [3,7], the Nilsson's orbitals for deformation parameter $\delta = 0.3$ that could explain this level are the $1/2 + [411]$ and $1/2 - [541]$. But one expects to find the $1/2 + [411]$ orbital at lower energy and the best candidate to explain it is the 580.8 keV ($J\pi = 1/2+$) level, as reported by Lee [18]. The remaining interpretation for the 855.0 keV level is as belonging to the $1/2 - [541]$ orbital. According to our results we have to choose $J\pi$-values between 3/2+, 5/2+, 7/2+ and 5/2− for the new level. Looking at the Nilsson's scheme once more and comparing it with the orbitals already assigned to ^{159}Tb [18], we find the most probable interpretation for this level as being the $J\pi = 5/2-$ member of the band $1/2 - [541]$. In this interpretation, which agree with Tippet and Burke [7] and Boyno and Huizenga [6], this new level observed in the decay of ^{159}Gd should be the same level that these authors reported

with energy values of 890(2) keV and 893(3) keV, respectively.

Assuming this interpretation one could question why we didn't observe the eletromagnetic transitions to the levels 3/2+ and 5/2+ of the ground-state rotational band. Using the rotational model without band admixture, simple calculations have been performed to obtain the relative intensities between the observed 753.6 keV transition to the 7/2+ level and the supposed transitions with 891.3 keV and 833.1 keV to the 3/2+ and 5/2+ levels, respectively. The results indicate that the intensity of the transition to the 3/2+ level would be 0.2 times the intensity of the observed 753.6 keV transition, explaining why it was not observed in our spectra. For the supposed transition to the 5/2+ level, the calculated intensity would be 1.3 times the intensity of the 753.6 keV transition, and we could have observed it. But one must notice that Coriolis coupling effects can produce large deviations of the Alaga's rules [22]. A good example can be taken in the ^{159}Tb itself, whose transitions between the 363.5 keV ($J\pi = 5/2-$) level and the levels of the ground-state band seem to be very supressed if compared with theoretical predictions using the Nilsson model [23], mainly the transition to the 5/2+ level. But to obtain more conclusive answers detailed theoretical calculations are needed.

V. SUMMARY

The ^{159}Gd β^--decay has been revised by following the gamma-ray emission of ^{159}Tb. Two new gamma transitions have been included in the ^{159}Tb scheme and the existence of a new branch for the ^{159}Gd beta-decay has been established. A level with 891.3 keV belonging to ^{159}Tb has been evidenced for the first time through the ^{159}Gd β^--decay. The results of the present work support the suggestion for the classification of this level given by other authors.

VI. ACKNOWLEDGMENTS

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VII. APPENDIX

In the energy calibration performed in this work, eight calibration spectra have been aken with standard sources of ^{133}Ba (four spectra) and ^{152}Eu (four spectra) simultaneously vith the source of ^{159}Gd. The procedure of measuring both sources together eliminates part f the systematic errors, since the peaks of both sources are affected simultaneously. By epeating several times the measurement of the same spectrum the statistical errors become maller. It is better to repeat the measurement than to measure a longer time because gain nd zero level fluctuations tend to increase with increasing counting time and because the itting programs do not fit well peaks with very large areas.

From the eight calibration spectra the least-square method has been applied to interpoate the strongest lines belonging to the ^{159}Gd decay (58 keV, 79 keV, 226 keV, 290 keV, 05 keV, 348 keV, 363 keV, 560 keV, 581 keV, 617 keV and 855 keV) and the line of 842 eV of ^{152m}Eu (9 h.) which was present as contamination. The energy was assumed to be a econd degree polynomial of the channel number. The energy values of the ^{133}Ba and ^{152}Eu, rom 53 keV up to 1112 keV were taken from the tables of A. Lorentz [24]. The 964 keV

transition of ^{152}Eu was discarded in the calibration due to disagreement between different references (see Ref. [25]). In this step the reduced chi-square obtained was 1.10 with 68 degrees of freedom.

The energy values of the strongest transitions cited above have been averaged taking into account the covariances, and the results have been used later in a calibration for the sum of all spectra taken with the source of ^{159}Gd without the standard sources. The final energies of all transitions belonging to the ^{159}Gd have been taken from this last calibration. The reduced chi-square obtained in this "self-calibration" was 0.97 with 9 degrees of freedom.

In the next step a least-squares calculation to check the consistency with the cascade-crossover of the decay scheme was performed. The reduced chi-square obtained was 1.64 with 11 degrees of freedom.

It should be stressed that whenever possible all covariances have been taken into account until the final result. Only the covariances between the energy values of the standard sources have not been considered because they are not published.

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FIGURE CAPTIONS

Fig. 1. Gamma-ray spectrum following the ^{159}Gd decay. The contaminants and the nergies of the ^{159}Tb transitions are labelled. The upper and lower energy scales correlate ith the upper and lower spectra, respectively. Energy/channel ratio: 0.30 keV/channel.

Fig. 2. Fit of the squared FWHM for singlets in the range from 226 keV to 348 keV.

Fig. 3. Gamma-ray coincidence spectrum with gates at 581 keV (a) and 560 keV (b). nergy/channel ratio: 0.35 keV/channel.

Fig. 4. Decay scheme of ^{159}Gd. The *logft* values were calculated according to Gove and 1artin [21].

TABLE CAPTIONS

Table I. Energies and intensities of the gamma-rays following the ^{159}Gd decay.

Table II. Summary of the gamma-gamma coincidences in the ^{159}Gd decay.

TABLES

TABLE I.

Energy	Relative Intensity		
(keV)	this work	reference [17]	reference [4]
58.9998(15)	18.9(9)	19.1(8)	21(2)
79.5131(18)	0.417(11)	0.37(6)	0.38(4)
137.515(4)	0.0550(13)	0.05(1)	0.06(1)
210.7828(24)	0.178(4)	0.16(3)	0.165(25)
226.0405(11)	1.89(4)	1.80(4)	1.96(10)
237.341(4)	0.0652(14)	0.059(12)	0.072(11)
246.5(3)[a]	< 0.0008[b]	0.012(7)	—
269.0(3)[a]	< 0.0004[b]	0.013(9)	—
273.62(12)	0.0065(25)	—	—
274.163(18)	0.0478(25)	0.056(11)	0.054(13)
290.2864(15)	0.275(5)	0.23(5)	0.28(3)
305.5491(11)	0.527(10)	0.51(2)	0.55(4)
348.2807(10)	2.05(4)	1.99(8)	2.00(15)
363.5430(10)	100	100	100(5)
371.0(5)[a]	< 0.0003[b]	0.006(4)	—
429.1(5)[a]	< 0.0003[b]	0.005(4)	—
479.84(6)[c]	0.00206(19)	—	—
536.730(11)	0.0137(4)	0.018(9)	0.010(3)
559.623(5)	0.187(6)	0.19(2)	0.20(2)
580.809(5)	0.578(19)	0.60(4)	0.57(4)
616.234(17)	0.0159(7)	0.016(6)	0.020(5)
617.616(7)	0.134(5)	0.15(3)	0.13(2)
674.26(5)	0.00263(20)	<0.008	0.0034(10)

753.74(6)	0.00153(17)	—	—
854.948(19)	0.0212(18)	0.020(6)	0.021(3)

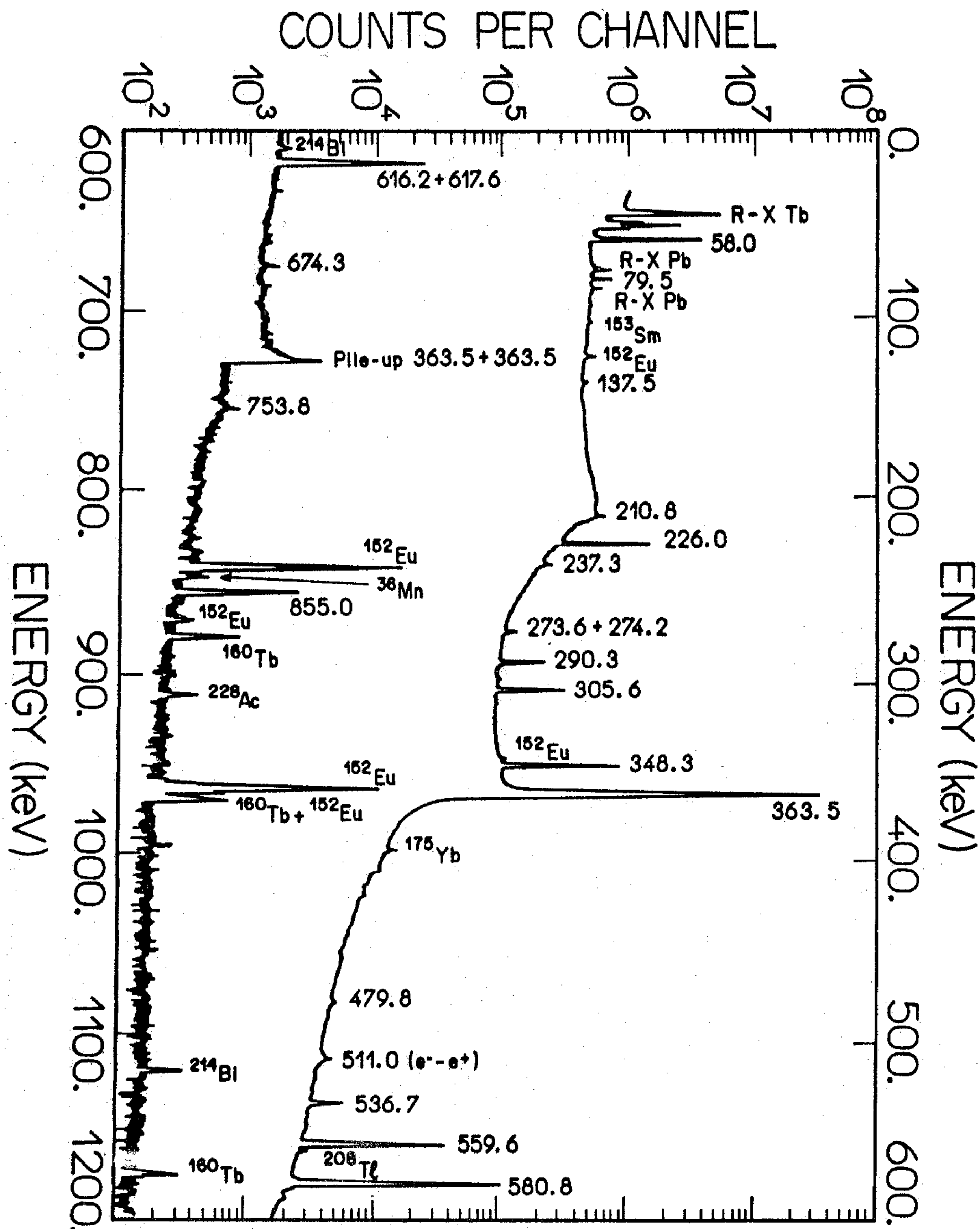
a. Extracted from Darwish et al. [17]

b. A transition with an intensity larger than the quoted value has 95% probability of detection in our spectra but was not observed.

c. Transition with half-life compatible with the ^{159}Gd decay but couldn't be included in the known level scheme of ^{159}Tb.

TABLE II.

Gate(keV)	Gammas in coincidence (keV)
X-ray K_α	58.0, 79.5, 210.8, 226.0, 290.3, 305.6, 479.8, 536.7, 559.6, 616.2, 753.8
58	79.5, 210.8, 226.0, 290.3, 305.6, 559.6
80	58.0, 210.8, 226.0, 536.7
137	210.8, 226.0, 536.7
237	559.6, 617.6
273.6 + 274.2	559.6, 580.8, 617.6
560	237.3, 273.6
581	274.2
616.2 + 617.6	58.0, 237.3, 273.6



COUNTS PER CHANNEL
ENERGY (keV)
ENERGY (keV)
R-X Tb
58.0
R-X Pb
79.5
R-X Pb
153Sm
152Eu
137.5
210.8
226.0
237.3
273.6 + 274.2
290.3
305.6
152Eu
348.3
363.5
175Yb
479.8
511.0 (e⁻-e⁺)
536.7
559.6
208Tℓ
580.8
214Bi
616.2 + 617.6
674.3
Pile-up 363.5 + 363.5
753.8
152Eu
56Mn
855.0
152Eu
160Tb
228Ac
152Eu
160Tb + 152Eu
214Bi
160Tb

Figure 1

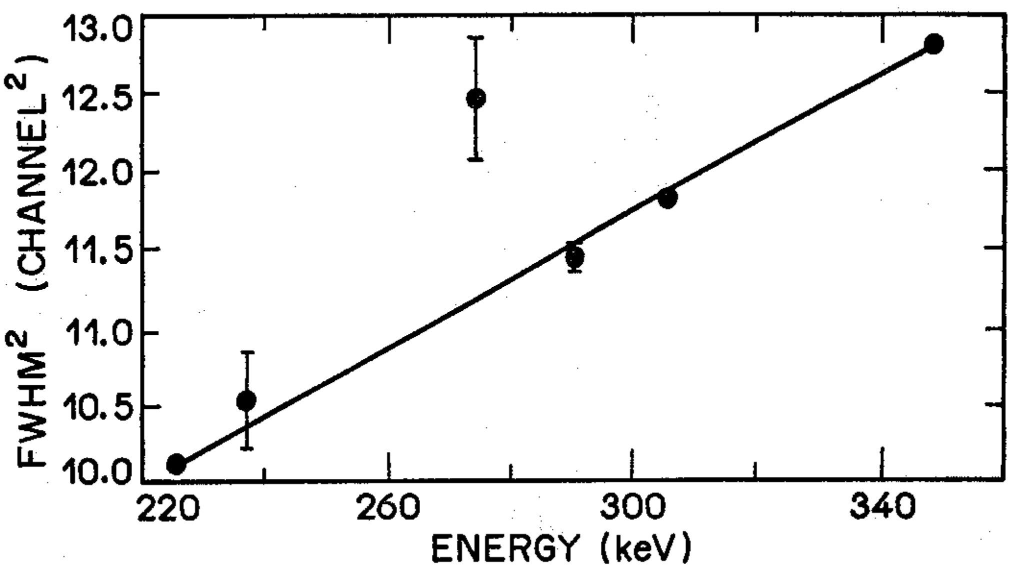

13.0
12.5
12.0
11.5
11.0
10.5
10.0
FWHM^2 (CHANNEL^2)
220
260
300
340
ENERGY (keV)

Figure 2

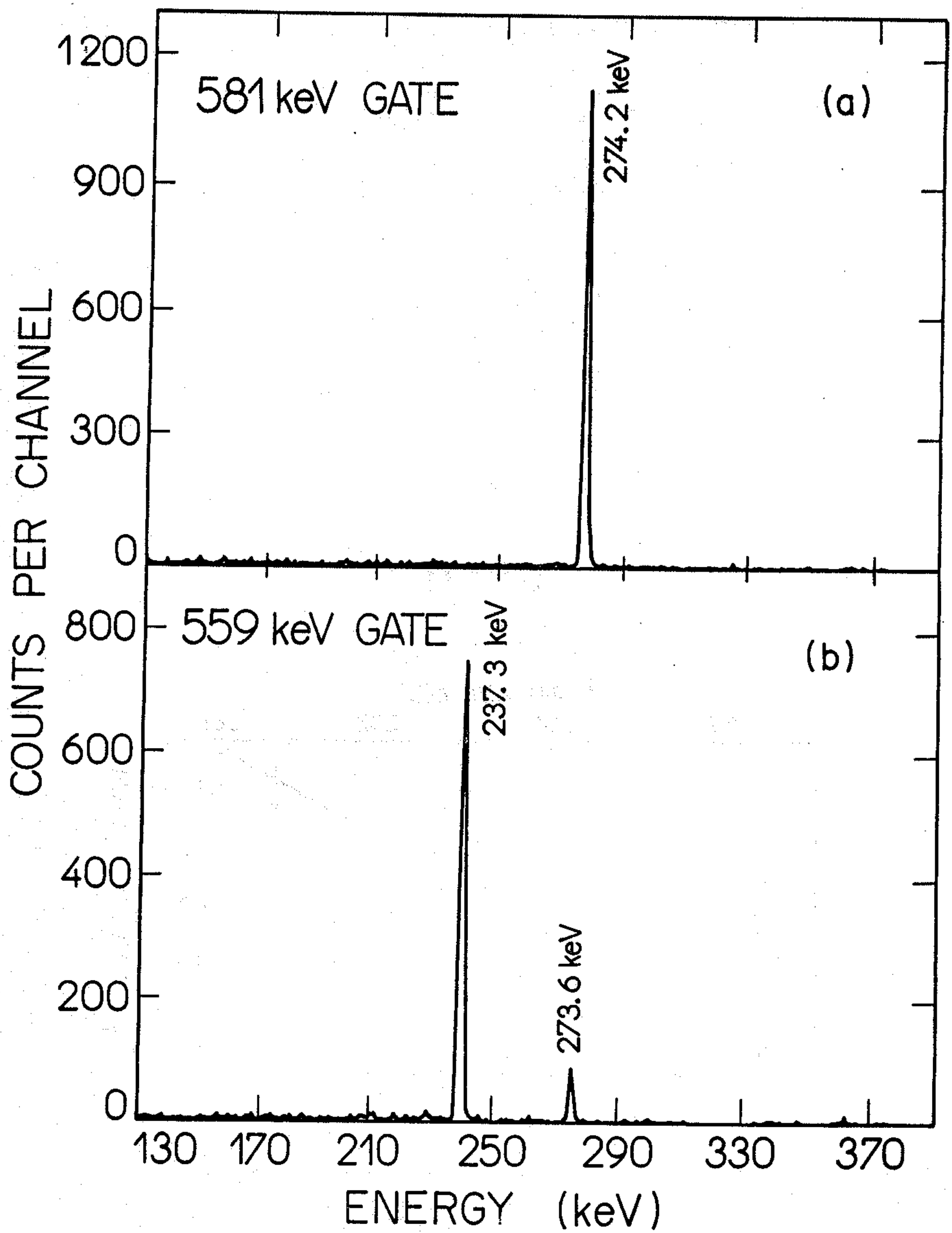

COUNTS PER CHANNEL
1200
900
600
300
0
581 keV GATE
274.2 keV
(a)
800
600
400
200
0
559 keV GATE
237.3 keV
273.6 keV
(b)
130
170
210
250
290
330
370
ENERGY (keV)

Figure 3

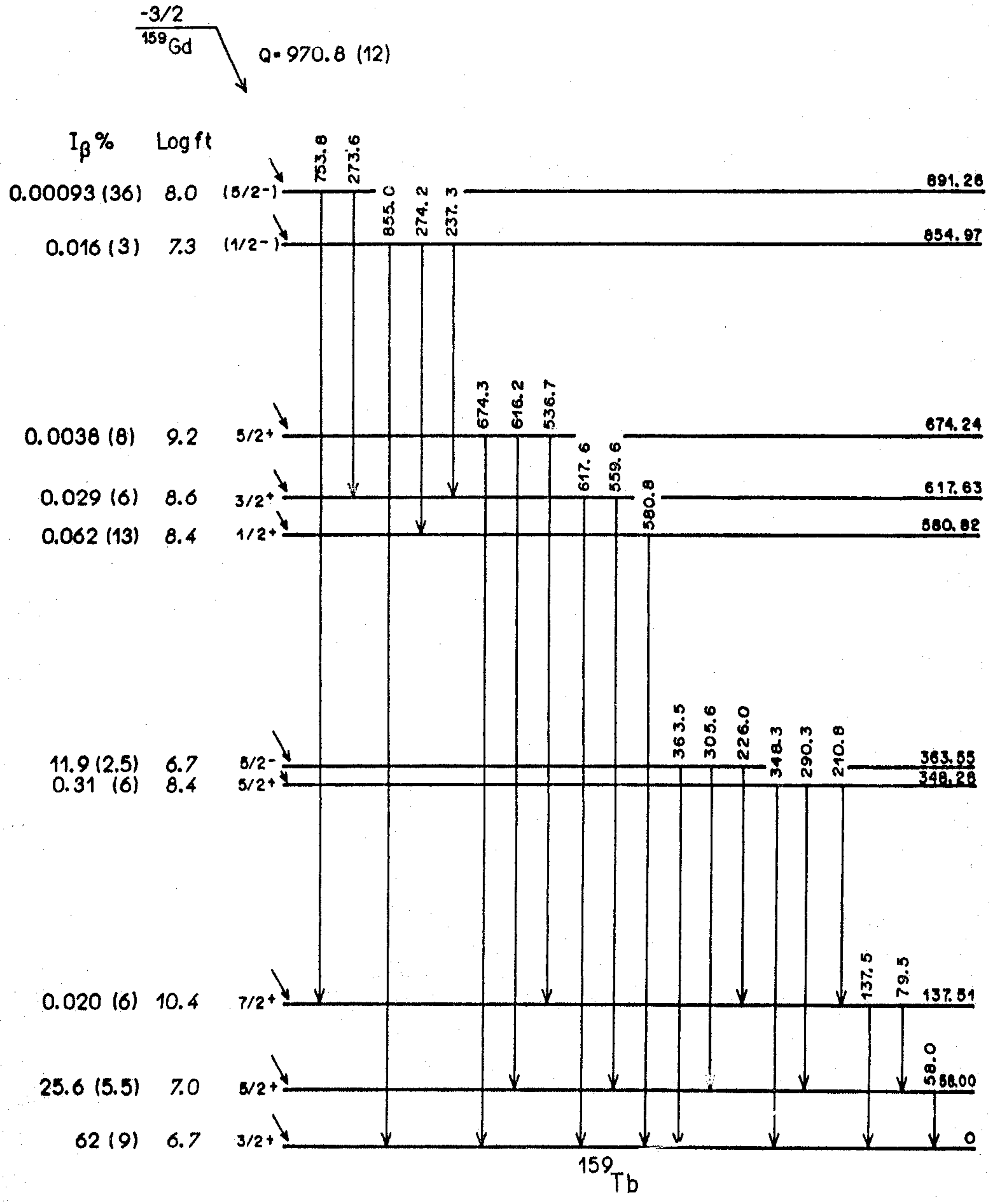

-3/2
159Gd
Q= 970.8 (12)
Iβ %
Log ft
0.00093 (36) 8.0 (5/2-)
0.016 (3) 7.3 (1/2-)
0.0038 (8) 9.2 5/2+
0.029 (6) 8.6 3/2+
0.062 (13) 8.4 1/2+
11.9 (2.5) 6.7 5/2-
0.31 (6) 8.4 5/2+
0.020 (6) 10.4 7/2+
25.6 (5.5) 7.0 5/2+
62 (9) 6.7 3/2+
753.8
273.6
855.0
274.2
237.3
674.3
616.2
536.7
617.6
559.6
580.8
363.5
305.6
226.0
348.3
290.3
210.8
137.5
79.5
58.0
891.28
854.97
674.24
617.63
580.82
363.55
348.28
137.51
58.00
0
159Tb

Figure 4