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THE DECAY OF ^{159}Gd

JOHN C. HILL and M. L. WIEDENBECK
Department of Physics, University of Michigan, Ann Arbor, Michigan †

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Abstract: Precision energy measurements on four gamma rays in the ^{159}Gd → ^{159}Tb decay were performed with a 2 m curved-crystal spectrometer. Energies of the other gamma rays and all gamma intensities were determined with a Ge(Li) spectrometer. A level scheme is proposed for ^{159}Tb which includes a level at 854 keV. The status of the 617 keV doublet has been clarified. On the basis of these measurements a proposal is made concerning the nature of the 854 keV level.

E | RADIOACTIVITY ^{159}Gd [from ^{158}Gd(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin. ^{159}Tb deduced levels, J, π, log *ft*. Enriched target, Ge(Li) detector.

1. Introduction

The levels of ^{159}Tb have been studied extensively through the decay of ^{159}Gd [refs. [1-4]], ^{159}Dy [refs. [5-7]] and through Coulomb excitation [8-11]. Properties of the levels of ^{159}Tb have been used to test various models for odd-mass deformed nuclei. Two investigators [12,13]) have given rather complete decay schemes for ^{159}Gd, but the status of a level at 860 keV and a gamma ray doublet at 617 keV is unclear. The only work carried out with lithium-drifted germanium spectrometers was by Ewan and Tavendale [14]), who observed a gamma ray at 334 keV which has not been seen by other investigators. This investigation was undertaken to clarify the above problems and construct a decay scheme based on measurements with a high-resolution curved-crystal spectrometer and Ge(Li) spectrometers. Gamma-gamma coincidences were studied with the aid of Ge(Li) spectrometers. The observed bands are discussed in some detail.

2. Source preparation

Samples of Gd_2O_3 enriched to 97.6 % in ^{158}Gd were irradiated with thermal neutrons from the University of Michigan Ford Reactor. Flat (ribbon) sources composed of a Gd_2O_3-epoxy mixture were exposed to a flux of 2×10^{13} n/cm^2 · sec for about 48 h. These sources were used in the 2 m curved-crystal spectrometer. Sources for use with the Ge(Li) spectrometer were composed of several mg of Gd_2O_3 dissolved in HNO_3 and irradiated in the reactor for about 36 h. Samples used with the Ge(Li) spectrometer were chemically purified after irradiation. The rare-earths were

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first purified as a group using the procedure of Stevenson and Nervik [15]). Gadolinium was then separated from the other rare-earths by elution from an ion-exchange column containing Dowex 50 cation resin. The elutant used was 1 *M* lactic acid adjusted to a *pH* of 3.4 as suggested by Stevenson and Nervik [15]). The chemical separation took about 8 h. No interfering activities were observed for sources less than 5 d old.

3. Gamma-ray energies

The energies of the four most intense gamma rays were measured with the 2 m curved-crystal spectrometer described by Reidy and Wiedenbeck [16]). Diffraction

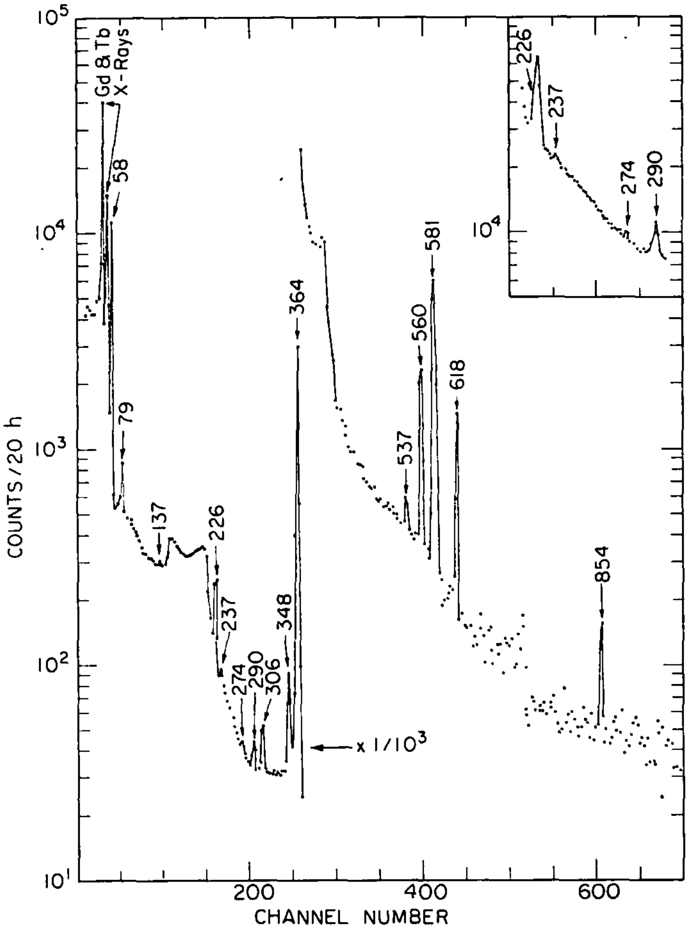

Fig. 1. The pulse-height spectrum of gamma radiation accompanying the decay of ^{159}Gd. The source distance to the 5 mm Ge(Li) spectrometer was 2 cm. No absorber was used. All energies are in keV.

from a new quartz (310) crystal provided the energy measurement of the 58 keV gamma ray. Measurements involving the other three gamma rays were performed with a germanium (400) crystal. Both crystals were calibrated using the 411.800 keV transition in ^{198}Au as a standard. The sources were aligned in the spectrometer on the first-order reflection of the 364 keV gamma ray in ^{159}Gd. The resolution widths (FWHM) of the diffraction profiles were approximately 25″ of arc.

The profile of the 364 keV gamma ray was measured in second order. The profiles of the 58, 226 and 348 keV gamma rays were measured in first order. All other gamma rays were too weak to be measured with the curved-crystal spectrometer. During energy measurements, the profile of each gamma ray was scanned three times. The measured energies are listed in table 1. The errors were determined by the method of Reidy and Wiedenbeck [16]).

TABLE 1
Gamma-ray energies and relative intensities

Energy (keV)	Relative intensity c)	Energy (keV)	Relative intensity c)
58.00±0.01 a)	18.0 ±3.0	348.17±0.08 a)	2.0 ±0.1
79.45±0.2 b)	0.38 ±0.07	363.56±0.03 a)	100.0
137.7 ±0.3 b)	0.042±0.026	536.7 ±0.4 b)	0.018±0.012
210.8 ±0.3 d)	0.090±0.035	559.9 ±0.3 b)	0.17 ±0.03
226.00±0.04 a)	1.8 ±0.1	581.1 ±0.3 b)	0.55 ±0.04
236.9 ±0.4 b)	0.055±0.036	616.3 e)	0.009±0.006 d)
274.2 ±0.6 b)	0.065±0.040	617.7 ±0.3 b)	0.13 ±0.04
290.2 ±0.3 b)	0.24 ±0.03	854.5 ±0.4 b)	0.014±0.008
305.6 ±0.2 b)	0.54 ±0.04		

a) Energy measured using curve-crystal spectrometer.
b) Energy measured using Ge(Li) spectrometer.
c) Intensites normalized to 100 for the 363.56 keV gamma ray.
d) Values from coincidence measurements.
e) Energy difference between 674.3 and 58.00 keV levels (not measured directly).

The gamma-ray spectrum was measured with a lithium-drifted germanium spectrometer having an area of 4 cm^2 and a depletion depth of 0.5 cm. The resolution width (FWHM) obtained for the 662 keV gamma ray from ^{137}Cs was 3.4 keV. A typical gamma spectrum for ^{159}Gd is shown in fig. 1. All gamma rays ascribed to ^{159}Gd were checked for the correct [17]) half-life of 18.6 h. No effects due to coincidence summing were observed. The energies of all gamma rays were measured with the Ge(Li) spectrometer. The spectrum was calibrated using the four ^{159}Gd gamma rays measured with the curved-crystal spectrometer along with standard [18]) gamma rays from ^{139}Ce, ^{7}Be, ^{137}Cs and ^{54}Mn. The energies and errors of all gamma rays were determined as in earlier work [19]) and are given in table 1.

The gamma spectrum between 220 and 295 keV is shown in detail in the inset in fig. 1. Two weak gamma rays can be seen at 237 and 274 keV. A gamma ray at 211 keV was observed in coincidence measurements but was not seen in singles spectra due to a high Compton background from the 364 keV gamma ray.

4. Gamma-ray intensities

Relative gamma intensities were determined from full-energy peaks observed using the Ge(Li) detector. The intensity and its error were determined by methods used in earlier work [19]). The efficiency as a function of energy has been determined for our detector by Donnelly *et al.* [20]). Intensities of gamma rays at 138, 237, 274, 537 and 854 keV have especially large errors due to their low intensity and high background. The intensity of the 211 keV gamma ray was determined from coincidence measurements. Intensities of the components of the doublet at 617 keV are discussed in sect. 5.

TABLE 2
Upper limits for various gamma transitions

Energy (keV)	Upper limit intensity [c])
180 [a])	0.013
334 [b])	0.04
491 [a])	0.0008
506 [a])	0.0008
674 [a])	0.008
717 [a])	0.004
796 [a])	0.003

[a]) Missing transition between levels in our decay scheme.
[b]) Reported in ref. [14]).
[c]) Intensity relative to 100 for the 364 keV gamma ray.

A search was made for a 334 keV gamma ray reported by Ewan and Tavendale [14]) as well as for a transition from the 674 keV level to the ground state using singles spectra from the Ge(Li) spectrometer. Upper limits for gamma decay from the 854 keV level to members of the ground-state band were established from singles measurements. The limit on decay to the 674 keV level was based on spectra in coincidence with the triplet of gamma rays at 560, 581 and 618 keV. Limits on decay from the 854 keV level to the 348 and 364 keV levels were based on spectra in coincidence with the gamma rays at 348 and 364 keV. Upper limits for all these transitions are given in table 2.

5. Gamma-gamma coincidence measurements

Gamma-gamma coincidence studies were carried out using a 7.6 cm × 7.6 cm NaI(Tl) spectrometer and Ge(Li) spectrometers. The detectors were oriented at 180° to each other. A lead shield was used to minimize backscatter. The gating pulse for the multi-channel analyser was always obtained from the NaI spectrometer. The coincidence resolving time was about 50 nsec and a 0.5 μsec delay was introduced to estimate the contribution from random coincidences. All spectra are corrected only for random coincidences.

The spectrum observed in coincidence with the triplet of gamma rays at 560, 581 and 618 keV is shown in fig. 2. A Ge(Li) spectrometer having an area of 4 cm^2 and a depletion depth of 0.5 cm was used. The true-to-chance ratio was about 35. Strong coincidences were observed with gamma rays at 58, 237 and 274 keV. The peak at 237 keV corresponded to coincidences with the gamma transition at 581 keV. The peak at 274 keV corresponded to coincidences with the gamma transitions at 618 and 560 keV depopulating the 618 keV level.

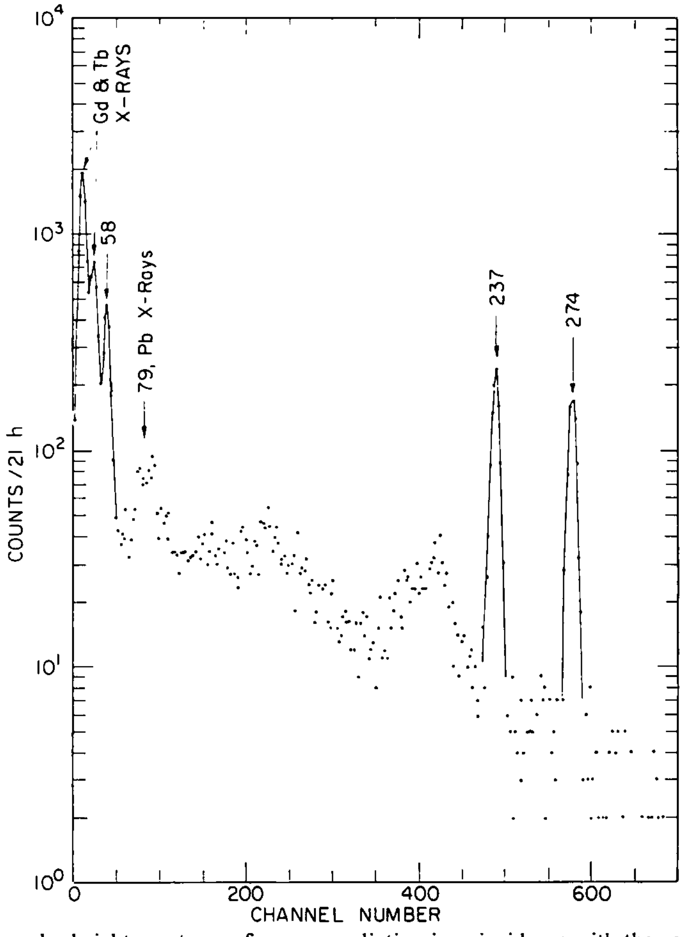

Fig. 2. The pulse-height spectrum of gamma radiation in coincidence with the gamma rays at 560, 581 and 618 keV. A 5 mm Ge(Li) spectrometer was used. All energies are in keV.

The spectrum observed in coincidence with the gamma rays at 58 and 79 keV is shown in fig. 3. A 17 cm^3 coaxial Ge(Li) spectrometer was used. The true-to-chance ratio was about 15. Strong coincidence peaks were observed with gamma rays at 58, 79, 211, 226, 290, 306 and 560 keV. Very weak coincidence peaks were observed with gamma rays at 237, 274, 581 and 618 keV. All strong coincidence peaks represented real coincidences with the 58 or 79 keV gamma rays. The peaks at 237 and 274 keV corresponded to coincidences with Compton distributions from gamma rays at 560, 581 and 618 keV. The very weak peaks at 581 and 618 keV will be discussed in detail below.

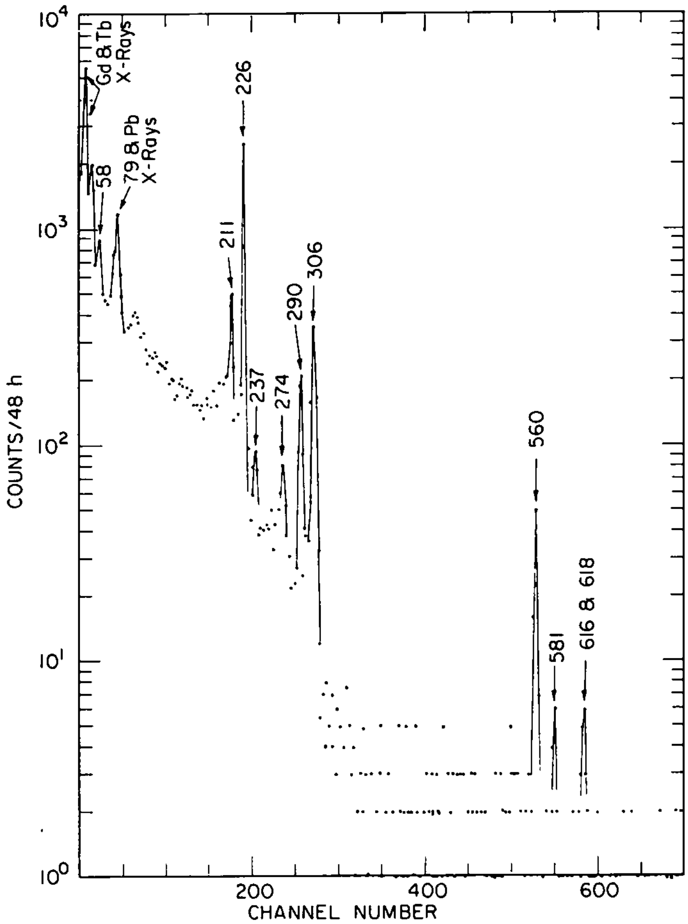

Fig. 3. The pulse-height spectrum of gamma radiation in coincidence with the gamma rays at 58 and 79 keV. A 17 cm^3 coaxial Ge(Li) spectrometer was used. All energies are in keV.

The 211 keV gamma ray depopulating the 348 keV level was observed for the first time in ^{159}Gd decay. Ryde *et al.* [7]) have observed this gamma ray in the decay of ^{159}Dy. Its energy was determined from the coincidence spectrum using ^{159}Gd gamma rays at 226, 290, 306 and 364 keV as calibration points. Its intensity was measured relative to the 226 keV gamma ray. These values are given in table 1.

The weak peaks at 581 and 618 keV were studied carefully to determine the status of a possible transition between the 674 and 58 keV levels. The peak at 581 keV was the result of coincidences with the Compton distribution from the 274 keV gamma ray. The peak at 618 keV resulted from coincidences with the Compton distribution from the 237 keV gamma ray plus coincidences between the 58 keV gamma ray and a transition of about 616 keV depopulating the 674 keV level. We thus propose a doublet whose components have energies of 616.2 and 617.7 keV, respectively. The relative intensity of the members of the doublet was determined from the relative intensities of the 581 and 618 keV gamma rays in the coincidence and singles spectra. The intensity of the lower-energy component of the doublet is about 7 % of that of the higher-energy component. Because of poor statistics, large errors were set on the intensity of the low-energy component.

A search was carried out for coincidences with the 348 and 364 keV gamma rays using the 17 cm^3 coaxial Ge(Li) spectrometer. In a 17 h run, no true coincidences were observed other than those with X-rays.

6. Decay scheme

The gamma transition energies and intensities and their coincidence relationships have been interpreted on the basis of the decay scheme shown in fig. 4. In addition to well-known excited states at 58, 138, 348 and 364 keV, levels at 581, 618 and 674

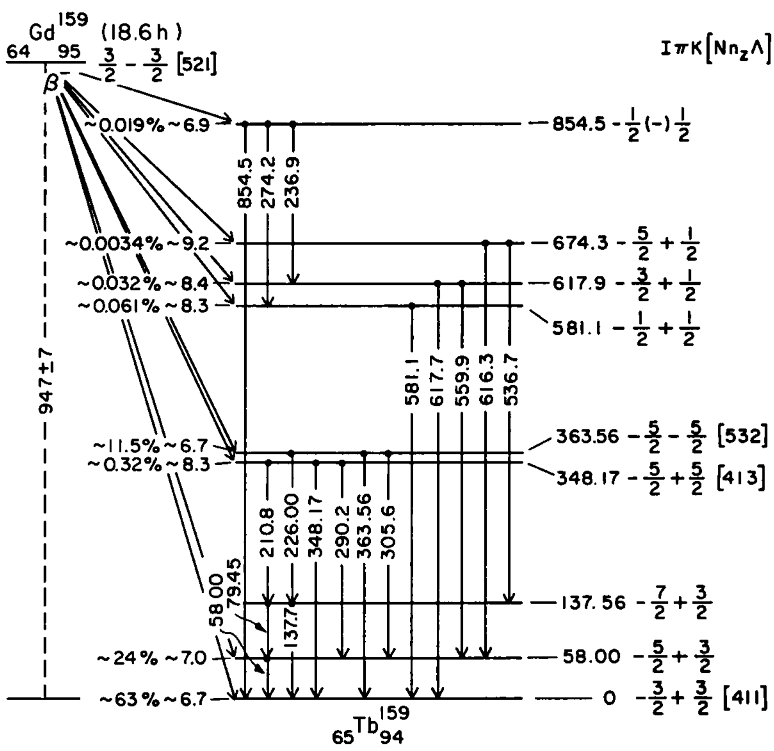

Fig. 4. The decay scheme of ¹⁵⁹Gd from the present studies.

confirmed the results of more recent investigations [12,13]). The existence of a level at 854 keV reported only by Funke *et al.* [13]) was confirmed. The existence of a gamma doublet at 617 keV was established. No evidence was found for a gamma transition at 334 keV reported earlier [14]).

The Q-value for the ^{159}Gd decay has been given by Mattauch *et al.* [21]) to be 947 ± 7 keV. The relative intensity of beta rays feeding the ground state and the 58 keV level of ^{159}Tb was obtained from the work of Nielsen *et al.* [1]). The log *ft* assignments for the other levels were based on gamma intensity measurements of this investigation. Internal conversion corrections for the 58 and 79 keV gamma rays were made using known mixing ratios [22]) and the tables of Hager and Seltzer [23]). Intensity corrections for higher-energy gamma rays were made in a manner consistent with the spin assignments in the proposed decay scheme. The assumption of zero beta feeding to the 138 keV level was consistent with our intensity measurements. A discussion of the individual levels and bands follows.

The ground state. The spin of the ^{159}Tb ground state has been measured to be $\frac{3}{2}$ by two groups [24,25]). This value agrees with that expected for the 65th odd proton in the Nilsson diagram. The spin of the ground state of ^{159}Gd has been measured [26]) to be $\frac{3}{2}$.

The 58.00 keV *level.* The energy of the gamma transition from the first excited to the ground state was measured to be 58.00 ± 0.01 keV. This value is in excellent agreement with the value of 57.99 ± 0.01 keV obtained by Chupp *et al.* [27]) using a bent quartz-crystal spectrograph. This level has been Coulomb excited by many investigators [8-11]) who interpreted it as the $\frac{5}{2}$ member of the ground-state band. The lifetime of the level has been measured to be $(1.3 \pm 0.4) \times 10^{-10}$ sec by Berlovich *et al.* [28]).

The 137.56 keV *level.* The energy of this level was measured to be 137.56 ± 0.04 keV. This value was obtained from the difference in the energies of the 363.56 and 226.00 keV transitions. The value is in reasonably good agreement with the value of 137.50 ± 0.03 keV obtained from the data of Chupp *et al.* [27]) using the value of 79.51 ± 0.02 keV for the energy of the gamma transition between the first and second excited states. This level has been Coulomb excited and interpreted as the $\frac{7}{2}$ member of the ground-state band.

The ground and first two excited states in ^{159}Tb have been classified by Mottelson and Nilsson [29]) as members of a rotational band based on the $(411)\frac{3}{2}^+$ state. They also classified the ground state of ^{159}Gd as $(521)\frac{3}{2}^-$. Using 65 MeV ^{16}O ions, Bromley [10]) has excited the $\frac{23}{2}$ level of the ^{159}Tb ground state band. He found it necessary to introduce third-order Coriolis coupling in order to interpret the level spacings correctly.

Branching ratios for beta and gamma transitions in odd-mass deformed nuclei generally follow the asymptotic selection rules calculated within the framework of the unified model [29,30]). Following the terminology of this model, beta decay to the ground and first excited states of ^{159}Tb is first-forbidden "unhindered". This classification is consistent with the measured log *ft* values of 6.7 and 7.0, respectively. The absence of beta feeding to the second excited state is consistent with the classification of the corresponding beta transition as first-forbidden unique "hindered".

The "hindrance factor" for the 58 keV gamma transition was calculated from the measured lifetime [28]) of the 58 keV level and the single-particle estimate of Moszkowski [31]). The statistical factor was taken to be 1, and a mixing of 1.4 % E2 as measured by Novakov and Hollander [22]) was used. The hindrance factor was found to be 9 consistent with the unhindered nature of intraband gamma transitions.

The 348.17 keV *level.* The energy of the gamma transition from this level to the ground state was measured to be 348.17±0.08 keV. The level decays to the first three members of the ground-state band by emission of 348, 290 and 211 keV gamma rays. The ratio of the corresponding gamma intensities is 2.0/0.24/0.09 in good agreement with the ratio 2.0/0.26/0.08 determined by Ryde *et al.* [7]) from ^{159}Dy decay.

TABLE 3

Comparison of measured gamma intensity ratios with the Alaga rules

Energy (keV)	Intensity ratio from Alaga rules $L = 1$	$L = 2$	Measured ratio	Hindrance factor [a])
348.17	100	100	100	
290.2	43	150	12 ± 1.6	
210.8	7	83	4.5 ± 1.7	
363.56	100	100	100	3.1×10^4
305.6	43	150	0.54 ± 0.04	3.4×10^6
226.00	7	83	1.8 ± 0.1	4.2×10^5
617.7	100	100	100	
559.9	150	7	131 ±44	
536.7	100	100	100	
616.3	96	18	50 ±45	
674.3	14	27	<44	

[a]) Based on single-particle estimate of Moszkowski [31]). Transitions assumed to be pure E1.

Ryde *et al.* have determined the three above transitions to be mixed M1E2, and Persson [12]) has found the 348 keV transition to be predominantly M1. The 348 keV level is thus $\frac{3}{2}^+$ or $\frac{5}{2}^+$. Under this restriction, the only single-particle state available in this region energy is (413)$\frac{5}{2}^+$. Diamond *et al.* [9]) have Coulomb excited the $\frac{7}{2}$ member of this band using 60 MeV ^{16}O ions. They cite the spacing of the $\frac{5}{2}$ and $\frac{7}{2}$ levels as additional evidence for a K of $\frac{5}{2}$.

The beta transition to the 348 keV level is first-forbidden hindered. This designation is consistent with the measured log *ft* of 8.3. Gamma transitions from the 348 keV level to the ground-state band are hindered by the asymptotic selection rules. Intensity ratios for these transitions are compared with the predictions of the Alaga rule [30]) in table 3. The agreement is not very good, but this is not surprising in view of the hindered nature of the transitions.

The 363.56 keV *level.* The energy of the gamma transition from this level to the ground state was measured to be 363.56±0.03 keV. The level decays to the first three members of the ground-state band by emission of 364, 306 and 226 keV gamma rays. Nielsen *et al.* [1]) have measured the K-conversion coefficient for the 364 keV transition and an upper limit for the conversion coefficient for the 226 keV transition. They designated both transitions as E1. Persson [12]) has determined the 306 keV transition to be E1 from an upper limit on its conversion coefficient. The 364 keV level is therefore $\frac{5}{2}^-$, and the only available single-particle state is $(532)\frac{5}{2}^-$.

The beta transition to this level is allowed and hindered. This classification is consistent with the measured log *ft* of 6.7. Gamma transitions from the level are hindered by asymptotic selection rules. Intensity ratios in table 3 for these transitions are in obvious disagreement with the predictions of the Alaga rule. The lifetime for the 364 keV level has been measured by several investigators [32–34]) and most recently by Malmskog *et al.* [35]), who obtained a value of $(1.5\pm0.1)\times10^{-10}$ sec. Using this lifetime and our relative intensities, we have calculated the hindrance factor relative to the Moszkowski single-particle estimate. The results are given in table 3. Malmskog *et al.* obtained similar results using the relative intensities of Ewan and Tavendale [14]). Such large hindrance factors are a well-known feature of $\Delta K = 1$ E1 transitions, and many attempts have been made to explain them [36–38]). Malmskog *et al.* have successfully accounted for the main features in ^{159}Tb by considering the effects of pairing correlations, Coriolis coupling and octupole vibrations.

The 581.1 keV *level.* The energy of the gamma transition from this level to the ground state was measured to be 581.1 ± 0.3 keV. The level decays only to the ground state. Raghavan [34]) has measured the lifetime of this level to be 1.1 ± 0.15 psec. The spin assignments for the 581, 618 and 674 keV levels will be discussed as a unit below.

The 617.9 keV *level.* The energy of this level was measured to be 617.9 ± 0.3 keV. This value was obtained from the sum of the energies of the 58.00 and 559.9 keV gamma rays. The level decays only to the ground and first excited states.

The 674.3 keV *level.* The energy of this level was measured to be 674.3 ± 0.5 keV. This value was obtained from the sum of the energy of the 137.56 keV level and the 536.7 keV gamma ray. The level decays only to the first and second excited states.

The three levels at 581, 618, and 674 keV have been interpreted as members of a $K = \frac{1}{2}$ band [9,12]). The parity of the band is positive, since Raghavan [34]) has shown the 581 keV transition to be mixed M1E2. The $K = \frac{1}{2}$ interpretation is consistent with the decay of the 581 keV level only to the ground state, the small spacing between the 581 and 618 keV levels and the irregular ratio of the spacings between the three band members.

Intensity ratios are given in table 3 for transitions between the 581 keV band and the ground-state band. The ratios agree with the predictions of the Alaga rule for mixed M1E2 transitions. The hindrance factor for the 581 keV transition relative to the Moszkowski single-particle estimate was calculated to be 9 from the data of Raghavan. The log *ft* values of 8.3, 8.4 and 9.2 were measured for the beta decay to the 581, 618 and 674 keV levels, respectively. This result is consistent with a classification of first-forbidden hindered for the beta transitions.

The high $\log ft$ values rule out interpretation of the 581 keV band in terms of a pure $(411)\frac{1}{2}^+$ single-particle state. Diamond *et al.* [9]) have tentatively identified a state at 971 keV as the $(411)\frac{1}{2}^+$ single-particle orbital. The most plausible interpretation of the 581 keV band is as the K_0-2 gamma vibrational band of the ground state. A pure vibrational band would be expected to decay by emission of E2 radiation only, but our data clearly indicate the radiation to be mixed M1E2. Reich and Bünker [39]) have interpreted the 581 keV band as a mixture of the ground-state vibrational band with the $(411)\frac{1}{2}^+$ single-particle state.

The 854.5 keV *level.* The energy of the gamma transition from this level to the ground state was measured to be 854.5 ± 0.4 keV. The level also decays to the first two members of the 581 keV band. The placement of the above level was confirmed from observation of coincidences between the 237 and 274 keV transitions and transitions depopulating the 581 keV band.

A $\log ft$ value of 6.9 was measured for beta decay to the 854 keV level. This value limits the spin of the level to $\frac{1}{2}$, $\frac{3}{2}$ or $\frac{5}{2}$. Absence of decay to any $\frac{5}{2}$ or $\frac{7}{2}$ level ruled out a spin of $\frac{5}{2}$. For a level with $K = \frac{3}{2}$ and a spin and parity of $\frac{3}{2}^+$ or $\frac{3}{2}^-$, decay by E1 and M1 transitions to the spin $\frac{5}{2}$ levels at 348 and 364 keV would be expected to successfully compete with decay to levels in the 581 keV band. Very low upper limits have been set on such decays in table 2. The weakness of the 854 keV transition relative to the 274 keV transition mildly favors a K of $\frac{1}{2}$ for the 854 keV level.

On the basis of the above arguments, we have designated the spin of the 854 keV level to be $\frac{1}{2}$. No single-particle state with $K = \frac{1}{2}$ exists in this energy region except $(411)\frac{1}{2}^+$. In ^{159}Tb, this orbital has been associated with a 971 keV band observed by Diamond *et al.* [9]). We thus think it possible for the 854 keV level to be the first member of a K_0-2 gamma vibrational band built on either the $(413)\frac{5}{2}^+$ or the $(532)\frac{5}{2}^-$ single-particle state. A measurement of the parity of the 854 keV level would aid in choosing between the two above possibilities. The low $\log ft$ value of 6.9 mildly favors the negative-parity state in analogy with $\log ft$ considerations for the 581 keV band. A further example of such a state exists [40]) in ^{187}Re where a gamma vibrational band at 686 keV is built upon a $(514)\frac{9}{2}^-$ single-particle state at 206 keV. The weakness of the 854 keV gamma ray relative to the 237 and 274 keV gamma rays is consistent with the interpretation of the 854 keV level as vibrational in nature.

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References

1) K. O. Nielsen, O. B. Nielsen and O. Skilbreid, Nucl. Phys. **7** (1958) 561
2) S. S. Malik, N. Nath and C. E. Mandeville, Phys. Rev. **112** (1958) 262
3) Kasuke Takahashi, J. Phys. Soc. Japan **17** (1962) 1229
4) B. N. Subba Rao, Nucl. Phys. **36** (1962) 342

5) B. H. Ketelle and A. R. Brosi, Phys. Rev. **116** (1959) 98
6) E. I. Biryukov, O. I. Grigorev, B. S. Kuznetsov and N. S. Shimanskaya, Izv. Akad. Nauk SSSR (ser. fiz.) **25** (1961) 109
7) H. Ryde, L. Persson and K. Oelsner-Ryde, Ark. Fys. **23** (1962) 195
8) M. C. Olesen and B. Elbek, Nucl. Phys. **15** (1960) 134
9) R. M. Diamond, B. Elbek and F. S. Stephens, Nucl. Phys. **43** (1963) 560
10) D. A. Bromley, Nucl. Instr. **28** (1964) 160
11) F. Boehm, G. Goldring, G. B. Hagemann, G. D. Symons and A. Tveter, Phys. Lett. **22** (1966) 627
12) L. Persson, Ark. Fys. **25** (1963) 307
13) L. Funke, H. Graber, K. H. Kaun, H. Sodan and L. Werner, Nucl. Phys. **70** (1965) 353
14) G. T. Evan and A. J. Tavendale, Can. J. Phys. **42** (1964) 2286
15) P. C. Stevenson and W. E. Nervik, U.S. Atomic Energy Commission Report NAS-NS-3020(1961)
16) J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr. **33** (1965) 213
17) W. R. Daniels and D. C. Hoffman, J. Inorg. Nucl. Chem. **28** (1966) 2424
18) C. M. Lederer, J. M. Hollander and I. Perlman, Table of isotopes (John Wiley and Sons, New York, 1967) p. 561
19) J. C. Hill and M. L. Wiedenbeck, Nucl. Phys. **A98** (1967) 599
20) D. P. Donnelly, H. W. Baer, J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr. **57** (1967) 219
21) J. H. E. Mattauch, W. Thiele and A. H. Wapstra, Nucl. Phys. **67** (1965) 1
22) T. Novakov and J. M. Hollander, Nucl. Phys. **60** (1964) 593
23) R. S. Hager and E. D. Seltzer, U. S. Atomic Energy Commission Report CALT-63-60 (1967)
24) J. M. Baker and B. Bleaney, Proc. Roy. Soc. **A245** (1958) 156
25) C. A. Hutchinson and E. Wong, J. Chem. Phys. **29** (1958) 754
26) A. Y. Cabezas, I. Lindgren and R. Marrus, Phys. Rev. **122** (1961) 1796
27) E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson and H. Mark, Phys. Rev. **112** (1958) 518
28) E. E. Berlovich, M. P. Bonitz and V. V. Nikitin, Izv. Akad. Nauk SSSR (ser. fiz.) **25** (1961) 218
29) B. R. Mottelson and S. G. Nilsson, Mat. Fys. Skr. Dan. Vid. Selsk. **1**, No. 8 (1959)
30) G. Alaga, Phys. Rev. **100** (1955) 432
31) S. A. Moszkowski, in Alpha-, beta and gamma-ray spectroscopy, ed. by K. Siegbahn (North-Holland, Amsterdam, 1965)
32) S. Gorodetzky, R. Manquenoville, R. Richert and A. Knipper, J. Phys. Rad. **22** (1961) 699
33) G. A. Vartapetyan, Z. A. Petrosyan and A. G. Khudaverdyan, ZhETF (USSR) **41** (1962) 1704
34) R. S. Raghavan, Phys. Rev. **143** (1966) 947
35) S. G. Malmskog, A. Marelius and S. Wahlborn, Nucl. Phys. **A103** (1967) 481
36) Y. T. Grin and I. M. Pavlichenkow, Phys. Lett. **9** (1964) 249
37) M. N. Vergnes and J. O. Rasmussen, Nucl. Phys. **62** (1965) 233
38) G. Monsonego and R. Piepenbring, Phys. Lett. **21** (1966) 180
39) C. W. Reich and M. E. Bunker, Izv. Akad. Nauk SSSR (ser. fiz.) **31** (1967) 42
40) K. M. Bisgård, L. J. Nielsen, E. Stabell and E. Veje, Izv. Akad. Nauk SSSR (ser. fiz.) **31** (1967) 18