Investigation of Branching Ratios Between Isomeric States of ^{154}Tb

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Half-lives and branching ratios of the three isomeric states of ^{154}Tb have been measured from irradiation of gadolinium with 45- and 65-MeV protons. The spin assignments $7^{\pm}$, $3^{\pm}$, and $0^{\pm}$ previously suggested were confirmed as representing the m_2, m_1, and g states, respectively. The branching from the m_2 to m_1 isomers was found to be weak, approximately $1.8 \pm 0.6\%$. Branching from the m_1 to g state was quite substantial, measured to be $21.8 \pm 0.7\%$.

INTRODUCTION

In the past three years, much research has been directed to studying the decay characteristics of the neutron-deficient isotopes of terbium, especially ^{154}Tb,[1-7] which are at the lower limit of the highly deformed region. The existence of three isomeric states of ^{154}Tb was first suggested by Riedinger *et al.*[4] The spins and parities of these states are now thought to be 7^-, $3^{\pm}$, and 0^+ [4,6,7] with respective half-lives of 22.5, 9.0, and 21.8 h.[2-4] It is the purpose of the present work to confirm the existence and suggested ordering[4,6] of these three states, and to measure the branching between them by following their decay characteristics.

EXPERIMENTAL

The target arrangement was identical to that used in previous nuclear reaction studies in the McGill Radiochemistry Laboratory.[8] Gadolinium oxide of natural abundance was mounted in a thin-walled aluminum tube and irradiated in the internal beam of the McGill University synchrocyclotron with protons of 45 to 65 MeV, for periods of 1.5 to 2 min. The target was slit open and the irradiated samples were deposited on a card suitable for counting. Counting began as early as two hours after irradiation making use of a 30-cm^3 Ge(Li) detector with associated 4096-channel pulse-height analyzer. Samples were counted at intervals of 0.5–3 h for as much as 120 h after irradiation. The intensity of individual peaks in each spectrum was determined after subtraction of the underlying Compton background. There were no problems with resolution of γ rays of interest in this work (see Fig. 1). Transitions of excited levels of ^{154}Gd populated following β decay of the three isomeric states were measured. The work reported includes 11 measurements of the decay from the m_1 to g states and 4 of the decay from the m_2 to m_1 state.

RESULTS AND DISCUSSION

Four γ-ray transitions at 226.1, 540.1, 2064.1, and 2187.8 keV, depopulating levels in the daughter nucleus ^{154}Gd, were followed for periods up to 120 h. Previous work[6] suggests that these transitions are populated *only* following decay of the m_2, m_1, g, and g states, respectively.

A. Half-Life Measurements

Analysis of the decay curve of the 226-keV transition, one of the most intense peaks associated with decay of the 7^- isomer,[6] shows a single component decay (Fig. 2). The statistically weighted average of a series of four measurements was found to be 22.6 ± 0.6 h in excellent agreement with previous measurements[5,6] and with a somewhat reduced limit of error. There seems no question that the 226.1-keV transition arises following decay of the m_2 state.

Measurement of the 540-keV transition, associated with decay of the $3^{\pm}$ isomer exhibits the

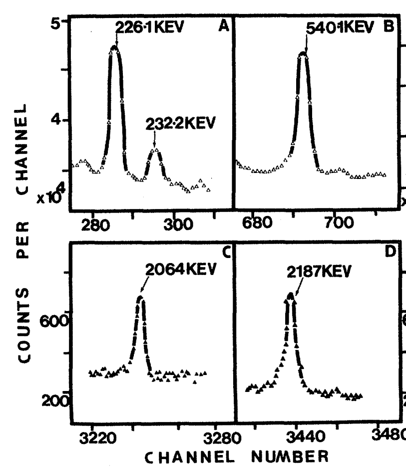

FIG. 1. Observed activities in 40 channels around peaks of interest in this work. (Scales on left and right are for A, C and B, D, respectively.)

characteristics of a long half-life parent feeding a short half-life daughter (Fig. 3).

The activity of each component was resolved, using the CLSQ decay curve analysis program[9] and the half-life measured for the m_2 transition. Eight measurements, statistically weighted, yield a half-life of 9.0 ± 0.5 h. Again, agreement with work of Sousa *et al.*[6] is excellent; however, we find a 10% shorter half-life than Ageev, Mitrovich, and Feoktistov[3] (9.9 ± 0.1 h) from their spallation work of 680-MeV proton bombardment of ^{182}Ta followed by chemical separation of the rare earths. It is to be noted that the possibility that the 21.4-h component (rather than the 22.6-h m_2 state) is the parent of the 540-keV transition is eliminated in the paragraph following.

Measurements of the 2064- and 2187-keV transitions (associated with the 0^+ isomer)[6] indicate that there is growth from a shorter lived component (see Fig. 4). This establishes that the 0^+ state must lie below the $3^\pm$ in energy and cannot be the parent of the 9.0-h activity. The half-life of the 0^+ isomer determined by statistical weighting of 11 measurements was found to be 21.4 ± 0.5 h, consistent with previous literature values.[2,4] It is noteworthy that this represents the first measurement of a statistically significant difference in the half-lives of the m_2 and g states. Furthermore, the relative intensities of the 2064- and 2187-keV transitions, both exhibiting growth, are independent of proton bombarding energy while the 226-keV peak showing no growth varies with energy relative to the 2064- and 2187-keV peaks. Together these facts indicate absolute confirmation of two isomers with similar half-lives.

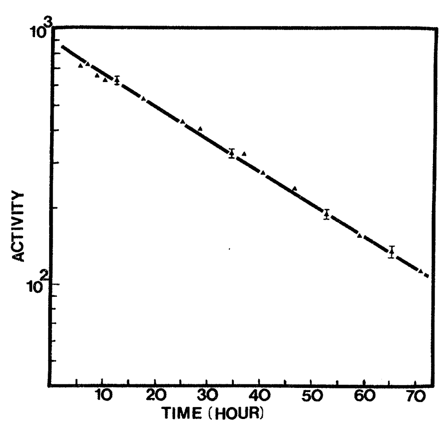

FIG. 2. Experimental decay curve for the peak at 226.1 keV (45-MeV bombarding energy; activities are measured in counts per minute).

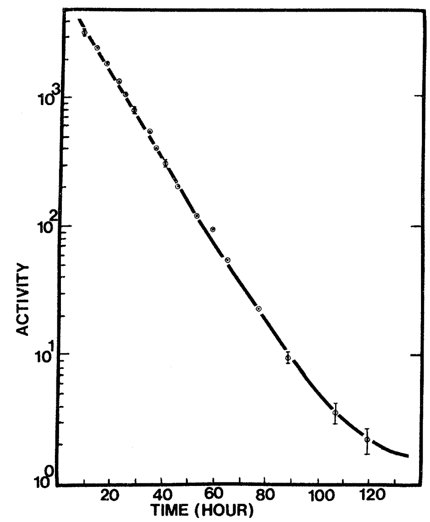

FIG. 3. Experimental decay curve for the peak at 540.1 keV (45-MeV bombarding energy; activities are measured in counts per minute).

B. Branching Ratios

The relative γ-ray intensities for transitions following the β decay of the three states are known from the comprehensive studies of Riedinger *et al.*[4] and Sousa *et al.*[6] The fraction of decays from one isomeric state to another has been determined by careful analysis of the growth and/or decay of these states.

From the 540-keV transition growth, one can

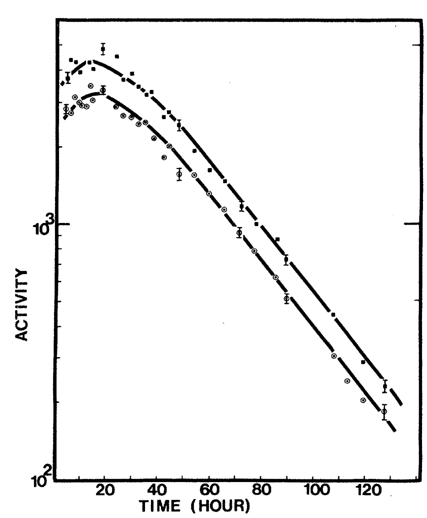

FIG. 4. Experimental decay curves for the peaks at 2187 keV (top curve) and 2064 keV (bottom curve). (45-MeV bombarding energy; activities are measured in counts per minute).

measure the apparent intensity of the $m_2 \to m_1$ transition; this measurement, which is independent of the conversion coefficient for the $m_2 \to m_1$ transition, may be compared to the intensity of the 226-keV transition, which represents a known[6] fraction of $m_2 \to {}^{154}$Gd transition. Four measurements of this branching fraction indicate that the decay of $m_2 \to m_1$ accounts for $1.8 \pm 0.6\%$ of all decays of m_2. This is, as suggested in Ref. 6, a branch of less than 2%.

The growth and decay of the peaks at 2064 and 2187 keV give a measure of the m_1 to g transition. In conjunction with the data on decay of the 540-keV peak, the fraction of decays of m_1 to the ground state may be calculated. Decay of the m_2 state to m_1 and thence from m_1 to g is a second-order correction to decay of the 2064 and 2187 peaks but by a process of iteration, it has been made. Results of the analysis of 11 measurements show a branch to the ground state of $21.8 \pm 0.7\%$, larger than might be expected,[6] but not inconsistent with an $E3$ transition.

C. Discussion

It was previously suggested that the ground-state Nilsson configuration for ^{154}Tb is $\frac{3}{2}^+[411]_\pi + \frac{3}{2}^+[651]_\nu \to 0^+$, $\Sigma = 0$, and for the m_2 isomer is $\frac{3}{2}^+[411]_\pi + \frac{11}{2}^-[505]_\nu \to 7^-$, $\Sigma = 1$.[4] Because of the presence of two neutron states of differing parity, $\frac{3}{2}^+[651]$ and $\frac{3}{2}^-[521]$, the parity of the spin-3 m_1 isomer was not known. However, many isomers attributed to the $\frac{3}{2}[521]$ orbital have been observed among rare-earth isotopes of the same region.[10] It is suggested, based upon the branching fractions measured in this work, that the parity of this state is negative, i.e., that the m_1 configuration is likely to be $\frac{3}{2}^+[411]_\pi + \frac{3}{2}^-[521]_\nu \to 3^-$ and the $m_2 \to m_1$ transition is $E4$. With a 1.8% branch, the partial half-life for the $m_2 \to m_1$ transition is 4.52×10^6 sec (52.3 day); it is doubtful that an $M4$ transition of reasonable energy could occur with such rapidity. Assuming the m_1 is 3^-, the partial half-life of the $3^- \to 0^+$, $m_1 \to g$ transition is 1.48×10^5 sec (1.7 day), which is longer than normally expected for an $E3$ transition of the order of 100 keV. One must conclude then that the ground and first excited states differ in energy by only a very small amount. It is significant in this respect that the neighboring isotones of $N = 89$, ^{153}Gd and ^{155}Dy, have ground states $\frac{3}{2}^+$,[11] and $\frac{3}{2}^-$,[12] respectively, illustrating the similarity in energies of the [651] and [521] Nilsson states.

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