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Decay of a New 5.8-min ^{150}Tb Activity*

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A new short-lived isomer of ^{150}Tb has been identified. The mass assignment was confirmed by excitation functions and cross bombardments. The 5.8 ± 0.2-min activity is probably a 9^+ state ($\pi h_{11/2}\nu f_{7/2}$) and decays chiefly to an (8^+) state at 2554.4 keV in ^{150}Gd with a log*ft* value of 4.1. No isomeric transition to the 3.1-h ^{150}Tb was observed. The γ-ray spectrum was investigated with Ge(Li) detectors. The 19 γ rays observed were assigned to 10 excited levels (in keV) at 638.05, 2^+; 1134.35, 3^-; 1288.4, (4^+); 1700.9, (5^-); 1936.8, (6^+); 2116.1, (6^+); 2211.2, (7^-); 2392.5; 2554.4, (8^+); and 2906.0. The energy spacing of the positive-parity states in ^{150}Gd suggests a close correspondence to a vibrator model although low-spin members of multiplets corresponding to multiphonon states are not observed. The quasiband representation of Sakai appears also to be a useful way of interpreting these states. Three negative-parity states form a sequence which may correspond to a combination of octupole and quadrupole phonons or an octupole quasiband.

I. INTRODUCTION

Isomerism among Tb nuclides is a common occurrence.[1] For spherical nuclei of $Z=65$, the $h_{11/2}$ proton orbital lies relatively low in energy, while in the deformed region the $\frac{11}{2}^-[505]$ neutron orbital is available to produce low-lying, high-spin odd-odd isomers. At the time this work was begun, only a 3.1-h ^{150}Tb was known[2-4]; its spin was believed to be low, since its decay to ^{150}Gd strongly populated states of spin 4 or less.[3,4] Hence it appeared profitable to search for a high-spin, presumably short-lived isomer of ^{150}Tb.

In addition to gaining insight into the systematics of the odd-odd Tb species, we felt that the decay study of a high-spin ^{150}Tb might reveal interesting new structure information on higher-lying states in ^{150}Gd. A recent γ-ray and conversion-electron study of the reaction[5] ^{151}Eu(p, $2n\gamma$) ^{150}Gd has established levels of spin possibly as large as 5. Insufficient information is available, however, to establish quasiband structure[6] or other evidences of the systematics of collective states in ^{150}Gd. This 86-neutron nucleus might show vibrational character[7] or perhaps resemble the transitional 88-neutron nucleus ^{152}Gd.

In this paper we report the discovery of a 5.8-min ^{150}Tb. Its decay strongly resembles that of 4.2-min ^{152m}Tb in which a large fraction of the β-decay intensity goes to a single high-lying level of high spin in the daughter Gd nucleus.[1] As this manuscript was being prepared, we learned of the work of Arlt and co-workers[8] at Dubna, who have also identified the same nuclide. Their results are in good agreement where the two sets of data overlap. They propose only a partial decay scheme.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source Preparation

Sources of ^{150}Tb suitable for singles and coincidence γ-ray determinations were prepared by the reactions ^{151}Eu(α, 5n) ^{150}Tb with 60-MeV ^{4}He ions or ^{151}Eu(^{3}He, 4n) ^{150}Tb with 35-MeV ^{3}He ions. The target material was Eu_2O_3 in which ^{151}Eu was enriched to at least 95%. For most irradiations beam currents were 2 to 5 μA and irradiation times ranged from 0.5 to 6 min. Experimental details were as described previously.[1] Chief contaminants were 4.2-min ^{152m}Tb, ^{28}Al, ^{29}Al, and ^{14}O. Arlt *et al.*[8] used the reactions ^{139}La(^{16}O, 5n)^{150}Tb and ^{141}Pr(^{12}C, 3n)^{150}Tb to prepare their sources.

For a few of the experiments, a gas-transport method was used to carry nuclear-reaction products, including ^{150}Tb recoiling from a Eu_2O_3 target, approximately 30 m to a low-background area. Details of the method will be described in a separate publication.[9] Constant-activity sources of the short-lived species were obtained by operating the transport system continuously.

B. Mass Assignment and Half-Life of the New Activity

Since some of the intense γ rays from the new short-lived activity had the same energy as those observed in the decay of 3.1-h ^{150}Tb, it seemed likely that the short-lived activity was an isomer of ^{150}Tb. Excitation functions were determined to confirm the mass assignment. The γ rays from the new activity decayed with a half-life of 5.8 ± 0.2 min, in agreement with that reported (6.0 ± 0.2 min) by Arlt *et al.*[8]

In Fig. 1 are shown γ-ray spectra of sources produced with ^{4}He-ion bombarding energies of 50, 60, and 70 MeV on a ^{151}Eu target. The Q values[10] for producing ^{152}Tb, ^{151}Tb, ^{150}Tb, and ^{149}Tb from

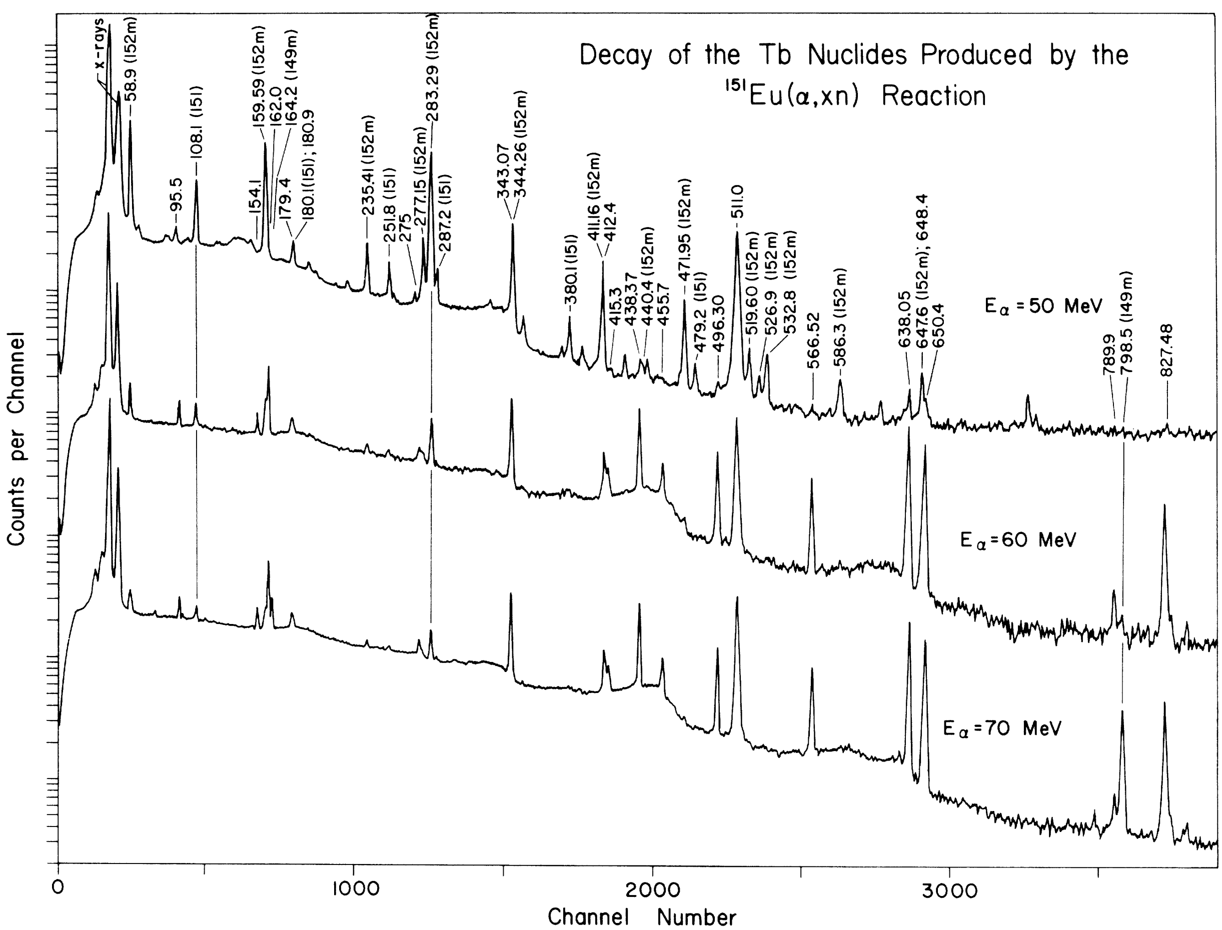

FIG. 1. Spectra of γ rays from the decay of Tb nuclides produced in the ^{151}Eu(α,xn) reactions with α particles of 50, 60, and 70 MeV. Peaks are labeled by γ-ray energies in keV. Mass numbers of Tb nuclides are given in parentheses except for those γ rays assigned to 5.8-min ^{150}Tb.

^{151}Eu(α, xn) are −25.8, −32.9, −41.6, and −49.2 MeV, respectively. At 50 MeV, the γ-ray spectrum is essentially that of ^{152m}Tb; the 108.1-keV line indicates that ^{151}Tb is also present. At 60 MeV, only the more intense ^{152m}Tb lines remain, the ^{151}Tb line is weak, and γ rays associated with the new 5.8-min activity are quite evident. At 70 MeV the spectrum is rather similar to that at 60 MeV, but transitions at 164.2 and 798.5 keV, which have been assigned to ^{149}Tb decay,[11] are now present. From these data it is clear that the new activity could not have mass 149 or 152. Since the 108.1-keV transition in ^{151}Tb does not have a 5.8-min component, the new activity is not likely to have mass 151. The only remaining choice is 150.

The possibility that the activity was an isomer of ^{150}Gd was ruled out on the basis of the following experiment: A target of Sm_2O_3 enriched in ^{152}Sm was irradiated with 80-MeV ^{4}He ions. Transitions from ^{149}Gd decay were observed, indicating that the bombarding energy was sufficient to produce ^{150}Gd, but there was no evidence for a 5.8-min activity.

C. Singles γ-Ray Spectra

The singles γ-ray spectra were obtained with two Ge(Li) detectors. One was a 6-cm^2×(10-mm-drifted-depth) planar detector with resolution 1.2 keV at 122 keV which was used in the energy region up to 1.3 MeV. A 50-cm^3 coaxial detector (resolution 5 keV at 1332 keV) was used to obtain spectra up to 3.5 MeV. Typical spectra are shown in Figs. 2 and 3. The detectors were calibrated for efficiency and energy by methods previously described.[1] Energies and intensities of γ rays were obtained with the code RAGS.[12]

Detailed inspection of the spectra indicated that the peaks in the regions 179-181 and 648-650 keV were doublets. These energy regions are shown on an expanded scale in Figs. 4 and 5. In the former case (Fig. 4) the data were inadequate to permit resolving the doublet. We have assumed that the two lines contributing have equal intensities, and appropriately large errors have been assigned. The resolution of the doublet at 648-650 keV (Fig. 5) was relatively straightforward. In some of the spectra the weak 275-keV line appeared to be a doublet, but interference from the strong 277.15-keV line from ^{152m}Tb prevented detailed treatment. While in the decay scheme proposed there is a place for transitions of 274 and 276 keV, the present evidence is not adequate to show that both transitions occur.

With the 50-cm^3 detector a number of γ rays were observed in the region from 827 keV to about 1800 keV (Fig. 3). Several weak γ rays have the correct half-life to be 5.8-min ^{150}Tb and have the correct energy to be the crossover transitions for some of the more intense low-energy lines. A detailed analysis of the intensities of the weak high-energy lines indicates, however, that these peaks can be accounted for by the summing of coincident transitions. No evidence was found for γ rays of 1278 and 1694 keV which were reported in Ref. 8.

γ rays attributed to 5.8-min ^{150}Tb and their intensities are listed in Table I. Transition energies and intensities are generally in agreement with those reported in Ref. 8 where there is overlap.

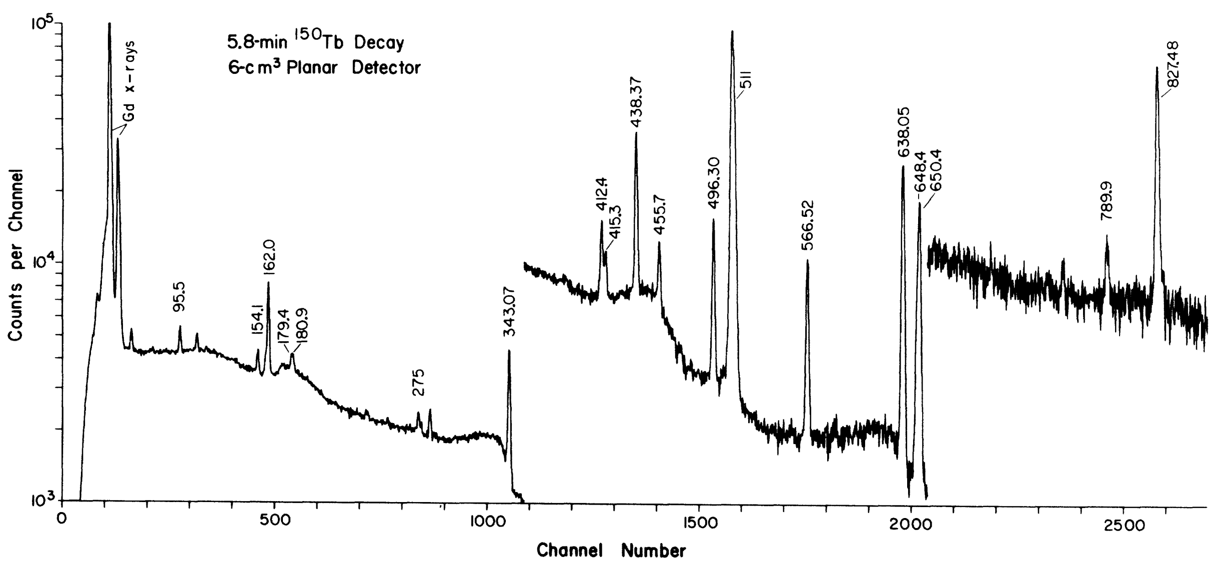

FIG. 2. Low-energy portion of γ-ray spectrum. Peaks labeled by energy (in keV) decayed with a 5.8 ± 0.2-min half-life and are attributed to an isomer of ^{150}Tb.

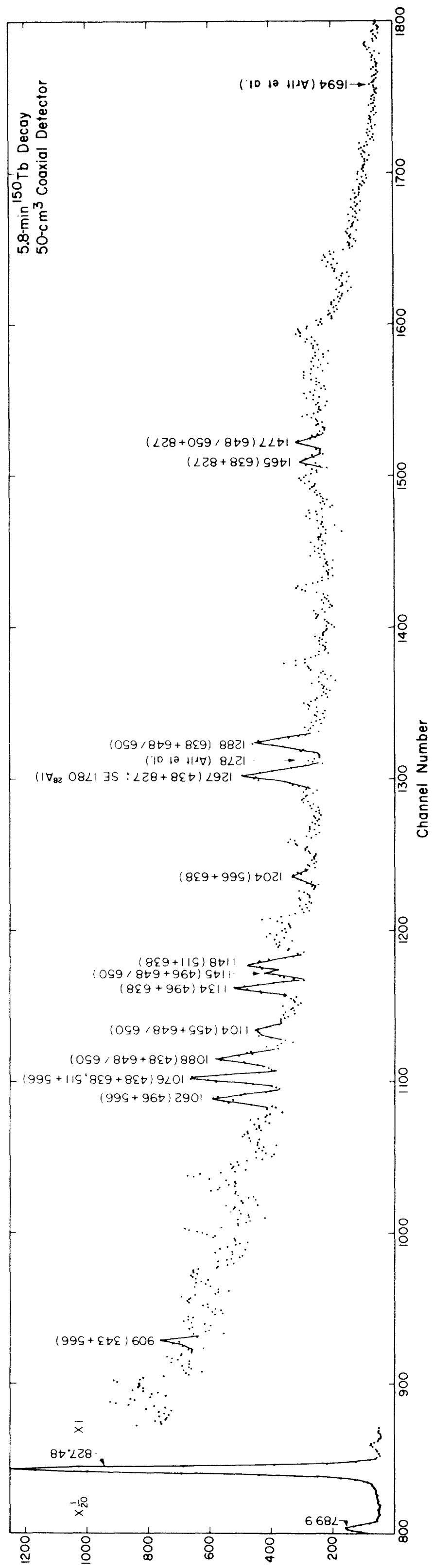

FIG. 3. High-energy portion of γ-ray spectrum. Peaks labeled by energy (in keV) decayed with a 5.8-min half-life but their intensities are those expected for the sum lines indicated. The notation 648/650 means either member of the doublet. The positions of the high-energy γ rays reported in Ref. 8 are indicated.

In Ref. 8 the doublets observed in this work were not resolved and several of the weaker lines were not reported.

D. Coincidence Spectra

Coincidence spectra were taken with several combinations of two Ge(Li) detectors, operated in a two-parameter mode, essentially as described in an earlier report.[1] To summarize briefly, we operated at a resolving time of about 100 nsec; the singles rate of a typical source was about 50 000/sec. Windows on the spectrum of the gating detector were set digitally.

Table II summarizes the results of the experiments. Windows were placed on every γ ray believed to belong to 5.8-min ^{150}Tb. The γ rays of 275 and 179–181 keV were too weak for useful information to be obtained. Some of the coincidences observed resulted from contamination by 4.2-min ^{152m}Tb which was inevitably present in the sources.

In Fig. 6 are shown some typical coincidence spectra. In the spectrum (a) gated by the 638.05-keV γ ray, essentially all of the γ rays in the singles spectrum are seen, consistent with the fact that the 638.05-keV transition is the $2^+ \rightarrow 0^+$ transition. The spectra in (b) and (c) resulted from gates set on the two sides of the doublet in the region 648-650 keV. While neither spectrum is clean, intensity differences of some of the coincident γ rays (e.g., 827.48 keV) are quite apparent. Spectrum (d) resulted from a window placed on a flat region of the singles spectrum in this energy region.

E. Search for an Isomeric Transition

All of the γ rays decaying with a 5.8-min half-life as seen with a conventional Ge(Li) detector, which typically has a low-energy cutoff at about 40 keV, were found to be in coincidence with the 638.05-keV $2^+ \rightarrow 0^+$ transition in ^{150}Gd or with transitions which were in coincidence with the 638.05-keV γ ray. No γ ray corresponding to an isomeric transition could be assigned.

A Si(Li) detector of resolution 330 eV at 5.9 keV was used to study the spectrum in the energy range 3 to 60 keV. An intense spectrum of Gd x rays was seen together with weak Tb x rays. An x-ray–γ coincidence experiment was carried out in which a gate was set on the Tb x-ray region. The only γ rays in coincidence were those from the ^{152m}Tb contamination of the source. No evidence could be found for an isomeric transition.

III. LEVEL SCHEME OF ^{150}Gd

A. Levels Populated in 5.8-min ^{150}Tb Decay

The level scheme of ^{150}Gd which is consistent with all of the information obtained from the decay of 5.8-min ^{150}Tb is shown in Fig. 7. We have assumed that the 2^+ level at 638.05 keV and the 3^- level at 1134.35 keV, which have been reported in both the 3.1-h decay of ^{150}Tb (Refs. 3 and 4) and in ^{151}Eu(p, $2n\gamma$)^{150}Gd spectra,[5] are well established. The 5.8-min decay data confirm these assignments. A preliminary analysis of the data indicated several potential cascade-crossover relationships. Transition energies were determined with as high accuracy as possible to lend confidence to energy sums as a means of establishing these relationships.

The construction of the level scheme is relatively straightforward by a bootstrap approach. The γ rays of 638.05, 650.4, 827.48, and 438.37 keV form a group of particularly strong transitions in cascade. From its intensity one judges that the 650.4-keV γ ray must feed the 2^+ level. A level at 1288.4 keV has also been reported in 3.1-h ^{150}Tb decay[3] and p, $2n\gamma$ studies.[5] The 650.4-keV transition is the crossover for the 154.1-496.30-keV cascade, thus placing the 154.1-keV line. Similarly the 412.4-keV line must feed the level at 1288.4 keV, since the 566.52-keV transition is the crossover for the 154.1-412.4-keV cascade. This produces a level at 1700.9 keV, also seen in 3.1-h ^{150}Tb decay[3] and in p, $2n\gamma$ spectra.[5] The 415.3-keV line is next placed feeding the 1700.9-keV level and the 827.48-keV transition is the crossover for the 412.4-415.3-keV cascade. This results in a level at 2116.1 keV. Placing the 438.37-keV transition on top of the cascade produces a level at 2554.4 keV.

Another set of γ rays which appears to be in cascade are the transitions of 162.0, 455.7, 648.4-650.4 (either or both), and 638.05 keV. If both the 648.4- and 650.4-keV transitions are assumed to be present, the sum of the energies is 2554.6 keV and this cascade represents an alternative route for deexcitation of the 2554.4-keV level. From intensities, the 648.4-keV transition is expected to feed the level at 1288.4 keV; this places a level at 1936.8 keV. The 827.48-keV transition is also the crossover for the 179.4-648.4 cascade. The intensity of the 455.7-keV transition places it next higher in the cascade leading to a level at 2392.5 keV which is fed by the 162.0-keV transition.

The 343.07-keV γ ray appears to be crossover for the 162.0-180.9-keV cascade. This places a level at 2211.2 keV, which then accounts for the coincidence relationship between the 343.07- and 95.5-keV γ rays. The 438.37-keV transition is the crossover for this pair of γ rays.

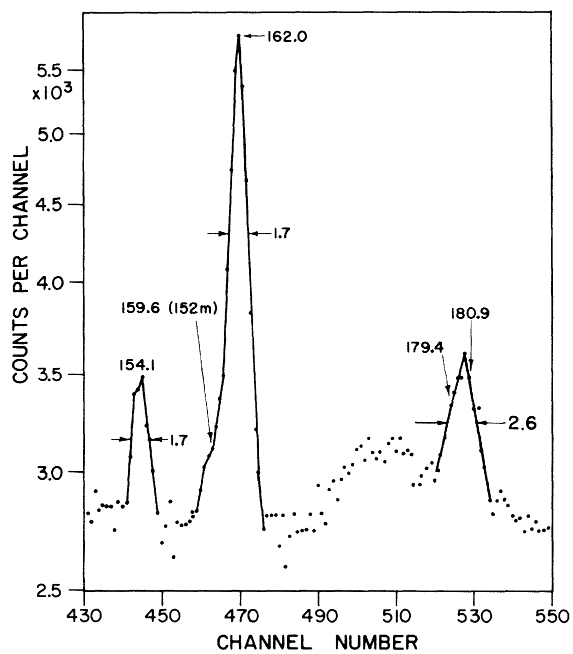

FIG. 4. The region between 150 and 190 keV on an expanded scale. The width of the peak at about 180 keV is significantly greater than the widths of the 154.1- and 162.0-keV peaks. Widths are given in keV.

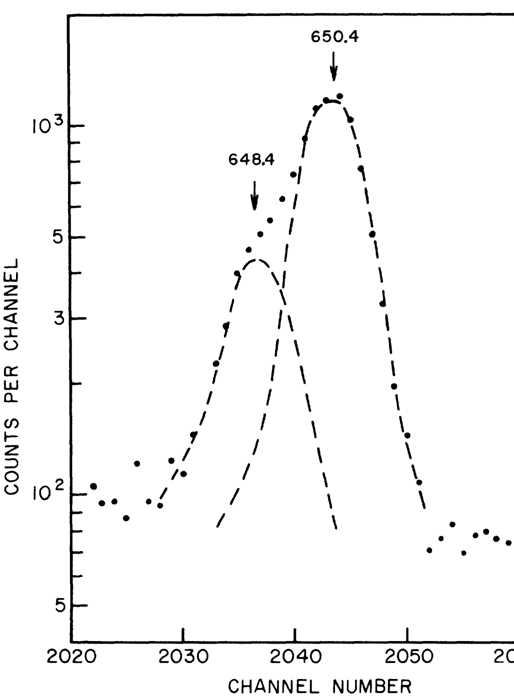

FIG. 5. The region near 650 keV on an expanded scale. The line shape of the strong 638.05-keV γ ray was used to resolve the doublet.

TABLE I. Energies and intensities of γ rays from the decay of 5.8-min ^{150}Tb.

E_γ (keV) This work	E_γ (keV) Ref. 8 [a]	I_γ This work	I_γ Ref. 8	Assignment this work
95.5(2)		5(1)		2211.2 → 2116.1
154.1(2)		10(1)		1288.4 → 1134.35
162.0(2)	161.0	73(5)	60(20)	2554.4 → 2392.5
179.4(6)		14(7)		2116.1 → 1936.8
180.9(6)		14(7)		2392.5 → 2211.2
275(1)		19(7)		2211.2 → 1936.8
343.07(10)	343.0	250(20)	250(25)	2554.4 → 2211.2
412.4(2)		98(6)		1700.9 → 1288.4
	413.0		150(20)	
415.3(2)		40(5)		2116.1 → 1700.9
438.37(10)	438.0	420(30)	420(40)	2554.4 → 2116.1
455.7(2)	455.0	120(30)	90(25)	2392.5 → 1936.8
496.30(10)	496.0	235(10)	275(30)	1134.35 → 638.05
510(1)		... [b]		2211.2 → 1700.9
566.52(10)	566.0	220(20)	230(20)	1700.9 → 1134.35
638.05(10)	638.0	≡1000	≡1000	638.05 → 0
648.4(3)		180(20)		1936.8 → 1288.4
	650.0		870(30)	
650.4(3)		700(30)		1288.4 → 638.05
789.9(4)		23(9)		2906.0 → 2116.1
827.48(10)	828.0	410(30)	450(50)	2116.1 → 1288.4
	1278.0		≈35	
	1694.0		≈15	

[a] Error in energy was estimated in Ref. 8 to be 1.0 keV below 1 MeV.
[b] Not annihilation radiation; presence of γ ray inferred from coincidence experiment. See text.

TABLE II. γ-γ coincidence relationships observed in the decay of 5.8-min ^{150}Tb.

Principal transition in gate (keV)	Coincident γ rays [a] (keV) Definite	Coincident γ rays [a] (keV) Probable
95.5	343, 638, 827	412–415, 648–650
154.1	438, 496, 638, 827	162, 648–650
162.0	456, 496, 638, 648–650	275, 827, β^+
343.07	96, 412–415,[b] 496, 567, 638, 648–650, β^+	275, 678,[b] 827
412.4	343, 438, 638, 648–650, β^+	154, 412–415, 496
415.3	412–415, 438, 496, 567, 638, 648–650	96, 162, 343, 456
438.37	412–415, 638, 648–650, 827	496, 567
455.7	162, 638, 648–650	
496.30	154, 343, 438, 567, 638, β^+	412–415, 648–650
566.52	343, 412–415, 438, 496, 638, β^+	179–181
638.05	96, 154, 162, 179–181, 343, 412–415, 438, 456, 496, 567, 648–650, 827, β^+	
648.4	162, 179–181, 456, 638	275, 343,[b] 438, 648–650
650.4	162, 179–181, 343,[b] 412–415,[b] 438, 456, 638, 827, β^+	648–650
789.9	496, 567, 638, 648–650, 827	412–415
827.48	96, 438, 638, 648–650	154, 162, 179–181, β^+

[a] Energies of coincident γ rays were rounded off for convenience in listing. Both members of the doublets 179–181, 412–415, and 648–650 are not necessarily present. The entry β^+ indicates that 511-keV γ rays were observed; either annihilation radiation or the 510-keV γ ray (or both) were present.
[b] Possible contribution from ^{152m}Tb contamination.

The spectrum gated by the 789.9-keV γ ray shows the 827.48-keV γ ray to be strongly in coincidence. Other coincident γ rays are consistent with those expected from the deexcitation of the 2116.1-keV level. This places a level at 2906.0 keV. Since no other transitions are associated with this level, the assignment is considered to be tentative.

The levels proposed in ^{150}Gd from 3.1-h ^{150}Tb decay,[3] from ^{151}Eu(p, $2n\gamma$)^{150}Gd spectra,[5] from the work of Arlt *et al.*[8] on the short-lived ^{150}Tb decay, and from the present work agree on the levels at 638.05, 1134.35, 1288.4, and 1700.9 keV. Kewley *et al.*[5] very tentatively suggest a level at 2116.1 keV. The other levels at 1936.8, 2211.2, 2392.5, 2554.4, and 2906.0 keV are proposed here for the first time.

The scheme in Fig. 7 satisfactorily accounts for all of the observed γ rays in a unique way. Intensity balance is satisfactory except for the levels at 2211.2 and 1700.9 keV; too little intensity deexcites the former, and the latter requires appreciable direct feeding by β decay. If these two levels were directly coupled, however, both problems would be solved. The energy difference of 510 keV makes it difficult to observe such a transition in a straightforward way.

B. Evidence for a 510-keV Transition

If the level scheme in Fig. 7 is correct, positron and electron-capture decay of 5.8-min ^{150}Tb leads primarily to the 2554.4-keV level. Both the 438.37- and 343.07-keV γ rays depopulate this level and would be in coincidence with annihilation radiation. The 343.07-keV γ ray is also in coincidence with the proposed 510-keV transition, while the 438.37-

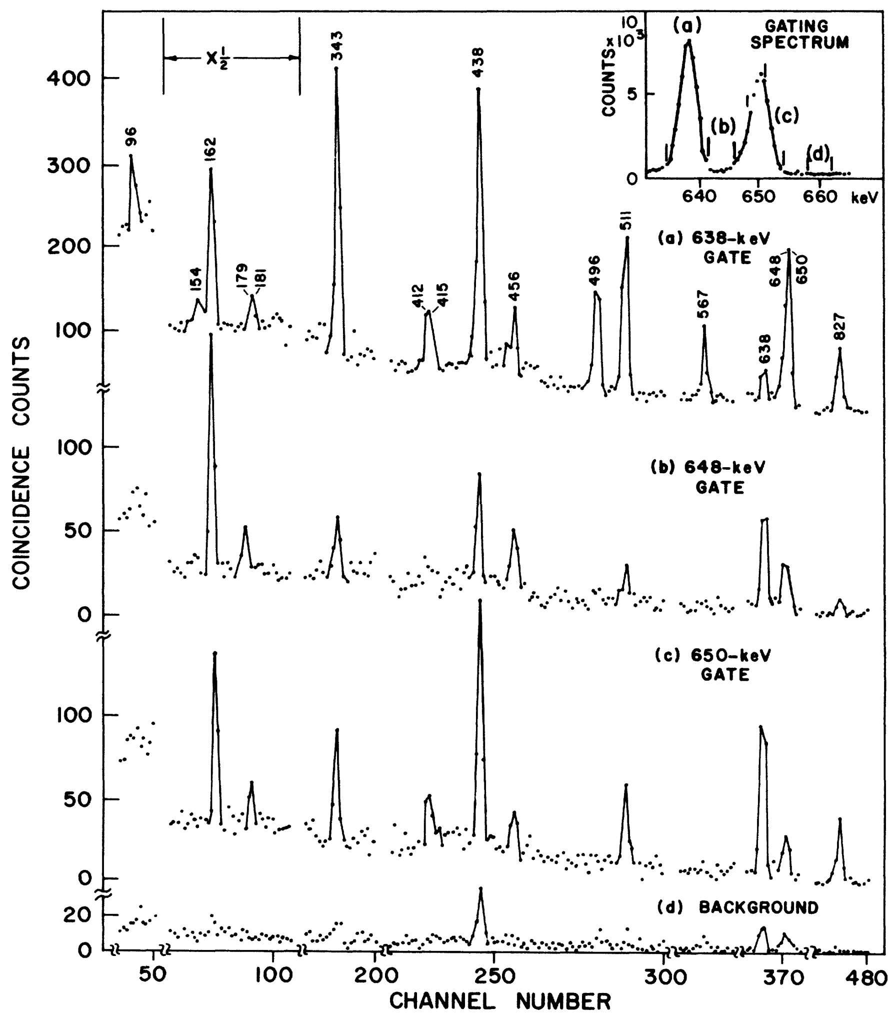

FIG. 6. Coincidence spectra gated by (a) the 638.05-keV transition, (b) the 648.4-keV transition, (c) the 650.4-keV transition, and (d) a flat background region. The singles spectrum in the gating detector and the position of the gates are shown in the inset. Peaks are labeled by energy rounded to the nearest keV.

keV γ ray is not. Thus the intensity ratio of the two γ rays, I_{343}/I_{438}, should depend on whether a coincidence requirement is imposed.

To test this notion, we used the gas-transport system to provide a constant activity source of 5.8-min ^{150}Tb. Two Ge(Li) detectors were placed at 90° and shielding was used between the detectors to reduce the 511-511 background. When no coincidence requirement was imposed, the ratio of peak areas (I_{343}/I_{438}) in the recording detector was 0.50 ± 0.03 (no correction has been made for detector efficiency). In the spectrum in coincidence with the region 509 to 512 keV, the ratio was 1.95 ± 0.79. This large enhancement of the 343.07-keV intensity is direct evidence for the existence of the postulated 510-keV transition.[13]

C. Spins and Parities of Levels in ^{150}Tb and ^{150}Gd

According to the mass tables of Garvey *et al.*,[10] the mass difference ^{150}Tb – ^{150}Gd is 4.49 MeV. The proposed decay scheme of 5.8-min ^{150}Tb implies that at least 74% of the β transitions occur to the 2554.4-keV level. The log*ft* value for this transition is then no more than 4.1, which corresponds to an allowed transition. Since multipolarities are not known, β-decay branching is based on γ-ray intensities rather than transition intensities. log*ft* calculations for branching to other levels in ^{150}Gd, presumably weakly populated, could not be made reliably.

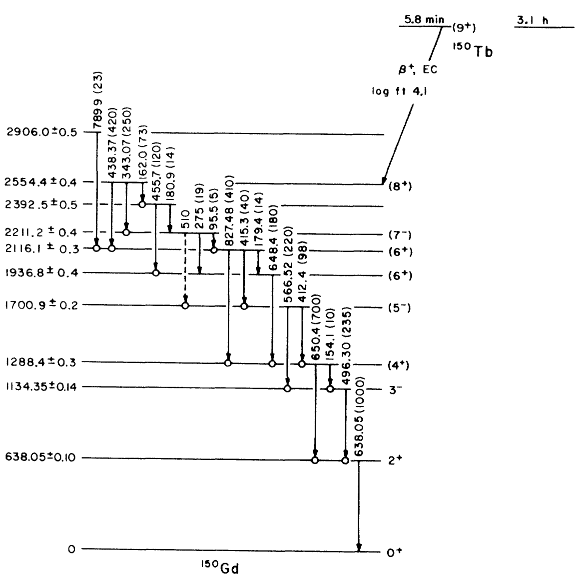

FIG. 7. Level scheme of ^{150}Gd as populated in the decay of 5.8-min ^{150}Tb. All energies are in keV. Intensities are given in parentheses. Circles identify transitions whose placement has been confirmed by coincidence data. The 510-keV transition was not observed directly but inferred from a coincidence experiment (see text).

The ground states[2] of the 85-neutron nuclei ^{149}Gd and ^{147}Sm are $\frac{7}{2}^-$, presumably $f_{7/2}$ states; this is also the case for the 87-neutron species[2] ^{151}Gd and ^{149}Sm. Low-lying proton orbitals in the region of $Z = 65$ include $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$. The log*ft* value is low, characteristic of allowed transitions in which only a spin-flip occurs. The $d_{3/2}$ or $s_{1/2}$ proton orbitals cannot be involved, since all of the low-lying neutron orbitals in the region of 86 neutrons have negative parity. The β transition could, however, be the $h_{11/2}$ proton state decaying to the $h_{9/2}$ neutron orbital in ^{150}Gd. If the neutron orbital in 5.8-min ^{150}Tb is $f_{7/2}$, then 5.8-min ^{150}Tb is likely to be either 2^+ or 9^+. Since the decay strongly populates a high-lying level in ^{150}Gd for which the shortest γ-decay chain to ground is four members, the 9^+ assignment appears to be the more likely. The 3.1-h ^{150}Tb is possibly a 1^- state[4]; the lack of an observable direct transition between the 5.8-min and 3.1-h isomers is not surprising.

The 2554.4-keV level is then taken to be a two-quasineutron state $(h_{9/2}f_{7/2})_{8^+}$. Since we have not determined conversion coefficients or other indicators of multipolarity, we cannot make direct I^π assignments to other levels in ^{150}Gd. We adopt, however, the assignments made in the p, $2n\gamma$ studies[5] [1134.35, 3^-; 1288.4, (4^+)] and use decay patterns to make the tentative I^π assignments shown in Fig. 7. We have assumed that transitions must be $E1$, $M1$, or $E2$.

IV. DISCUSSION

In Fig. 8 the excited levels of ^{150}Gd are drawn to suggest a quasiground-state band[6] with the 2^+, 4^+, and (6^+) states at 638.05, 1288.4, and 1936.8 keV,

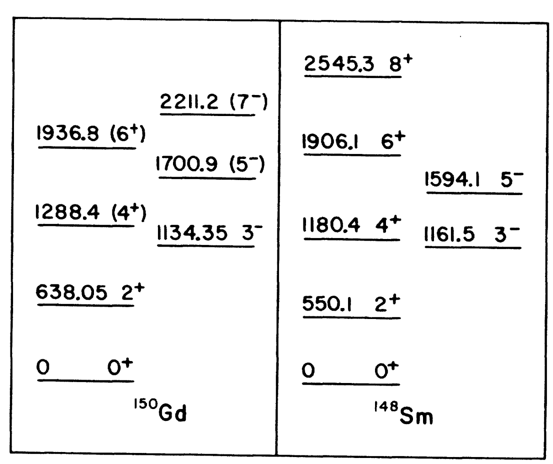

FIG. 8. Comparison of levels (given in keV) in the 86-neutron nuclei ^{150}Gd and ^{148}Sm (Ref. 6).

respectively. The three negative-parity levels at 1134.35, 1700.9, and 2211.2 keV may constitute an octupole quasiband in an extension of Sakai's terminology.[6]

In terms of a vibrator model the negative-parity levels might be considered to be a $\lambda = 3$ phonon coupled to $\lambda = 2$ phonons. The lower-spin members of the multiphonon levels are not observed, because the spin of the feeder level is high and the deexcitation paths favor populating levels of high spin. Similarly if the level at 1288.4 keV is taken to be a two-phonon 4^+ state, the 0^+ and 2^+ members of the triplet are not likely to be observed in 5.8-min ^{150}Tb decay. In the $p, 2n\gamma$ study, however, a (2^+) level at 1430.2 keV and a possible 0^+ level at 1149 keV have been tentatively suggested as the remaining members of the two-phonon triplet.[5]

The 86-neutron nuclides ^{148}Sm (Ref. 6) and ^{150}Gd have very similar level schemes as shown in Fig. 8. The systematic behavior of level energies in the even-Z 86-neutron nuclides which Wilhelmy *et al.*[14] have noted for Xe, Ba, Ce, Nd, and Sm is smoothly extended to Gd. The present results are in good agreement with the pairing-plus-quadrupole model of Kumar and Baranger[7] which predicts ^{150}Gd to be spherical in its ground state; the onset of deformation is with 88-neutron nuclides such as ^{148}Nd, ^{150}Sm, and ^{152}Gd.

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