BRIEF REPORTS

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Decay properties of ^{154}Tm and observation of fine structure in its α-particle spectrum

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Decay properties of the high- and low-spin isomers of ^{154}Tm were investigated following the on-line mass separation of $A=154$ nuclides produced in ^{64}Zn irradiations of ^{92}Mo and ^{94}Mo. The α-decay branching ratio of the high-spin isomer was determined and two γ rays were added to its $(\beta^{+}+\text{EC})$ decay. In addition, fine-structure peaks were observed in the α spectra of both isomers. [S0556-2813(97)01412-X]

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Some years ago, with the use of the OASIS on-line isotope separator facility [1] at the Lawrence Berkeley Laboratory's SuperHILAC, results on the decay properties of ^{154}Lu and ^{154}Yb were reported [2]. In the case of ^{154}Lu, 15 β-delayed-proton (3.2–5.7 MeV) and 8 β-delayed-α-particle (8.5–11.5 MeV) decay events were observed. To confirm that ^{154}Lu was indeed the precursor of these delayed-particle decays, additional experiments dealing with $A=154$ radioactivities were performed. The additional measurements produced more than double the previous number of both proton and α-particle events as well as the observation of K x rays in coincidence with the delayed protons, confirming their assignment to ^{154}Lu β decay. The interested reader is referred to a 1991 annual report [3] wherein these results are discussed briefly.

In this paper, we present data from the second set of experiments that deal with the decay properties of the low- and high-spin isomers of ^{154}Tm. These activities were identified via their α decays in 1964 by Macfarlane [4]. While the α decays have since then been studied and confirmed by several other investigators (see Refs. [5, 6]) the ^{154}Tm β^{+} and electron capture (EC) decay branch has been reported on only once, and that was in an unpublished form [7]. Our data add two γ rays to this $(\beta^{+}+\text{EC})$ decay and determine the α-decay branching ratio of the high-spin isomer. In addition, we observe weak transitions in the α spectra of both ^{154}Tm isomers.

Self-supported metal foils 1.85 and 2.08 mg/cm^2 thick of ^{92}Mo (97% enrichment) and ^{94}Mo (92% enrichment), respectively, were bombarded with ^{64}Zn ions extracted from the SuperHILAC. At the center of the targets the ^{64}Zn incident energies were calculated to be about 265 and 285 MeV for ^{92}Mo and ^{94}Mo, respectively. After mass separation, the $A=154$ products were transported to a fast cycling tape system and positioned in an array of detectors. The detector system consisted of a Si particle ΔE-E telescope and a hyperpure Ge detector facing the radioactive layer, and a 1-mm-thick plastic scintillator and an n-type Ge detector (relative efficiency of 52.3%) located on the other side of the tape. Also, a 24.3% n-type Ge detector oriented at 90° with respect to the other two Ge detectors, was placed ~4.5 cm from the radioactive source (see Ref. [8] for a drawing of this arrangement). Coincidences among γ rays, x rays, positrons, and α particles were recorded in an event-by-event mode, with all events tagged with a time signal for lifetime information. Collection and counting cycles of 16 s were used. Singles data were acquired with the 52.3% n-type and the hyperpure Ge detectors in a multispectrum mode with the cycle time divided into eight time bins. Additionally, singles spectra were accumulated with the 24.3% detector to provide data in which geometrical summing effects in the detector were minimized.

Due to the poor efficiency for release of hafnium from the separator surface ionization source and the small cross sections for producing very proton-rich nuclei in neutron-evaporation reactions, ^{154}Hf $(\beta^{+}+\text{EC})$ decay (see Refs. [5, 6] for a summary of the nuclide's properties) was not observed with either target. This difficulty in evaporating neutrons from nuclei close to the proton drip line was evident in our production of ^{154}Lu in the ^{92}Mo (^{64}Zn, pn) reaction but not in the ^{94}Mo (^{64}Zn, $p3n$) reaction. In the case of the ^{92}Mo target, ^{154}Tm could be produced independently only in reactions involving molybdenum isotopes with $A\geqslant 94$; thus ^{154}Tm decay originated mainly from the low-spin isomer

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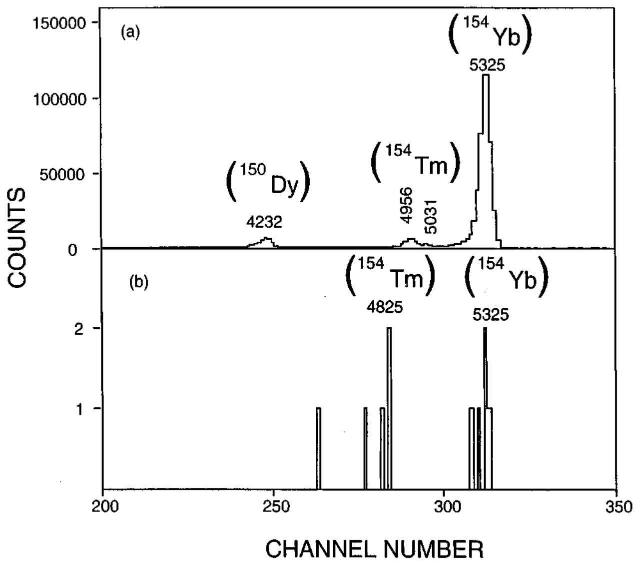

FIG. 1. α-particle spectral data obtained in ^{64}Zn bombardments of ^{92}Mo. (a) shows the total spectrum observed, while (b) shows α-decay events in coincidence with a 130-keV γ ray. Indicated energies are in keV.

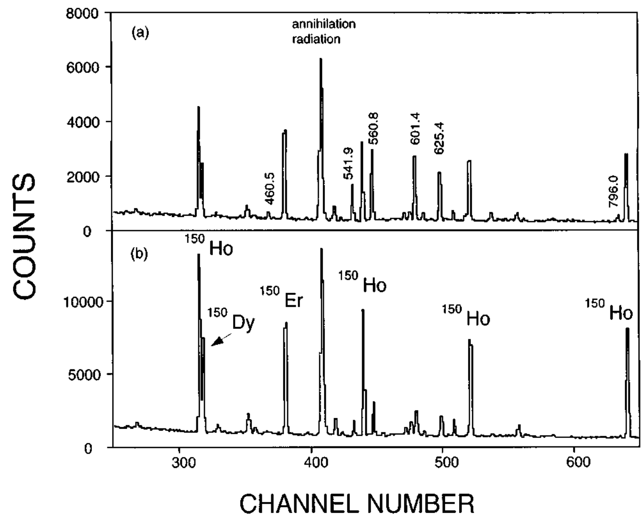

FIG. 2. γ-ray spectral data obtained in ^{64}Zn bombardments of ^{94}Mo. (a) shows the data accumulated during the first 4 s of counting, while (b) shows data accumulated during the last 12 s of counting. Transitions assigned to ^{154}Tm are labeled in (a) by energy in keV. Intense γ rays that belong to longer-lived nuclides are labeled in (b) by the isotope.

populated by ^{154}Yb $(\beta^{+}+\mathrm{EC})$ decay. Contrastingly, in the ^{94}Mo experiment, where ^{154}Tm was produced following the evaporation of one neutron and three protons, it was the decay of the high-spin isomer that predominated.

Figure 1(a) shows the α-particle spectrum recorded in the Si ΔE-E telescope during the experiment with the ^{92}Mo target. The dominant peak, 5325(5) keV [5,6], is due to ^{154}Yb α decay. Also observed are the 4956(3)- and 5031(3)-keV [5,6] α transitions of the ^{154}Tm low- and high-spin isomers, respectively. (The ^{150}Dy α peak originates from the following decay sequence: $^{154}\mathrm{Yb}\rightarrow{}^{150}\mathrm{Er}\rightarrow{}^{150}\mathrm{Ho}\rightarrow{}^{150}\mathrm{Dy}$.) The only γ ray that we observe to follow the $(\beta^{+}+\mathrm{EC})$ decay of the ^{154}Tm low-spin isomer is the 560.8-keV transition which connects the first-excited (2^{+}) and ground (0^{+}) states in ^{154}Er [5,6]. Because evidence [2,5,6] shows that the parent ^{154}Tm state most probably has a spin and parity of 2^{-}, the 560.8-keV γ ray should encompass the bulk of the low-spin isomer's $(\beta^{+}+\mathrm{EC})$ decay strength. Based on that assumption we determined its α-decay branching ratio by comparing the absolute intensities of the 4956-keV α peak and the 560.8-keV γ ray. The resultant ratio of 0.54(5) agrees within error limits with the only previously available value of 0.44(15) [9].

Coincidences between the α particles shown in Fig. 1(a) and photons recorded in the 52.3% Ge detector revealed K x rays, annihilation radiation, and a γ ray at 130(1) keV. A gate was set on this 130-keV transition and α particles that gave rise to these γ-ray events were back projected. The coincident α-decay spectrum generated in this manner is displayed in Fig. 1(b). One sees, in addition to random events from ^{154}Yb, a group at 4825(15) keV. This α transition cannot be associated with ^{154}Yb because the first-excited state in ^{150}Er is located at 1578.9 keV [10]. We assign it to the ^{154}Tm low-spin species since a 130.0-keV γ ray has been observed to follow ^{150}Er $(\beta^{+}+\mathrm{EC})$ decay [11] in which low-spin levels (including one at 130.0 keV) in ^{150}Ho were populated. Our proposal is that the 130-keV γ ray that we observe in coincidence with the 4825-keV α peak is the same transition as that seen in ^{150}Er decay. The intensity of this weak α transition *vis-a-vis* the main 4956-keV peak is $4.5(20)\times10^{-3}$.

Figures 2(a) and 2(b) show γ-ray data recorded in the 52.3% n-type Ge detector with the ^{94}Mo target during the first 4 and last 12 s of the 16-s counting cycle, respectively. γ rays assigned to the 3.3-s ^{154}Tm level are labeled by energy in Fig. 2(a). In addition to the four previously known [7] transitions at 541.9, 625.4, 601.4, and 560.8 keV, we observe two other γ rays, 460.5 and 796.0 keV. The four transitions seen earlier constitute the main cascade in ^{154}Er, 8^{+} (2329.5 keV)$\rightarrow6^{+}$ (1787.6 keV), $\rightarrow4^{+}$ (1162.2 keV), $\rightarrow2^{+}$ (560.8 keV), $\rightarrow0^{+}$ (0.0 keV), while the 796.0-keV γ ray has been observed in-beam [5,6] and is proposed to deexcite an (8^{+}) level at 2583.6 keV to the 1787.6-keV 6^{+} level. The new 460.5-keV γ ray was not seen in coincidence with the other five transitions. Table I summarizes the γ-ray data for the ^{154}Tm high-spin isomer. It should be noted that γ-ray intensities were not given in Ref. [7].

With a Q_{EC} of 4.51 MeV for ^{154}Tm [5,6] and by the assumption of no γ-ray feeding from higher-lying levels, we

TABLE I. Energies and intensities of γ rays following the $(\mathrm{EC}+\beta^{+})$ decay of the ^{154}Tm high-spin isomer.

E_γ (keV)	I_γ (relative)[a]
460.5(2)	8(3)
541.9(1)	57(8)
560.8(1)	100
601.4(1)	95(5)
625.4(1)	88(5)
796.0(2)	20(4)

[a]Normalized to a value of 100 for the 560.8-keV transition. For intensity per 100 decays of the ^{154}Tm high-spin isomer, multiply by 0.42(5).

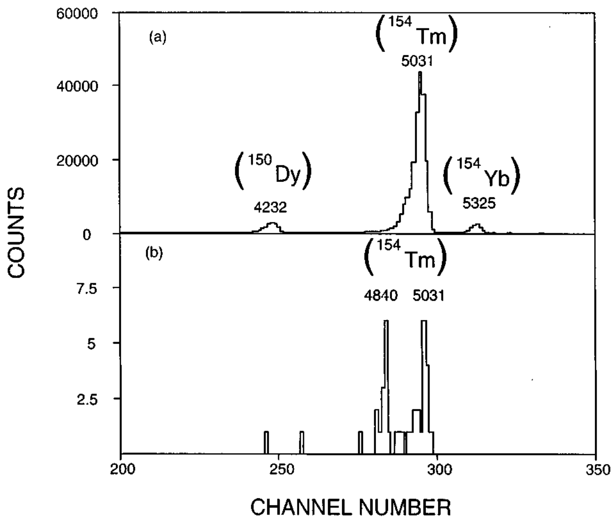

FIG. 3. α-particle spectral data obtained in ^{64}Zn bombardments of ^{94}Mo. (a) shows the total spectrum, while (b) shows α-decay events in coincidence with a 197-keV γ ray. Indicated energies are in keV.

estimate a logft value of ~4.2 for the $(EC+\beta^{+})$ population to the 2329.5-keV state in ^{154}Er. The allowed nature of this $(EC+\beta^{+})$ transition agrees with the suggested 9^{+} and 8^{+} assignments [5,6] for the Tm parent and Er daughter levels, respectively. For the 2^{+}, 4^{+}, and 6^{+} states γ-ray intensities (taking into account error limits) listed in Table I are consistent with no direct feedings from ^{154}Tm. In the case of the 2583.6-keV level, once again assuming no feeding from higher-lying states, one calculates a logft value of ~4.5 in agreement with its proposed (8^{+}) assignment [5,6].

The total α-particle spectrum recorded in the $\Delta E - E$ telescope is shown in Fig. 3(a). Here the dominant peak, at 5031 keV, is that of the ^{154}Tm high-spin isomer. By comparing the absolute intensity of this peak with that of the $2^{+}\rightarrow 0^{+}$ 560.8-keV γ ray we determined the high-spin level α branching to be 0.58(5). Coincidences between α particles and photons revealed the presence of a 197(1)-keV γ ray. Back-projected α particles in coincidence with this γ ray are shown in Fig. 3(b). In addition to random 5031-keV events a peak is seen at 4840(15) keV. We assign it to the ^{154}Tm high-spin isomer and suggest that it populates a new level located 197(1) keV above the ^{150}Ho (9^{+}) high-spin isomer [10]. The intensity of the 4840-keV α transition relative to that of the main 5031-keV peak is $2.4(5)\times 10^{-3}$.

The α-decay data for ^{154}Tm are summarized in Table II. Based on this information and using the formalism developed by Rasmussen [12] α-reduced widths (δ^2) were calculated for all four transitions. These widths (included in Table II) are to be compared with δ^2 values for ground-state-to-ground-state (s-wave) transitions of neighboring even-even

TABLE II. Summary of ^{154}Tm α-particle decays.

	E_{α} (keV)	I_{α} (relative)	δ^2 (keV)
Emitter			
^{154}Tm (low-spin)	4956(3)[a]	100[b]	49(8)
^{154}Tm (low-spin)	4825(15)	0.45(20)[b]	0.10(9)
^{154}Tm (high-spin)	5031(3)[a]	100[c]	57(11)
^{154}Tm (high-spin)	4840(15)	0.24(5)[c]	0.11(7)

[a]Energy from Refs. [5, 6].
[b]For intensity per 100 decays of the ^{154}Tm low-spin isomer, multiply by 0.54(5).
[c]For intensity per 100 decays of the ^{154}Tm high-spin isomer, multiply by 0.58(5).

α emitters which range [13] from 90 to 130 keV for $N=84$ parents and from 100 to 200 keV for $N=86$ parents. According to the rules for level assignments adopted by Nuclear Data Sheets (see, e.g., Refs. [5, 6]), states connected by α transitions have the same spin and parity if the hindrance factors (HF's) are less than four, where the HF is defined as the ratio of neighboring s-wave δ^2 values to that of the transition under consideration. For ^{154}Tm and its α-decay daughter ^{150}Ho the assignments of the high- and low-spin isomers have been adopted [5,6,10] to be 9^{+} and 2^{-}, respectively. The unhindered nature of the two main ^{154}Tm transitions shows that they connect pairs of these 9^{+} and 2^{-} states. The two ^{154}Tm fine-structure α decays have HF's of about 500 relative to their respective main transitions. These large retardations cannot be due primarily to nonzero l transfers because within the Rasmussen prescription [12] each additional unit of angular momentum changes the δ^2 value only by factors of 2 or 3. Thus in the case of the 4825-keV transition, which proceeds from the 2^{-} ^{154}Tm state to the 130.0-keV level in ^{150}Ho whose adopted [10] spin assignment is $(1^{+},2^{+},3^{+})$, the change in l cannot account for the observed HF. The parent and daughter levels connected by the α decay must have very different nuclear configurations. The same is probably true for the 4840-keV transition from the 9^{+} ^{154}Tm isomer though in this case the final state is a level in ^{150}Ho whose spin assignment is unknown.

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