# Gamma-Ray Transitions in $^{159}$Tb Following the $(n, n')$ Reaction

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Energy levels of $^{159}$Tb have been studied from the $\gamma$-ray spectrum produced by the $^{159}$Tb$(n,n'\gamma)$ reaction using a Ge(Li) detector. The spectrum shows peaks at 317, 331, 395, 440, and 520 keV which do not fit into the existing level scheme of $^{159}$Tb. The possibility that the $\gamma$-ray transitions found at 912, 947, and 976 keV might belong to a $1/2^+[411]$ rotational band is discussed. A $\gamma$ ray at 248 keV is interpreted as a transition originating in the recently found 386-keV level. The weak transition from the 429-keV level to the ground state has been detected. Some doublets in the $\gamma$ spectrum are discussed.

## I. INTRODUCTION

The excited states of $^{159}$Tb have been extensively studied and discussed from the $\beta$ decay of $^{159}$Gd,[1-5] Coulomb excitation,[6,7] resonance fluorescence,[8] the $^{160}$Gd$(p, 2n\gamma)$ reaction,[9] and from measurements with both the $(^3\mathrm{He}, d)$ and the $(\alpha, t)$ reactions on $^{158}$Gd.[10] As a result of these studies, several energy levels of $^{159}$Tb are well established. However, a number of details concerning the level scheme are still unclear. One of these is about a possible rotational $K^\pi = \frac{1}{2}^+$ band as reported by Diamond, Elbek, and Stephens,[6] the base state of which (at 971 keV) would be a nonspherical single-particle state with a Nilsson configuration $\frac{1}{2}^+[411]$. Brown *et al.*[5] are doubtful about this interpretation on account of the existence of a level at 855 keV to which they attribute the configuration $\frac{1}{2}^+[411]$, while they interpret the 971-keV level of Diamond, Elbek, and Stephens as a possible $\beta$ vibrational state built upon the $^{159}$Tb ground state. On the other hand, Hill and Wiedenbeck[4] describe the 855-keV level as the first member of a $K_0 - 2$ $\gamma$ vibrational band built on either the $\frac{5}{2}^+[413]$ or the $\frac{5}{2}^-[532]$ single-particle state. Theoretical calculations of Soloviev and Vogel[11] suggest that the 971-keV band might have $K^\pi = \frac{1}{2}^+$ and that it consists of a main component $\{\frac{5}{2}^+[413], 2^+\}$ with a significant admixture of $\{\frac{3}{2}^+[411], 2^+\}$. The presence of the latter admixture follows also from the calculations of Bunker and Reich.[12] In the recent work of Boyno and Huizenga,[10] which reports several new levels in addition to the older ones, the 855-keV state obtains the assignment of $J^\pi = \frac{1}{2}^-$ and configuration $\frac{1}{2}^-[541\downarrow]$. The levels at 974 and 1100 keV were interpreted, in accordance with the work of Diamond, Elbek, and Stephens, as two doublets with configuration $\frac{1}{2}^+[411\downarrow]$, the lower one having $J^\pi = \frac{1}{2}^+$ and $\frac{3}{2}^+$ and the other $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$.

A second point to be explained is the existence of some distinct lines at 273,[4,5] 317,[9] and 331 keV[2,6,7,9] which could not be fitted into the existing level scheme.

Thus it is evident that more information is still needed in order to draw definite conclusions about the position and character of the levels in $^{159}$Tb. The purpose of the present work was to get such information through the $^{159}$Tb$(n, n'\gamma)$ reaction. This reaction had been studied before by Romanenko *et al.*[13] who found $\gamma$ rays at 0.62, 0.97, 1.29, 1.42, 1.75, and 1.97 MeV with a NaI(Tl) detector. In our measurements, which were carried out with neutrons of 3.7-MeV energy, the $\gamma$ spectrum was taken with a 40-cm$^3$ Ge(Li) detector. The great number of $\gamma$ rays which appeared in this spectrum demonstrated the usefulness of the neutron reaction as an additional source of information on the level scheme of $^{159}$Tb.

The description of the experimental arrangement is given in Sec. II, the results of the measurements and their discussion in Sec. III.

## II. EXPERIMENTAL PROCEDURE

The neutrons were produced by the $^2\mathrm{H}(d, n)^3\mathrm{He}$ reaction. A beam of 5 $\mu$A of deuterons from a 1-MV Van de Graaff accelerator with an energy of 700 keV was focused onto a freon-cooled deuteron-occluded titanium target yielding about $10^{-8}$ neutrons/s. The scatterer was in the form of a ring, with an inside diameter of 10.8 cm and thick-

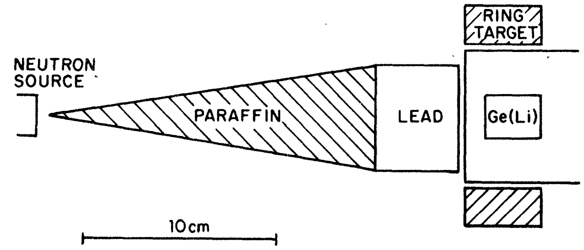


FIG. 1. Experimental arrangement with shielding cone of paraffin and cylinder of lead for observing the $\gamma$ rays from inelastic scattering of neutrons.

ness 2 cm, and of 99.99% pure terbium oxide powder packed into a thin ring-shaped polyethylene box. The ring was placed about 20 cm from the neutron source with its axis passing through it as drawn in Fig. 1. The $\gamma$ radiation was detected with a 40-$cm^3$ Ge(Li) detector, with a resolution of 3 keV at $E_\gamma = 1$ MeV, placed at the center of the ring. The detector was coupled to a computer which was used as a 4096 channel analyser. A cone of paraffin wax and a cylinder of lead were placed between the neutron source and the detector in order to shield the latter from the direct neutron flux and direct $\gamma$ radiation. In this arrangement the energy of the neutrons was approximately 3.7 MeV.

The relative efficiency of the detector for the geometry used in this experiment was determined with a $^{226}$Ra and a $^{46}$Sc source on the basis of the known relative intensities of the $\gamma$ rays from $^{226}$Ra and the fact that the 889- and 1120-keV peaks of $^{46}$Sc have the same intensity, as described in Ref. 14. To take self-absorption in the scatterer into account, the relative intensities of the $\gamma$ rays were measured both with and without the scatterer between the radioactive sources and the detector, and the mean of the two measured values was taken to be the detector efficiency corrected for self-absorption. After measurement of the $\gamma$ spectrum of $^{159}$Tb a background spectrum was taken with the same arrangement but without the scatterer.

The energies of the peaks in the $\gamma$ spectrum

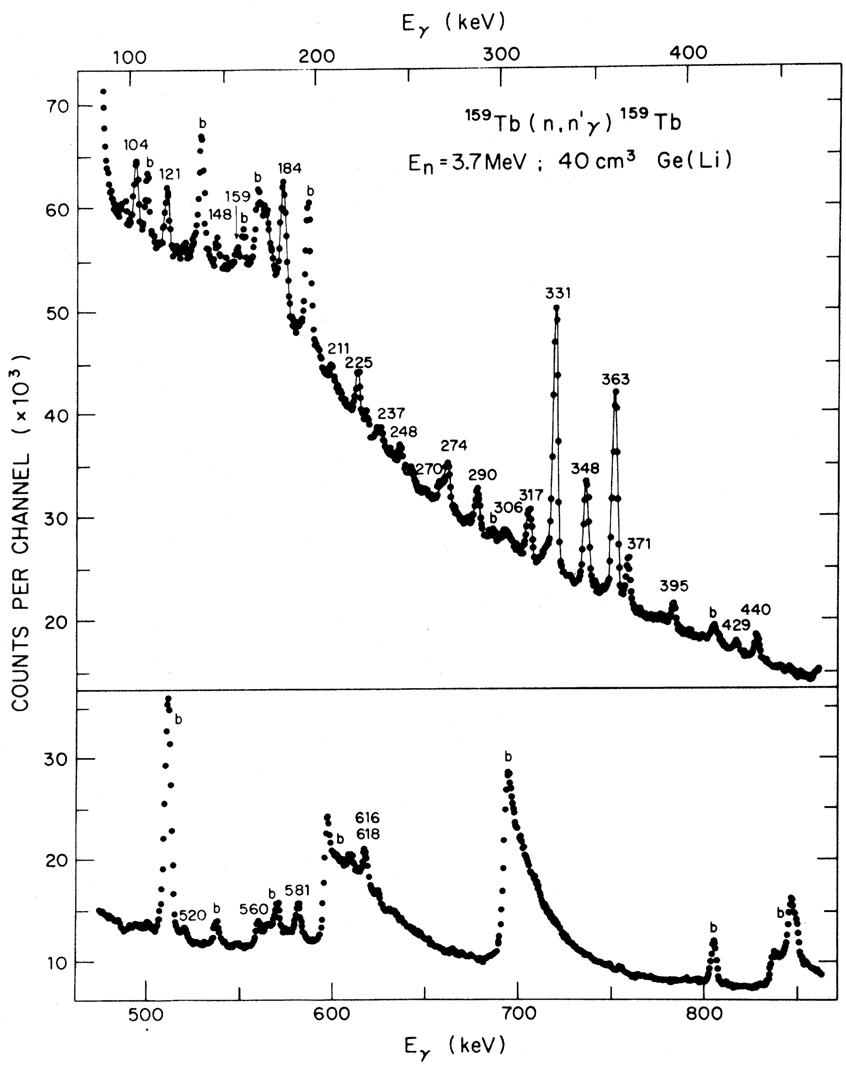


FIG. 2. Low-energy side of $\gamma$ spectrum following the inelastic scattering of neutrons from $^{159}$Tb. b denotes background peaks.

were found by calibration with radioactive sources of $^{137}$Cs, $^{57}$Co, $^{60}$Co, $^{226}$Ra, $^{46}$Sc, $^{22}$Na, and ThC″ as described in Ref. 14.

## III. RESULTS AND DISCUSSION

The energy spectrum of the $\gamma$ rays following the scattering of 3.7-MeV neutrons from $^{159}$Tb is given in Figs. 2 and 3, and the energies of the various peaks and their relative intensities are presented in Table I. From this table and the level scheme in Fig. 4 it is seen that the $(n, n'\gamma)$ reaction excites many of the $^{159}$Tb levels below 1 MeV which were known from various other reactions. Table I also shows that the excitation of $^{159}$Tb levels by neutron scattering is less selective than that by $\beta$ decay of $^{159}$Gd and by Coulomb excitation.

As to the $\gamma$ spectrum and the data in Table I, we make the following remarks.

The most striking feature of the spectrum is the presence of four quite intensive $\gamma$ peaks at 317, 331, 395, and 440 keV. The 331-keV peak is the most intensive one of the whole spectrum. Neither of these peaks fits into the existing level scheme of $^{159}$Tb. The 331-keV transition had already been found through Coulomb excitation of $^{159}$Tb (Refs. 6 and 7) and possibly through the $\beta$ decay of $^{159}$Gd (Ref. 2) but in all these cases its intensity was

TABLE I. $\gamma$ rays of $^{159}$Tb. Energies are in keV.

| $(n,n'\gamma)$ [a] Energy [b] | $(n,n'\gamma)$ [a] Rel. intensity | Transition | $(n,n'\gamma)$ (Ref. 13) | Coulomb excitation (Ref. 6) | Coulomb excitation (Ref. 7) | $^{159}$Gd $\beta$ decay (Ref. 1) | $^{159}$Gd $\beta$ decay (Ref. 2) | $^{159}$Gd $\beta$ decay (Ref. 3) | $^{159}$Gd $\beta$ decay (Ref. 4) | $^{159}$Gd $\beta$ decay (Ref. 5) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 58→0 | | | | | 58 | 58 | 58 | 58 |
| | | 138→58 | | | 80 | | 80 | 80 | 80 | 80 |
| 104 | 71±10 | 241→138 | | 104 | 104 | | | | | |
| 121 | 78±10 | 363→241 | | 121 | 122 | | | | | |
| 137 | | 138→0 | | 138 | 138 | | | 138 | 137 | 137 |
| 148 | 35±8 | 511→363 | | | 149 | | | | | |
| 159 | 27±8 | 699→511 | | | | | | | | |
| 184 | 284±15 | 241→58 | | 183 | 183 | | | | | |
| 211 | 41±8 | 348→138 | | | | 211 | | 211 | 211 | 211 |
| 225 | 103±12 | 363→138 | | 225 | 225 | 226 | 225 | 226 | 226 | 226 |
| 237 | 53±10 | 855→618 | | | | | | 245 | 237 | 237 |
| 248 | 54±10 | 386→138 | | | | | | | | |
| 270 | 62±10 | 511→241 | | 269 | 270 | | | | | |
| 274 | 124±12 | 855→581 | | | | | | 280 | 274 | 274 |
| 290 | | 348→58 | | | | | | | | |
| | | 429→138 | | 289 | | 290 | 290 | 290 | 290 | 290 |
| 305 | 59±10 | 363→58 | | 306 | | 305 | 306 | 305 | 306 | 305 |
| 307 | 30±10 | 669→363 | | | | | | | | |
| 317 | 185±14 | ? | | | | | | | | |
| 331 | 1079±50 | ? | | 331 | 332 | | 334 | | | |
| 348 | 423±30 | 348→0 | | 348 | 348 | 348 | 348 | 348 | 348 | 348 |
| 363 | 1000±50 | 363→0 | | 362 | 363 | 363 | 363 | 363 | 364 | 363 |
| 371 | 226±20 | 429→58 | | 371 | 371 | | | | | |
| 395 | 277±20 | ? | | | | | | | | |
| 429 | 40±12 | 429→0 | | 429? | | | | | | |
| 440 | 119±15 | ? | | | | | | | | |
| 520 | 97±16 | ? | | 522 | | | | | | |
| (537) | | 674→138 | | 536 | 538 | 536 | 537 | 536 | 537 | 537 |
| 560 | 77±14 | 618→58 | | 560 | 557 | 557 | 558 | 557 | 560 | 560 |
| 580 | 255±20 | 581→0 | | 580 | 580 | 580 | 579 | 580 | 580 | 580 |
| 616 | 145±20 | 674→58 | | 616 | 616 | | | 616 | 616 | 616 |
| 618 | 83±16 | 618→0 | $0.62\times10^3$ | 617 | 620 | 616 | 617 | 617 | 617 | 617 |
| (674) | | 674→0 | | 674 | | | | | | 674 |
| (855) | | 855→0 | | | | | | 860 | 855 | 855 |
| 912 | 30±14 | | | 920 | | | | | | |
| 947 | 43±14 | | | 949 | | | | | | |
| | | | | 965 | | | | | | |
| 976 | 53±16 | | $0.97\times10^3$ | 978 | | | | | | |

[a] Present work.

[b] The uncertainty is about 1 keV for the $\gamma$ rays up to 618 keV and about 3 keV for the three higher ones.

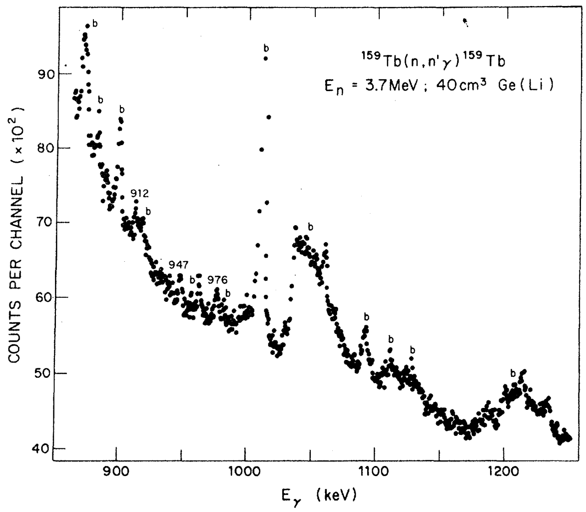


FIG. 3. High-energy side of $\gamma$ spectrum following the inelastic scattering of neutrons from $^{159}$Tb.

small. However, in the work carried out with the $^{160}$Gd($p$, $2n\gamma$) reaction[9] this transition was very strong. In the same work a rather strong 317-keV $\gamma$ ray was also detected. Lifetime measurements gave a half-life of 21 ns for the 331-keV $\gamma$ ray and a half-life of 15 ns for the 317-keV $\gamma$ ray. Nevertheless, preliminary coincidence data appeared to be insufficient to determine how both $\gamma$ rays fitted into the decay scheme of $^{159}$Tb. Continuation of such measurements may clarify the location of these $\gamma$ rays.

The possibility should be considered that some of the above $\gamma$ rays belong to another nucleus through the processes

$$^{159}\text{Tb} + n + 3.7\text{ MeV} \rightarrow {}^{159}\text{Gd} + p + 3.5\text{ MeV}$$

and

$$^{159}\text{Tb} + n + 3.7\text{ MeV} \rightarrow {}^{156}\text{Eu} + \alpha + 9.9\text{ MeV}.$$

From the tables given by Blatt and Weisskopf,[15] we find that the cross section for the inverse reaction is of the order of $10^{-29}$ cm$^2$ for the first reaction and $10^{-26}$ cm$^2$ for the second. Hence the ($n$, $p$) or ($n$, $\alpha$) reaction cannot be expected to produce $\gamma$ rays as strong as the above ones.

In the present work no $\gamma$ peaks have been found with an energy higher than 976 keV, in contrast with the NaI work of Ref. 13, where mainly $\gamma$ rays of energies higher than 1 MeV were detected and only two of energies below 1 MeV. This is due to the smaller efficiency of the Ge(Li) counter for high-energy $\gamma$ rays and to its much smaller background for the ($n$, $n'\gamma$) reaction in the low-energy region of the spectrum, as compared with the NaI counter.

The 912-, 947-, and 976-keV transitions in the present work might be the same as those at 920, 949, and 978 keV measured by Diamond, Elbek, and Stephens[6] (these authors report their 965-keV transition as probable, while in our spectrum apparently a background peak is present at that energy). It might therefore be concluded that the present work does indeed give additional support

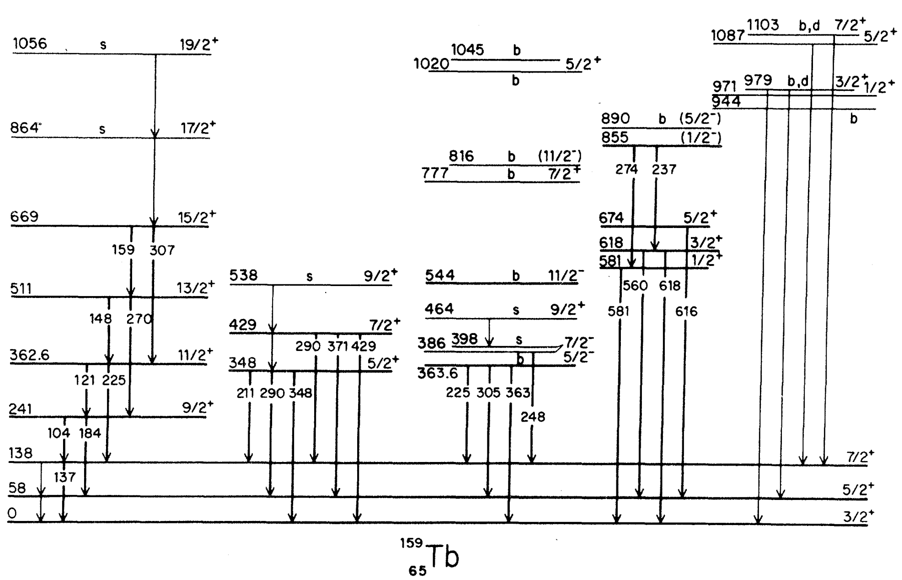


FIG. 4. Level scheme of $^{159}$Tb. The thicker lines indicate levels and transitions seen in the present experiment, while the thinner lines indicate previously identified levels or transitions not observed by neutron scattering. d denotes Ref. 6, s denotes Ref. 9, and b denotes Ref. 10.

to the existence of a rotational band based on a $\frac{1}{2}^+$[411] state at 971 keV, as assumed by Diamond, Elbek, and Stephens and Boyno and Huizenga (see Sec. I). However, it seems to us that there is still no convincing proof for this assumption because of the following facts: (a) No transition from the basic state of the rotational band has been observed; (b) the 947- (949-) keV $\gamma$ ray could also be a transition to the ground state from the level at $944 \pm 2$ keV measured by Boyno and Huizenga.

No transition from the 855-keV level to the ground state[3-5] has been observed in the present work, apparently due to the low intensity of this transition and the heavy background in the region where it should be found. Yet, the 855-keV state is certainly excited through the $(n, n'\gamma)$ reaction, as is proved by the presence of its deexcitation $\gamma$ rays at 237 and 274 keV to the 618- and 581-keV states, respectively. The existence of these $\gamma$ rays is consistent with all the various assignments bestowed on the 855 level, as mentioned in Sec. I. Therefore, more information on this level is still needed before any definite conclusion can be made about its character.

The 248-keV peak, which was not found in earlier work, can be explained as the transition from the recently found $\frac{7}{2}^-$ state at 386 keV, based on the $\frac{5}{2}^-[532\uparrow]$ configuration,[10] to the $\frac{7}{2}^+$ level at 138 keV. However, this interpretation is incompatible with the assignment $\frac{5}{2}^-$[532] to a $\frac{7}{2}^-$ level at 398 keV found by Shoup, Griffin, and Hull[9] (see Sec. I). The 245-keV peak found by Funke *et al.*[3] is apparently not identical with our 248-keV peak but with the 237-keV $\gamma$ ray, because of its coincidence with the 560- and 618-keV transitions.

The weak, and perhaps questionable, transitions at 520 and 429 keV in the spectra of Diamond, Elbek, and Stephens[6] are also weak in the present work, but their presence is established beyond doubt. The 520-keV $\gamma$ ray does not fit into the existing decay scheme of $^{159}$Tb. The 429-keV $\gamma$ ray is the weakest of the transitions from the $\frac{7}{2}^+$ level at 429 keV to the three lowest members of the ground-state rotational band.

The spectrum of Fig. 1 shows three doublets which are clearly separated. The doublet at 306 keV consists of a peak at 305 keV (the transition between the $\frac{5}{2}^-$ level at 363.6 keV and the $\frac{5}{2}^+$ level at 58 keV) and a peak at 307 keV (the transition between the $\frac{15}{2}^+$ level at 669 keV and the $\frac{11}{2}^+$ level at 363 keV). The 669-keV level was not excited through the reactions used in previous work except the $^{160}$Gd$(p, 2n\gamma)$ reaction of Shoup, Griffin, and Hull.[9]

A second doublet can be separated in a peak at 270 keV (the transition 511 keV $\to$ 241 keV) and the 274-keV peak which was mentioned above as the transition from 855 to 581 keV. The 270-keV $\gamma$ ray was found earlier through Coulomb excitation and the 274-keV $\gamma$ ray through $\beta$ decay of $^{159}$Gd. The $(n, n'\gamma)$ reaction of the present work apparently excites both levels at 511 and 855 keV.

The peaks of the doublet at 616 and 618 keV, which were already observed in earlier work, belong to the transitions 674 keV $\to$ 58 keV and 618 keV $\to$ 0, respectively. The other transitions from the 674-keV level to lower states, at 537 and 674 keV, do not appear in the spectrum of Fig. 1, apparently due to the heavy background existing in the region where they should be found.

Further work on $^{159}$Tb, with various reactions and including coincidence measurements, would undoubtedly be helpful in unravelling the complex level scheme of this nucleus.

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