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Brief Reports

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Fine structure in ^{153}Tm α decay

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In an investigation of $A=153$ isotopes fine structure was observed in ^{153}Tm α decay. Besides the previously known α transitions that feed the ^{149}Ho $h_{11/2}$ (0.0 keV) and $s_{1/2}$ (49.0 keV) isomers, two, very much weaker, α groups were found to populate the $d_{3/2}$ (220.4 keV) and $d_{5/2}$ (564.4 keV) states in ^{149}Ho. Based on the ^{149}Ho level scheme and on the Q_α values for the two main ^{153}Tm α transitions, we determine that the $h_{11/2}$ level in ^{153}Tm is the ground state and that the $s_{1/2}$ state lies 43±7 keV above it. Energy systematics for the $s_{1/2}$ and $h_{11/2}$ proton states in even-N odd-Z nuclei near $N=82$ are discussed.

The 5.11-MeV α-particle group known[1] for more than 20 years to follow the α decay of ^{153}Tm has recently been shown[2] to encompass, besides the main group at 5.103±0.003 MeV, a less intense peak at 5.096±0.004 MeV. This lower-energy peak is associated with the ^{153}Tm low-spin, $s_{1/2}$, isomer (whose existence was anticipated but not verified until the work of Schardt *et al.*[2]) while the 5.103-MeV peak follows the decay of the high-spin, $h_{11/2}$, state. In the present investigation by performing (α-particle)-(γ-ray) coincidence measurements, fine structure was observed in the ^{153}Tm α-decay spectrum.

A 1.85-mg/cm^2 foil of ^{92}Mo (enriched to 97.37%) was bombarded with 285-MeV ^{64}Zn ions from the Lawrence Berkeley Laboratory SuperHILAC. At the center of the target the ^{64}Zn energy was calculated to be 267 MeV. Reaction products with $A=153$ were then mass separated at the OASIS on-line facility,[3] collected with a programmable tape system, and transported to a counting station. There, a Si particle ΔE-E telescope and hyperpure Ge detector faced the radioactive layer, while a 1-mm thick plastic scintillator and an n-type Ge detector (relative efficiency of 52%) were located on the other side of the tape. In addition, a 24% n-type Ge detector, oriented at 90° with respect to the other two Ge detectors, was placed ~4.5 cm from the radioactive source. Coincidences between particles, γ rays, x-rays, and positrons were recorded in an event-by-event mode; all events were tagged with a time signal for half-life information. Collection and counting cycles of 1.28, 4.0, and 12.8 s were used in this investigation. Singles data were also taken with the 52% n type and the hyperpure Ge detectors in a multispectrum mode wherein cycle times were divided into eight equal time intervals.

Figure 1(a) shows the α-particle spectrum recorded in the Si ΔE-E telescope. Besides the ^{153}Tm α particles, one observes a 4.67-MeV group and a 3.91- and 4.01-MeV doublet. They are known to belong to the α decays of ^{153}Er (Ref. 4) and of the ^{153}Ho high- and low-spin isomers (Ref. 5), respectively. The full-width at half maximum for the α-particle peaks observed in our spectra was ~60 keV. Thus we could not resolve the two ^{153}Tm α groups reported in Ref. 2. However, we observed γ ray transitions that follow[6] the β decays of both the $s_{1/2}$ and $h_{11/2}$ ^{149}Ho isomers. In our investigation these ^{149}Ho γ rays can originate only from ^{153}Tm α decay. Therefore, in agreement with Ref. 2, there must be two α-decaying isomers in ^{153}Tm.

Low-lying levels in ^{149}Ho have been investigated[6,7] via the β decay of ^{149}Er. These studies established that four of the five states located below ~1 MeV were represented (in ascending order of excitation) by the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ proton orbitals; the fifth one, represented by the $h_{11/2}$ orbital, was assumed to be close in energy to the

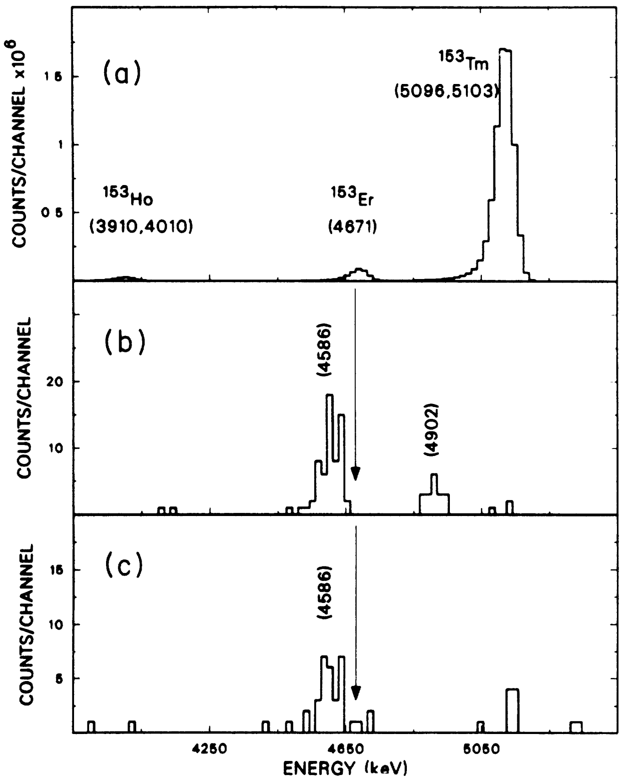

FIG. 1. Part (a) shows the singles α-particle spectrum measured at $A=153$, while parts (b) and (c) show α groups observed in prompt coincidence with the 171.4-, and 344.0-keV γ rays in ^{149}Ho, respectively.

$s_{1/2}$ level. A detailed decay scheme[8] for the ^{149}Er $h_{11/2}$ and $s_{1/2}$ isomers has recently been constructed. It verifies the sequence of the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ states and shows, for the first time, that the ground state in ^{149}Ho is the $h_{11/2}$ proton level while the $s_{1/2}$ state is isomeric and is located at 49.0 keV. The resultant excitation energies of the $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ states are 220.4, 564.4, and 1001.3 keV, respectively.

In parts (b) and (c) of Fig. 1 we show α spectra in prompt coincidence with the 171.4- and 344.0-keV γ rays that connect the $d_{3/2}\rightarrow s_{1/2}$ and $d_{5/2}\rightarrow d_{3/2}$ ^{149}Ho states, respectively. While the two transitions were too weak to be observed in the raw, total coincidence γ-ray spectra, they were visible in the spectrum (see Fig. 2) recorded by the 52% Ge detector in coincidence with α particles. Gates were set on the 171.4- and 344.0-keV peaks, and, α particles that gave rise to these γ-ray events were then back projected; the coincident α spectra generated in that manner are shown in Figs. 1(b) and 1(c), respectively. One sees that there are peaks, 4586±10 and 4902±15 keV, in Fig. 1(b) which, because of their very low intensities, could not be observed in the singles spectrum; one of them, 4586 keV, also appears in coincidence with the 344.0-keV transition [Fig. 1(c)]. Based on these coincidence relationships it is clear that the two new α groups represent fine structure transitions from ^{153}Tm which proceed to the $d_{5/2}$ and $d_{3/2}$ levels at 564.4 and 220.4 keV.

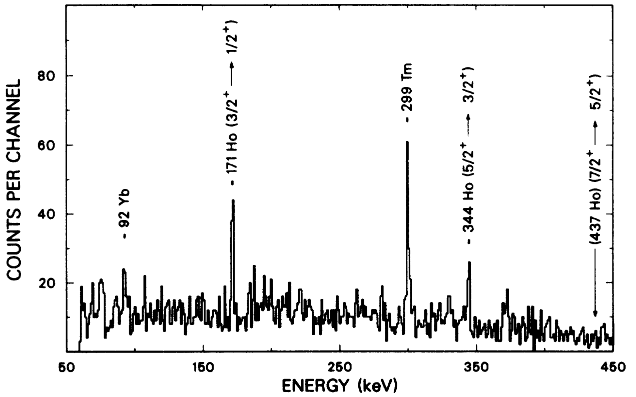

FIG. 2. Portion of the γ ray spectrum measured in prompt coincidence with α particles (transitions are labelled by energy and element). The 171.4- and 344.0-keV γ rays that deexcite the $d_{3/2}$ and $d_{5/2}$ levels in ^{149}Ho were used as gates to generate the α spectra shown in Figs. 1(b) and 1(c), respectively. The arrow marks the energy at which the 436.9-keV γ ray ($g_{7/2}\rightarrow d_{5/2}$ transition) should have been observed. The 91.8- and 299.3-keV peaks are intense γ rays in ^{153}Yb and ^{153}Tm β-decay, respectively; their presence in the figure is due to random coincidences.

The expected energies of the fine structure transitions for each ^{153}Tm isomer to the 564.4- and 220.4-keV states are [4553 (from $h_{11/2}$), 4594 (from $s_{1/2}$) keV] and [4888 (from $h_{11/2}$), 4929 (from $s_{1/2}$) keV], respectively. We, however, are unable to tell whether the 4586- and 4902-keV α groups originate from the $h_{11/2}$ ground state, or the $s_{1/2}$ isomer, or from both of these levels because of the small number of recorded events and the 60-keV energy resolution of the particle telescope. (Note that the widths of the two α groups are comparable to those of peaks in the singles spectrum, i.e., ~100 keV at the base.)

The intensities of the 4586- and 4902-keV peaks, *vis-à-vis* the main ^{153}Tm doublet, are $(4.5\pm0.6)\times10^{-5}$ and $(1.8\pm0.4)\times10^{-5}$, respectively. There is no indication in Fig. 2 of the 436.9-keV γ ray which connects the $g_{7/2}$ (1001.3 keV) and $d_{5/2}$ (564.4 keV) levels in ^{149}Ho; within our detection limits the intensity of the ^{153}Tm α transition to the 1001.3-keV state is $<6\times10^{-6}$. In general, our fine structure results are similar to those reported by Liang *et al.*[9] in their recent investigation of ^{151}Ho α decay to ^{147}Tb, i.e., transitions to the $g_{7/2}$ level at 719.2 keV were not observed, and the strongest fine structure decay was to the $d_{5/2}$ level at 354.1 keV. Additionally, they could only set intensity limits for the transitions to the $d_{3/2}$ level at 253.4 keV; as in our study these transitions must be substantially less intense than the ones that populate the $d_{5/2}$ state.

Our proposed ^{153}Tm α decay scheme is shown in Fig. 3 where α transitions are indicated to the $d_{3/2}$ and $d_{5/2}$ states from both the $h_{11/2}$ and $s_{1/2}$ parent levels. We also show the $h_{11/2}$ state as the ^{153}Tm ground state with the $s_{1/2}$ level isomeric at an excitation energy of 43±7 keV. This separation energy was deduced from the ^{149}Ho level scheme (Ref. 8) and Q_α values (Ref. 2) of the main ^{153}Tm α groups that connect the respective $h_{11/2}$ and $s_{1/2}$ states in the parent and daughter nuclei.

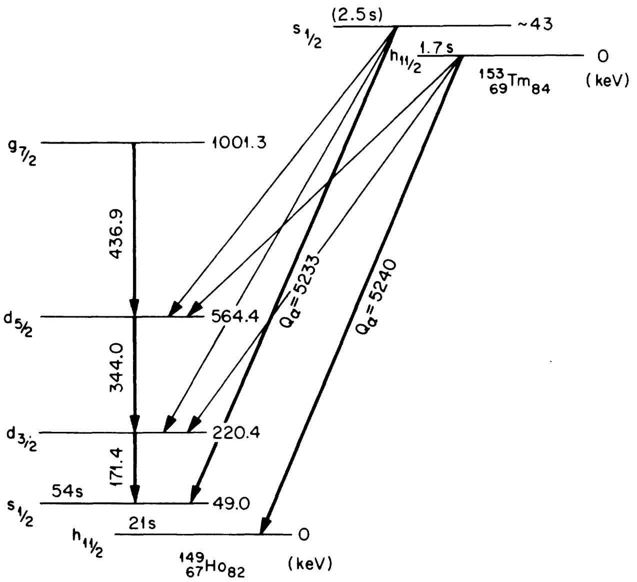

FIG. 3. Alpha-decay scheme of ^{153}Tm. The ^{149}Ho level scheme is from Ref. 8, while the Q_α values shown for the ^{153}Tm $h_{11/2}$ and $s_{1/2}$ isomers are from energies measured by Schardt *et al.* (Ref. 2). Because of the 60-keV (FWHM) resolution of our particle telescope we could not determine from which of the two isomers the fine structure ^{153}Tm α groups originate. Thus, transitions from both isomers to the 220.4- and 564.4-keV ^{149}Ho levels are indicated. The 2.5-s half-life of the ^{153}Tm $s_{1/2}$ isomer is taken from Ref. 2.

TABLE I. Excitation energies of $h_{11/2}$ and $s_{1/2}$ proton states.

Nucleus	$[Z,N]$	Energy (keV) $s_{1/2}$	Energy (keV) $h_{11/2}$	References
^{147}Tb	[65,82]	0.0	50.6	9
^{149}Tb	[65,84]	0.0	36.0	10
^{151}Tb	[65,86]	0.0	99.5	11
^{149}Ho	[67,82]	49.0	0.0	8
^{151}Ho	[67,84]	41.4	0.0	9
^{153}Ho	[67,86]	68[a]	0.0[a]	10,12
^{147}Tm	[69,78]	67	0.0	13
^{153}Tm	[69,84]	43	0.0	2,8
^{155}Tm	[69,86]	~ 41[b]	0.0[b]	14

[a] The excitation energy for the low-spin isomer in ^{153}Ho was originally reported (Ref. 12) to be ~ 60 keV. Our value of 68 keV is calculated by using α decay energies reported in Ref. 12 and the 36.0-keV excitation energy recently determined (Ref. 10) for the $11/2^-$ isomer in ^{149}Tb.

[b] Based on the assumption that the α group reported (Ref. 14) for the α decay of ^{155}Tm is in fact a doublet where the two α transitions originate from the $s_{1/2}$ and $h_{11/2}$ isomers in ^{155}Tm and feed the corresponding proton states in ^{151}Ho.

The two proton orbitals represent the lowest-lying levels in odd-Z even-N nuclei near $N = 82$ after the $g_{7/2}$ and $d_{5/2}$ orbitals have been filled at $Z = 64$. While these separation energies are important for determining masses from Q_{EC} and Q_α measurements and for providing level energies to compare with shell-model calculations, they are difficult to obtain because the two states are not connected by isomeric γ rays. Table I summarizes excitation energies of the $s_{1/2}$ and $h_{11/2}$ proton levels in ^{147,149,151}Tb (Refs. 9–11), ^{149,151,153}Ho (Refs. 8, 9, and 12), and ^{153}Tm (Refs. 2 and 8). We include energies for ^{147}Tm (deduced from direct proton decay results[13]) even though its neutron number of 78 removes it somewhat from the remainder of the nuclei listed in the table, and for ^{155}Tm where the value is based on the assumption that the single α group reported[14] for its α decay is in fact a doublet as is the case for ^{153}Tm. One notes that in terbium ($Z = 65$) the $s_{1/2}$ orbital is the ground state while in holmium ($Z = 67$) and thulium ($Z = 69$) the $h_{11/2}$ orbital is the ground state and the $s_{1/2}$ level has become a hole state; this reversal of level sequences between ^{147}Tb and ^{149}Ho was predicted by Hartree-Fock-Bogoliubov calculations.[7] Based on the information in Table I the $s_{1/2}$ orbital most probably is the first-excited level in ^{151}Tm (it and the $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ states have been observed[15] from ^{151}Yb β decay). However, as one proceeds to higher atomic numbers this orbital's energy should increase and at some point the low-lying $d_{3/2}$ state should drop below the $s_{1/2}$ state in excitation. This change in level ordering may provide an additional explanation as to why ^{155}Lu (Ref. 16) and ^{157}Lu (Ref. 17) have been observed to have only one α group, i.e., the low-spin isomer may be represented by the $d_{3/2}$ proton orbital. The change in the configuration would cause retardation in α decay and thus make it more difficult to resolve a close-lying doublet.

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