than 2 MeV.

Nonetheless, a lower limit on the half-lives of the two decay modes is set by the experiment, and the measured half-lives allow for a maximum contribution from the lepton-nonconserving neutrinoless decay mode of

$$\alpha=\left[\frac{\tau_{\frac{1}{2},0\nu}(\text{theoretical})}{\tau_{\frac{1}{2},0\nu}(\text{observed})}\right]^{1/2}=\left[\frac{2\times10^{15}}{3\times10^{18}}\right]^{1/2}=2\times10^{-2}.$$

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Decay of a New Isomer in ^{154}Tb to High-Spin Levels in ^{154}Gd

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Radioactive sources of ^{154}Tb made by the ^{153}Eu$(\alpha,3n)$ and ^{155}Gd$(p,2n)$ reactions have been studied with Ge(Li) and Si(Li) detectors. A new isomer ($T_{1/2}=22.5\pm1.5$ h; spin and parity probably 7^-) has been found in ^{154}Tb. This state decays primarily to an $I^\pi K=7^-7$ isomeric state at 2137.8 keV in ^{154}Gd. Quasiparticle configurations involving the $\frac{11}{2}^-[505]$ neutron orbital are proposed for both of these isomeric states, and retardation factors are determined for transitions from the 2137.8-keV state.

I. INTRODUCTION

Many studies have been devoted to the level structure of ^{154}Gd, one of the $N=90$ nuclei. Most of this work (for example the work of Meyer[1]) has been performed on the β decay of ^{154}Eu, which populates levels in ^{154}Gd below 1.9 MeV. However, there is an almost complete lack of information on higher-lying levels which could be populated in the electron-capture decay of ^{154}Tb ($Q\sim3.8$ MeV). Handley and Lyon[2] established the existence of two levels in ^{154}Tb, and later Harmatz, Handley, and Mihelich[3] assigned a half-life of 22 h and probable spin of 0 to one, and an 8-h half-life and possible spin of 3 to the other. In our studies of the ^{154}Tb decays, we encountered difficulty in attributing all γ rays with approximately 22-h half-lives to the decay of the spin-0 state. There is a group of 22 intense γ rays in the 2–3.5-MeV range which are assigned to levels decaying to both the ground and first excited states in ^{154}Gd (as shown by γ-γ coincidence experiments). The levels from which these transitions proceed must have low spins and thus should be populated by a low-spin 22-h parent. By contrast, there also are intense γ rays which decay with approximately 22-h half-lives and which seem to be associated with high-spin states, as evidenced by the presence of transitions from the 6^+ and 8^+ members of the ground-state band.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The existence of a high-spin isomer in ^{154}Tb was demonstrated by performing experiments on sources made in two ways: (1) by the ^{153}Eu(α, $3n$) reaction using 36-MeV α particles from the Argonne cyclotron, and (2) by the ^{155}Gd(p, $2n$) reaction using 15-MeV protons from the Notre Dame FN tandem accelerator. Using Ge(Li) detectors in singles and coincidence experiments, we have found over 300 γ rays up to 3.5 MeV, at least 15% of which result from decays of two or more of the three states in the parent. In addition, conversion-electron spectra were obtained with a 3-mm $\times$110-mm^2 Si(Li) detector, and half-lives were measured with a system employing 20-cm^3 Ge(Li) and thin NaI detectors.

Using large-volume Ge(Li) detectors, we obtained singles γ-ray spectra for sources made by the two different methods. The upper spectrum of Fig. 1 was accumulated with the 20-cm^3 Ge(Li) detector in an experiment on a source made by the ^{153}Eu(α, $3n$) reaction, while the lower one corresponds to an experiment on a ^{155}Gd(p, $2n$) source using the 40-cm^3 Ge(Li) detector. These spectra cannot be compared in detail, since the relative amounts of the various activities present are different. However, a comparison of the two shows that the 226.1-, 426.8-, and 1419.9-keV peaks are nearly absent in the (p, $2n$) source, while the 346.7-keV peak is greatly reduced. Approximately 30 γ rays are weaker in the proton-produced source exclusive of those proceeding from the first three members of the β- and γ-vibrational bands. By comparison, the group of intense γ rays in the

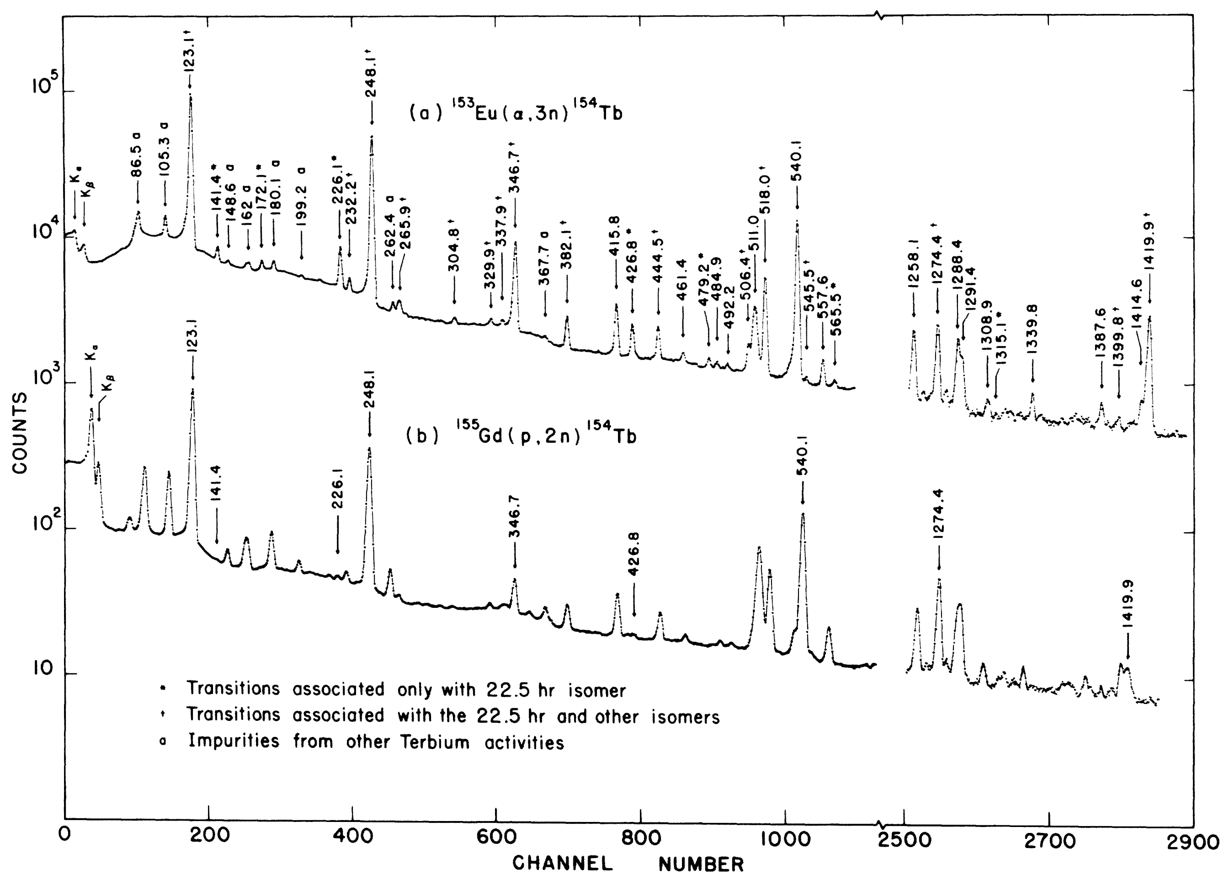

FIG. 1. γ-ray spectra of sources of ^{154}Tb made by the (a) ^{153}Eu(α,$3n$) and (b) ^{155}Gd(p,$2n$) reactions. Irradiation and counting times were comparable. The upper spectrum was obtained with a 20-cm^3 Ge(Li) detector and a 1.05-g/cm^2 Cu absorber. The lower spectrum was obtained with a 40-cm^3 Ge(Li) detector and no absorber. Spectrum (b) has been shifted down by two decades.

2–3.5-MeV region is not reduced in the $(p, 2n)$ source, indicating that the associated levels are indeed fed by a low-spin state in the parent. We have measured the decay rate of one of these γ rays (2064.1 keV) and found that it is due primarily to an activity of 21.8 ± 1.0 h, most likely the spin-0 isomer seen by Harmatz, Handley, and Mihelich[3] in their $^{155}Gd(p, 2n)^{154}Tb$ source. By following the decay of the 540.1-keV γ ray, the strongest one associated with the shortest-lived activity (spin 3), we measure the half-life to be 9.0 ± 1.0 h.

These experiments verify the existence of an activity due to a high-spin state in either ^{154}Gd or ^{154}Tb. We attribute the state to the parent, since the associated γ rays were still present after a source made by $(\alpha, 3n)$ had been chemically and isotopically separated from other material. The decay rate of the 226.1-keV γ ray indicates that the isomer has a half-life of 22.5 ± 1.5 h. Our data have enabled us to construct the partial decay scheme of the new isomer, shown in Fig. 2. The relative placement of the low-spin isomers is established by the fact that the decay curves for the γ rays associated with the spin-0 activity exhibit a characteristic 9.0–21.8-h growth-decay component. Possible 22.5-h γ rays at 267.5 and 565.5 keV are not placed in the level scheme. The transitions from the low-spin members of the γ band and from states in the β band are not shown in this figure, although these γ rays were observed. The 1419.9- and 993.0-keV γ rays are observed in coincidence with the 346.7-keV transition, while the 993.0-keV γ ray is also present in a gate set on the 426.8-keV peak. This leads to the placement of a level at 2137.8 keV. The 1645.9- and 1770.3-keV levels were first postulated by Harmatz, Handley, and Mihelich[3] and are fed also by the 540.1- and 415.8-keV γ rays (not shown in Fig. 2) which are in the 9.0-h activity. The placements of all transitions in Fig. 2, except for that of 1315.1 keV, have been verified by coincidence measurements.

Conversion-electron measurements on a source made by the $^{153}Eu(\alpha, 3n)$ reaction have led to experimental K-shell conversion coefficients for many transitions, some of which are listed in Table I. The γ-ray and K-electron intensities are

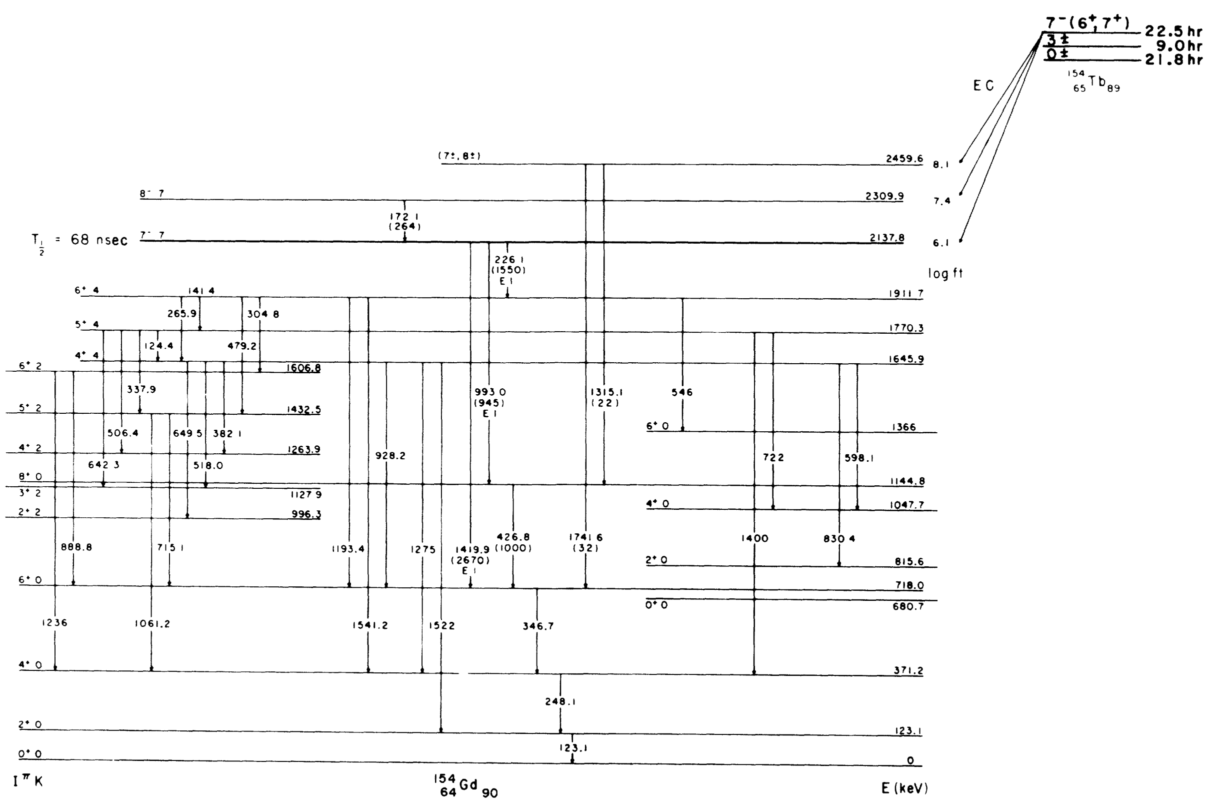

FIG. 2. Levels populated in the decay of the 22.5-h isomer in ^{154}Tb. Transition energies are given in keV and relative γ-ray intensities are shown in parentheses for the transitions from the high-spin states ($I \geq 7$). Transitions from the β band and from low-spin members of the γ band were observed but are not shown. The placements of all transitions, except for that of 1315.1 keV, are verified in coincidence measurements.

derived from simultaneous experiments on sources containing all three activities [using both the 40-cm^3 Ge(Li) and the Si(Li) detectors], and are normalized to the theoretical $E2$ internal-conversion coefficient[4] of the 248.1-keV $4^+ \to 2^+$ transition. The 1419.9-keV transition is $E1$ in character. The 993.0-keV peak in the Si(Li) spectrum cannot be resolved from that at 996.3 keV, but, by assuming $E2$ multipolarity for the latter transition (2^+, $\gamma \to 0^+$), we are able to place an upper limit on α_K for the 993.0-keV transition, indicating that it is also $E1$. The 2137.8-keV state is thus assigned spin and parity of 7^-.

The $E1$ character of the 226.1-keV transition then dictates $I^\pi = 6^+$, 7^+, or 8^+ for the 1911.7-keV state. This level is thought to be a member of the band containing the 1645.9- and 1770.3-keV states because of the similarity in the branching ratios for the transitions from these levels to the ground-state and γ bands. It appears that these levels are the 4^+, 5^+, and 6^+ members of a $K = 4$ band, in view of the observed transitions between the 1911.7- and 1645.9-keV states and the absence of appreciable $M1$ admixtures in the transitions between this and the $K = 2$, γ band.

We have performed timing measurements using a 4-mm NaI detector for K x rays (from the electron capture to the 7^- state) and gating with a 20-cm^3 Ge(Li) detector on γ rays depopulating the 2137.8-keV state. The details of these experiments will be reported at a later date.[5] We measure the half-life of the 2137.8-keV state as 68 ± 4 nsec. The 2310.8-keV level is established by coincidence and timing measurements, which show that the 172.1-keV transition precedes the 68-nsec state. The absence of other detectable transitions from the 2310.8-keV level indicates that it probably corresponds to a rotational excitation ($I^\pi K = 8^- 7$). By contrast, deexcitations of the 2459.6-keV level are observed only to the ground-state band.

III. DISCUSSION

The existence of high-spin isomers in odd-neutron nuclei in this region can be understood in terms of Nilsson orbitals. The ground state of ^{153}Gd ($N = 89$ as is ^{154}Tb) is $\frac{3}{2}$, commonly attributed to the $\frac{3}{2}^+[651]$ neutron orbital. For small deformations, the next three orbitals, $\frac{3}{2}^-[521]$, $\frac{5}{2}^+[642]$, and $\frac{11}{2}^-[505]$, are very close in energy. Isomers attributed to the $\frac{11}{2}^-[505]$ orbital have been observed in nine different odd-A Sm, Gd, Dy, or Er isotopes,[6] and it appears that this orbital is also

TABLE I. Experimental and theoretical K-shell internal-conversion coefficients for some of the relevant transitions in the decay of 22.5-h ^{154}Tb.

E_γ (keV)	$10^3 \times \alpha_K$ (experimental)	$10^3 \times \alpha_K$ (theoretical)[a] $E1$	$E2$	$M1$	Multipolarity
226.1	24.1 (2.5)	28	110	175	$E1$
232.2[b]	89.1 (8.5)	26	98	160	$E2$
248.1	82.0[c]	22.5	82	135	$E2$
304.8	42.5 (5.9)	13.3	44	77	$E2$
346.7	31.0 (2.5)	9.6	31	56	$E2$
382.1	26.2 (3.1)	8.6	23	44	$E2$
415.8[d]	6.4 (0.8)	6.2	18.5	35	$E1$
426.8	13.2 (4.0)	5.7	17.0	32	$E2$
444.5[b]	15.4 (1.1)	5.2	15.3	29	$E2$
479.2	12.3 (2.1)	4.4	13.0	24	$E2$
506.4	10.0 (1.1)	3.9	11.0	21	$E2$
518.0	11.3 (0.9)	3.8	10.6	20	$E2$
540.1[d]	3.9 (0.3)	3.4	9.4	17.6	$E1$
598.1	8.9 (1.8)	2.7	7.2	13.7	$E2$
649.5	6.8 (0.6)	2.25	5.9	11.0	$E2$
993.0	≤0.92[e]	0.98	2.4	3.8	$E1$
996.3	2.3[e]	0.97	2.3	3.8	$E2$
1004.7[b]	2.14 (0.17)	0.96	2.3	3.7	$E2$
1419.9	0.59 (0.13)	0.51	1.15	1.65	$E1$

[a] Theoretical values taken from Sliv and Band (see Ref. 4).
[b] These correspond to transitions from members of the β and γ bands and are expected to be $E2$.
[c] 248.1-keV conversion coefficient normalized to the theoretical $E2$ value.
[d] Transitions in the 9.0-h activity feeding the 1645.9-keV state.
[e] 996.3-keV conversion coefficient normalized to $E2$ to determine upper limit on α_K for the 993.0-keV transition.

giving rise to high-spin states in ^{152}Tb, ^{152}Eu, and ^{154}Tb. Takahashi, McKeown, and Scharff-Goldhaber[7] have observed an 8^- state at 147.8 keV in ^{152}Eu. They attributed it to the $\frac{11}{2}^-[505]$ neutron orbital coupling with the $\frac{5}{2}^+[413]$ proton orbital, which describes the ground states of the odd deformed Eu isotopes. Bowman, Sugihara, and Hamiter[8] have recently reported a 4.2-min state in ^{152}Tb with spin and parity of 8^+ $(\frac{11}{2}^-[505]_\nu+\frac{5}{2}^-[532]_\pi)$, which decays to a probable 7^+ state at 2394.5 keV in ^{152}Gd.

The logft of 6.1 for electron-capture decay from the high-spin isomer in ^{154}Tb to the 2137.8-keV state indicates either an allowed hindered or a first-forbidden unhindered transition.[9] Since the former is more likely in view of available orbitals, the parity of the 22.5-h isomer is probably negative. A spin of 6 for this state is not likely, since we can detect no direct population of the $I^\pi K=4^+4$ state in the 22.5-h activity and since the logft of 7.4 for decay to the 2310-keV state (8^-) would almost certainly rule out a second-forbidden transition. An 8^- assignment is unlikely, since the allowed transition to the expected 9^- member of the 7^- band is not seen. An assignment of 7^- is indicated, consistent with the available Nilsson orbitals. Coupling of the $\frac{11}{2}^-[505]$ neutron orbital with the $\frac{3}{2}^+[411]$ proton orbital, which describes ground states of the odd deformed Tb isotopes, gives $I^\pi=7^-$ for $\Sigma=1$ (i.e., spins parallel). This same neutron orbital can be coupled with the $\frac{3}{2}^+[651]$ neutron orbital, which is the ground state of ^{153}Gd, to give $I^\pi=7^-$ $(\Sigma=1)$ for the 2137.8-keV state in ^{154}Gd. The 2186.0-keV state, which is heavily populated in the 9.0-h decay, may well be the 4^- state resulting from the $\Sigma=0$ coupling of these orbitals, since the 415.8- and 540.1-keV transitions between this state and the 4^+ and 5^+ members of the $K=4$ band have $E1$ multipolarities (see Table I). Likely assignments for the states of interest are then:

22.5-h isomer (^{154}Tb):

$$\tfrac{3}{2}^+[411]_\pi+\tfrac{11}{2}^-[505]_\nu\to 7^-,\ \Sigma=1;$$

2137.8-keV state (^{154}Gd):

$$\tfrac{3}{2}^+[651]_\nu+\tfrac{11}{2}^-[505]_\nu\to 7^-,\ \Sigma=1;$$

2186.0-keV state (^{154}Gd):

$$\tfrac{3}{2}^+[651]_\nu+\tfrac{11}{2}^-[505]_\nu\to 4^-,\ \Sigma=0.$$

The spin and parity of the 2459.6-keV state can only be quoted as $7^\pm$ or $8^\pm$. The $\frac{3}{2}^-[521]$ neutron orbital is near the Fermi surface and thus we merely suggest that this state might result from the $\frac{3}{2}^-[521]_\nu+\frac{11}{2}^-[505]_\nu$ quasiparticle configuration, giving spin and parity of 7^+. The measured logft of 8.1 would not be unreasonable for such an assignment.

The 1419.9-keV $E1$ γ-ray transition $(\Delta K=7)$ is found to be retarded by a factor of 1.61×10^9 compared to the Weisskopf estimate, indicating a hindrance of 34 per degree of forbiddenness. This agrees with the general observations of Borggreen *et al.*[10] who find hindrances in the range of 57 to 95 for $\Delta K=8$ $E1$ transitions in heavier deformed nuclei. By contrast, the 226.1-keV $\Delta K=3$ $E1$ transition is hindered by a factor of 1.12×10^7, which corresponds to a retardation of 3.34×10^3 per degree of forbiddenness.

Very recently, Toriyama *et al.*[11] have reported a new isomer in ^{156}Tb with a half-life of 24.4 h and a spin greater than 3. It is quite possible that this isomer also results from the $\frac{11}{2}^-[505]$ neutron orbital, which indeed may be responsible for isomers over a wide range of nuclei with 87 to 93 neutrons.

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