Investigation of $A = 155$ and $A = 151$ nuclides: Identification of the ^{155}Tm $s_{1/2}$ isomer and of the ^{155}Yb β-decay branch

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(Received 19 June 1991)

The decay properties of ^{155}Lu, ^{155}Yb, ^{155}Tm, and of the α-decay daughters ^{151}Er and ^{151}Ho were investigated following the on-line mass separation of $A=155$ nuclides produced in ^{64}Zn irradiations of ^{95}Mo. In the study, the half-life of the low-spin isomer in ^{155}Lu was measured to be 140±20 ms, the β-decay branch of ^{155}Yb was identified by observing daughter γ rays and Tm K x rays, and the existence in ^{155}Tm of an $s_{1/2}$ isomer ($T_{1/2}=44\pm4$ s), in addition to the $h_{11/2}$ ground state ($T_{1/2}=21.6\pm0.2$ s) was established. Schemes for the β decays of ^{155}Yb, ^{155}Tm, and ^{151}Er are proposed. New information on ^{151}Er decay establishes the $s_{1/2}$ isomer in ^{151}Ho to be 41.1±0.2 keV above the $h_{11/2}$ ground state. Also, branchings of 90±5, 28±7, and 80^{+15}_{-20}% were determined for the α decays of ^{155}Yb, ^{151}Ho, and ^{151}Ho^m, respectively.

I. INTRODUCTION

With the use of the OASIS on-line isotope separator facility [1] at the Lawrence Berkeley Laboratory's SuperHILAC, we investigated the decay properties of $A=155$ nuclides and of their $A=151$ α-decay daughters. This study is part of our overall investigation of nuclei in the 82-neutron region of the periodic chart, with our more recent experiments involving isotopes located on the heavier side of the $N=82$ closed shell (see, for example, Refs. [2–5]). Here, we discuss the decay properties of $^{155}_{71}$Lu$_{84}$, $^{155}_{70}$Yb$_{85}$, $^{155}_{69}$Tm$_{86}$, $^{151}_{68}$Er$_{83}$, and $^{151}_{67}$Ho$_{84}$. Figure 1 summarizes the α-particle and (EC+β^+) decay chains investigated.

A self-supported metallic foil, 2.07 mg/cm^2 in thickness, of ^{95}Mo (enriched to 98.8%) was bombarded with 291-MeV ^{64}Zn ions extracted from the SuperHILAC. The ^{64}Zn energy at the midpoint of the ^{95}Mo foil was calculated to be 273 MeV. After mass separation the $A=155$ products were transported ionoptically to a fast cycling tape system and positioned between an array of detectors. These consisted of a Si particle ΔE-E tele-

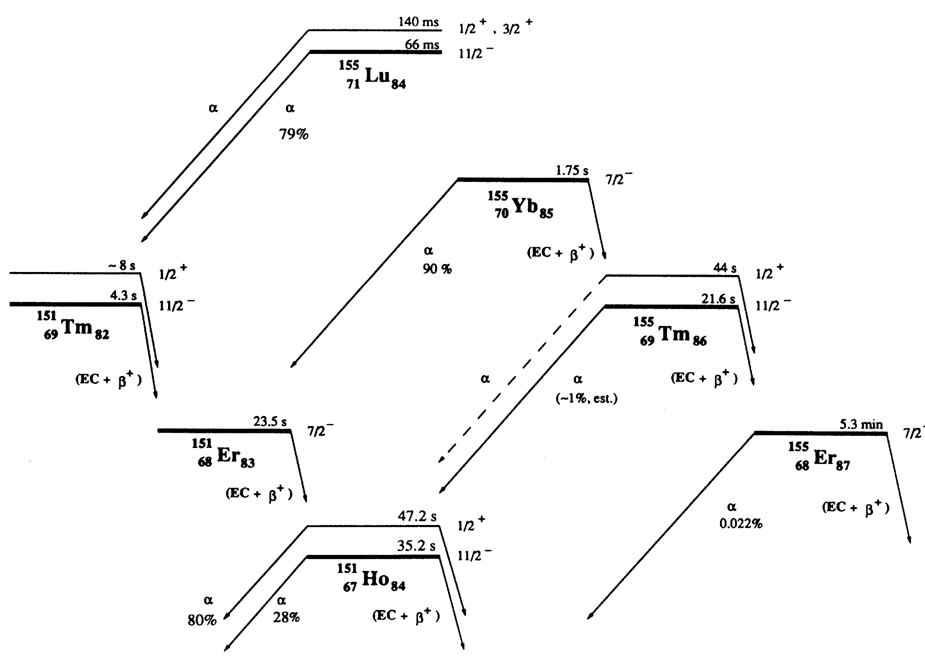

FIG. 1. Schematic summary of some of the decay chains investigated in this experiment.

scope 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. In addition, 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. [6] for a drawing of this arrangement). Coincidences between 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 half-life information. Two collection and counting cycles of 1.28 and 40 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 response were minimized. In the 1.28-s experiments the ΔE portion of the telescope was removed to improve the energy resolution for α-particle detection.

II. RESULTS AND DISCUSSION

A. The α-decaying levels in $^{155}_{71}Lu_{84}$

The isotope ^{155}Lu was first identified [7] by the observation of a 5.63-MeV α peak decaying with a 70-ms half-life. Hofmann *et al.* [8], in a survey study of α emission in the rare earths, reported seeing this same α group. More recently, Hofmann *et al.* [9], identified the α decay of a second low-lying state in ^{155}Lu.

Figure 2 shows the α spectrum recorded by the Si(Au) surface barrier detector during the 1.28-s counting cycles. Above the intense 5.194-MeV α peak, which belongs to ^{155}Yb decay (see Sec. II B), there are two weak α groups whose energies are close to those reported in Ref. [9] for

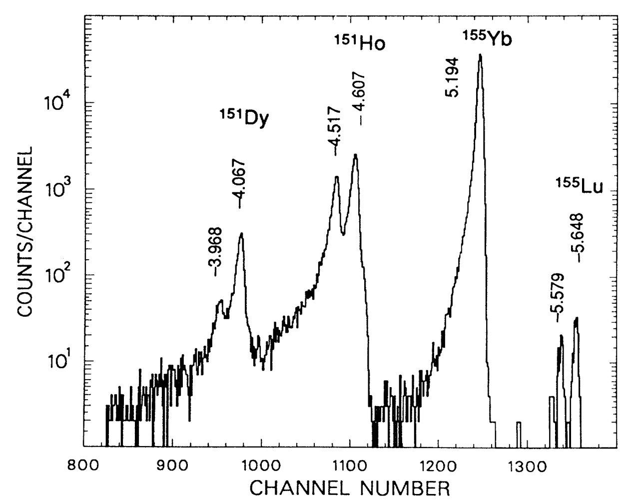

FIG. 2. α-particle spectrum measured during the 1.28-s counting cycles. The spectrum was recorded with only the E detector of the ΔE-E telescope in place. Energies are expressed in MeV.

the two low-lying ^{155}Lu levels. A shape analysis was made of the spectrum in Fig. 2 with the computer program SAMPO and the energy values adopted by Singh Szücs, and Johns [10] for ^{151}Ho (4.517 ± 0.003 MeV), ^{151}Ho^{m} (4.607 ± 0.003 MeV), and ^{151}Dy (4.067 ± 0.003 MeV) (produced in the decay sequences illustrated in Fig. 1) were used as internal calibration standards. In this way the α-decay energies of the ^{155}Lu isomers were determined to be 5.579 ± 0.005 and 5.648 ± 0.005 MeV. The corresponding energies measured by Hofmann *et al.* [9] are 5.575 ± 0.010 and 5.647 ± 0.005 MeV. We also determined a value of 5.194 ± 0.004 MeV for the E_α of ^{155}Yb. It agrees with the value of 5.199 ± 0.003 MeV adopted in Nuclear Data Sheets [11].

We determine a half-life of 66 ± 7 ms for the 5.648-MeV ^{155}Lu α group in agreement with the reported values of 70 ± 20 ms (Ref. [7]) and 70 ± 6 ms (Ref. [8] and [9]). We measure a half-life of 140 ± 20 ms for the 5.579-MeV group; in Ref. [9] a half-life was not given for it. We saw no evidence for the β-decay branch of ^{155}Lu. Given the low number of α-decay events observed this is not surprising because the α branch of the 5.648-MeV α emitter has been reported [7] to be (79 ± 4)%, while that of the 5.579-MeV α emitter is probably similar. (See Ref. [5], where the α branches of the two corresponding low-lying levels in the $N=84$ isotone, ^{153}Tm, have been determined to be ~90%.) One should also remember the generally lower efficiencies of γ-ray detectors and the more complex appearance of γ-ray spectra.

Of the two ^{155}Lu α emitters, the 5.648-MeV group is produced with a larger yield, i.e., it is twice as intense as the 5.579-MeV group (see Fig. 2) even though its counting rate, because of the difference in half-lives, is reduced more by the 90-ms tape transport time and the hold-up time in the separator ion source. The greater yield implies that the 5.648-MeV α emitter is a high-spin species, which in this mass region for odd-Z even-N nuclei is expected to be the $\pi h_{11/2}$ state. The 5.579-MeV α particles, in turn, must originate from a low-spin level. In Tb, Ho, and Tm nuclei with $N\approx82$, the lowest-lying low-spin state is the $\pi s_{1/2}$ level. However, based on energy systematics, a proposal was made in Ref. [4] that the $d_{3/2}$ orbital could drop below the $s_{1/2}$ state in lutetium isotopes. By using the α-decay-rate formalism developed by Rasmussen [12], a reduced width of 0.074 MeV was calculated for the 5.648-MeV α group. Since this value is comparable [13] to those of neighboring even-even nuclei with $N=84$, the α transition is allowed and most probably connects the $\pi h_{11/2}$ states in ^{155}Lu and ^{151}Tm (Ref. [14]). If the α branch of the 5.579-MeV emitter is also assumed to be 79%, then its reduced width is 0.066 MeV. The indication is that an unhindered decay is being observed. With the uncertain branch, however, we cannot say if the transition connects a $d_{3/2}$ or an $s_{1/2}$ level in ^{155}Lu with the 151Tm $s_{1/2}$ isomer located [14] at an excitation energy of about 50 keV.

B. Decay properties of $^{155}_{70}Yb_{85}$

As in the case of ^{155}Lu, ^{155}Yb was first identified [15] as an α-particle emitter whose α-decay branch was close to

100%. Until now, the isotope's β-decay branch has not been observed [11]. We identified ^{155}Yb (EC+β^+) decay by observing Tm $K\alpha_1$ x rays and several γ rays that decayed with the nuclide's half-life. The adopted [11] half-life is 1.72 ± 0.12 s. Based on a decay-curve analysis of the very intense 5.194-MeV α peak seen in our 40-s data we deduce a value of 1.75 ± 0.05 s.

Figure 3(a) shows the γ-ray spectrum, recorded during the 1.28-s cycles, in coincidence with Tm $K\alpha_1$ x rays. Six γ rays, labeled by their energies in Fig. 3(a), are assigned to ^{155}Yb decay. They are listed, together with their relative intensities in Table I. Spectra in coincidence with the two strongest transitions, i.e., 174.9 and 236.2 keV, are shown in Figs. 3(b) and 3(c), respectively, while a partial β-decay scheme for ^{155}Yb is shown in Fig. 4. Based on information available for neighboring even-Z odd-N nuclei, we believe that there are other γ rays to be observed and that the decay scheme is more complicated than the one that we have constructed. The spin and parity of ^{155}Yb is proposed to be $\frac{7}{2}^-$, since the $f_{7/2}$ single-neutron orbital, the first one available after the 82-neutron shell closure, describes the ground-state configuration of even-Z, odd-N nuclei in this mass region (see, for e.g., Ref. [5]). logft limits of >4.2, >4.0, and >4.1 were estimated for the β-decay feedings to the 174.9-, 236.2-, and 361.6-keV levels by using a $Q_{\rm EC}$ value of 6.03 MeV (Ref. [16]) and a total (EC+β^+) intensity based on the number of counts within the Tm $K\alpha_1$ peak and the 1.75-s component of the decay curve of the annihilation radiation peak. Even though the decay scheme in Fig. 4 is incomplete, one would not expect the lower limits to increase beyond logft values of 5.9 because of the strong intensities of the γ rays that deexcite these three levels. They are therefore consistent with assignments of $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{c}{2}^-$ for states populated in allowed β transitions from a $\frac{7}{2}^-$ parent. The levels should then deexcite to the ^{155}Tm $\pi h_{11/2}$ and $\pi s_{1/2}$ ground and isomeric states (see Sec. II C), respectively, where feeding strengths are expected to be about 2/1 in favor of the $\frac{11}{2}^-$ ground state based on the decay schemes of other $\upsilon f_{7/2}$ nuclei such as ^{153}Yb (Ref. [5]) and ^{151}Er (see Sec. II D). For both ^{153}Yb and ^{151}Er decays, all of the observed γ-ray strength to the $\frac{1}{2}^-$ isomer proceeds through a highly converted $d_{3/2}\rightarrow s_{1/2}$ transition whose energy is ~ 100 keV. For these reasons we believe that the 174.9-, 236.2-, and 361.6-keV γ rays proceed to the $\frac{11}{2}^-$ ground state and that the most likely assignments for the 174.9-, 236.2-, and 361.6-keV levels are $\frac{7}{2}^-$ or $\frac{9}{2}^-$.

TABLE I. Energies and photon intensities of γ rays observed to follow the (EC $+\beta^+$) decay of ^{155}Yb.

E_γ (keV)	I_γ (relative)[a]
125.4(3)	6(2)
174.9(1)	55(6)
205.1(2)	18(4)
236.2(1)	100
361.6(1)	46(5)
378.0(2)	26(6)

[a]Normalized to a value of 100 for the 236.2-keV transition.

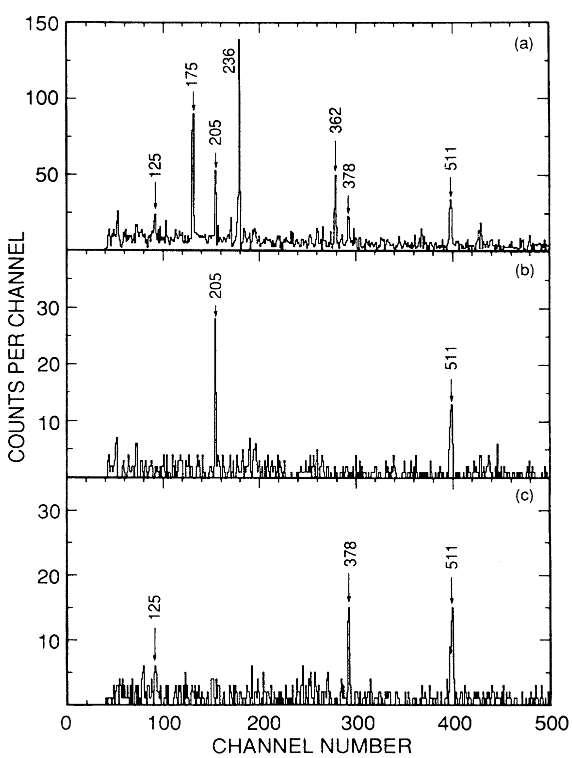

FIG. 3. Spectra recorded by the 52.3% n-type Ge detector during the 1.28-s counting cycles in coincidence with the following gates set with the hyperpure Ge detector: Tm $K\alpha_1$ x rays [part (a)], and the 174.9-keV [part (b)] and 236.2-keV [part (c)] γ rays assigned to ^{155}Yb decay.

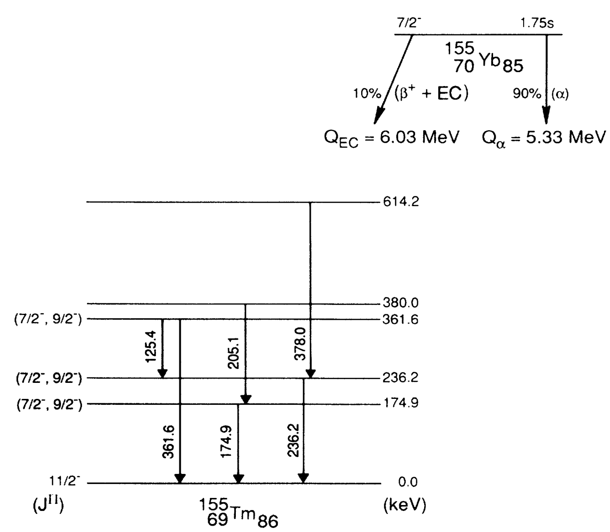

FIG. 4. Scheme proposed for ^{155}Yb (EC $+\beta^+$) decay to ^{155}Tm.

By comparing the $(\mathrm{EC}+\beta^+)$ intensity with that of the 5.194-MeV α group, the ^{155}Yb α branch was calculated to be 90 ± 5 %. Our value agrees with the only other experimental value reported [8] for ^{155}Yb, namely, 84 ± 10 %, which had been deduced by comparing the intensities of the ^{155}Yb and ^{159}Hf α groups observed in the same source. With a branch of 90% we calculate an α reduced width of 0.092 MeV. Because this width is close in value to those of neighboring even-even $N=84$ and 86 nuclei [13] the α decay is unhindered and thus connects states with similar configurations. We have already suggested that the ^{155}Yb ground state is an $f_{7/2}$ neutron level, and later in this paper we note that the same assignment for ^{151}Er is consistent with that nuclide's $(\mathrm{EC}+\beta^+)$-decay scheme.

C. Decay properties of $^{155}_{69}\mathrm{Tm}_{86}$

The isotope ^{155}Tm was also first identified [17] *via* its α decay; it was reported to have a half-life of 39 ± 3 s and to emit α particles with an energy of 4.45 ± 0.01 MeV. Subsequently, the nuclide's decay to ^{155}Er was investigated [18] and a half-life of 25 ± 4 s was determined. [No other results on ^{155}Tm decay have been reported (see Ref. [11]).] One explanation for the discrepancy between the two half-lives is that, since the sources in Ref. [17] were not mass separated, the presence of the 52.3-s ^{152}Ho high-spin isomer, whose α-decay energy is also 4.45 MeV, could distort the ^{155}Tm half-life. This potential problem was noted in Ref. [17], and the half-life adopted for ^{155}Tm, produced in the $^{144}\mathrm{Sm}(^{14}\mathrm{N},3n)$ reaction, was determined from α spectra measured at lower bombarding energies so as to minimize the effect of ^{152}Ho produced in the $^{144}\mathrm{Sm}(^{14}N,\alpha 2n)$ reaction.

Another possible explanation has recently come to light. It has been shown [19] that the single α-particle group assigned to ^{153}Tm in fact consists of two α peaks. The more intense one, 5.103 MeV, comes from the decay of the $h_{11/2}$ ground state, while the weaker one, 5.096 MeV, is emitted by the $s_{1/2}$ isomer. This prompted us in Ref. [4] to suggest that the ^{155}Tm 4.45-MeV α group is also a doublet which, in addition to the $h_{11/2}$ ground-state α decay, could encompass a contribution from the $s_{1/2}$ isomer. As we discuss below, we have now identified the $(\mathrm{EC}+\beta^+)$ decay of the $s_{1/2}$ isomer. Based on the decay curves of some of the intense γ rays that follow this decay, we measure the isomer's half-life to be 44 ± 4 s. Thus, in Ref. [17], where the ^{155}Tm half-life determination was made at lower incident energies, the 4.45-MeV α peak could have been primarily due to the $s_{1/2}$ ^{155}Tm isomer. Low-spin isomers have threshold energies for their production, which are lower than those of their high-spin counterparts (see, for example, Ref. [17]). The 4.45-MeV α peak would then have decayed with a half-life closer to that of the low-spin isomer rather than of the high-spin ground state.

In Ref. [17], ^{156}Tm, produced in the $^{147}\mathrm{Sm}(^{14}N,5n)$ reaction, was reported to have two α-decaying isomers, a low-spin species with an $E_\alpha=4.23\pm0.01$ MeV and a high-spin state with an $E_\alpha=4.46\pm0.01$ MeV. While the 80-s low-spin level has been observed in subsequent studies (see Ref. [20]), the (19 ± 3)-s high-spin state has not. It would appear that the 4.46-MeV group, in fact, results from the α decay from the $h_{11/2}$ ^{155}Tm ground state produced in the $(^{14}N,6n)$ reaction on ^{147}Sm. Indeed, based on the decay curve of the extremely intense 226.5-keV γ ray that follows the $(\mathrm{EC}+\beta^+)$ decay of the ^{155}Tm ground state, we determine a half-life of 21.6 ± 0.2 s, in agreement with the value in Ref. [18].

The α-particle spectrum recorded with the ΔE-E telescope during the last 35 s of the 40-s counting cycles is shown in Fig. 5. While Fig. 2 is dominated by 1.75-s ^{155}Yb, the most intense peaks in Fig. 5 are due to ^{151}Ho and $^{151}\mathrm{Ho}^m$. We indicate, on the low-energy shoulder of the ^{151}Ho peak, the location of the 4.45-MeV ^{155}Tm group. Its presence was established by making a careful shape analysis with the computer program SAMPO of all the observed α peaks. A more definitive study of the ^{155}Tm α-decay properties, however, would necessitate producing the nuclide without ^{155}Yb and the resultant interference of the ^{151}Ho and $^{151}\mathrm{Ho}^m$ α groups. Note in Fig. 5 the rather intense 3.968-MeV α peak of 4.1-h ^{149}Tb. This terbium nuclide was produced during several days of irradiations while investigating [2,4,5] $A=153$ isotopes and their $A=149$ α-decay daughters just prior to the start of the present study.

Figures 6 and 7 show singles spectra recorded during the full 40 s of counting with the hyperpure x-ray and the 24.3% n-type Ge detectors, respectively. For clarity in Fig. 7, only the intense γ-ray peaks of ^{155}Tm, ^{151}Er, and ^{151}Ho are labeled by energy and elemental symbol. Nuclidic assignments are based on coincidences with characteristic K x rays and with other γ rays, and on half-life measurements. Our identification of the $s_{1/2}$ ^{155}Tm isomer rests on the fact that the intense 88.1-keV as well as some of the other γ rays reported by Aguer *et al.* [18] decay with a half-life of 44 s rather than the 21.6-s half-life of the $h_{11/2}$ ground state. Table II summarizes energies and intensities of γ rays, which we assign to the ^{155}Tm $h_{11/2}$ ground state and $s_{1/2}$ isomer, and lists transition

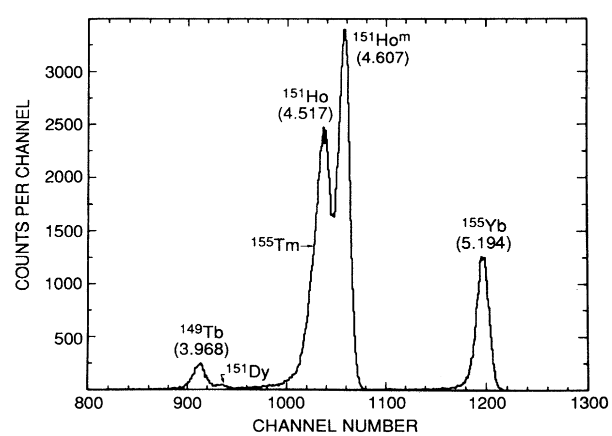

FIG. 5. α-particle spectrum recorded by the ΔE-E telescope during the last 35 s of the 40-s counting cycles. Energies are expressed in MeV.

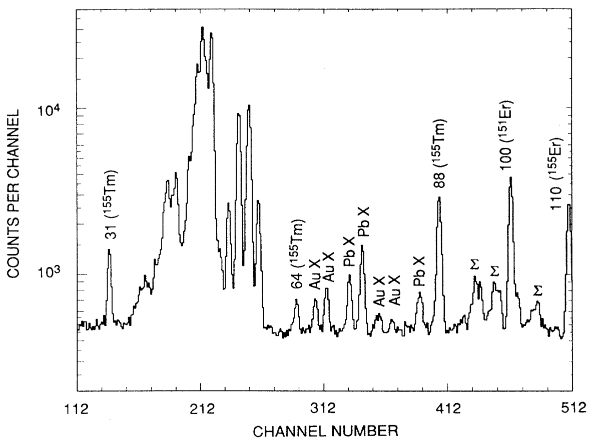

FIG. 6. Low-energy singles γ-ray spectrum recorded by the hyperpure Ge detector during the 40-s counting cycles. Σ indicate sum peaks.

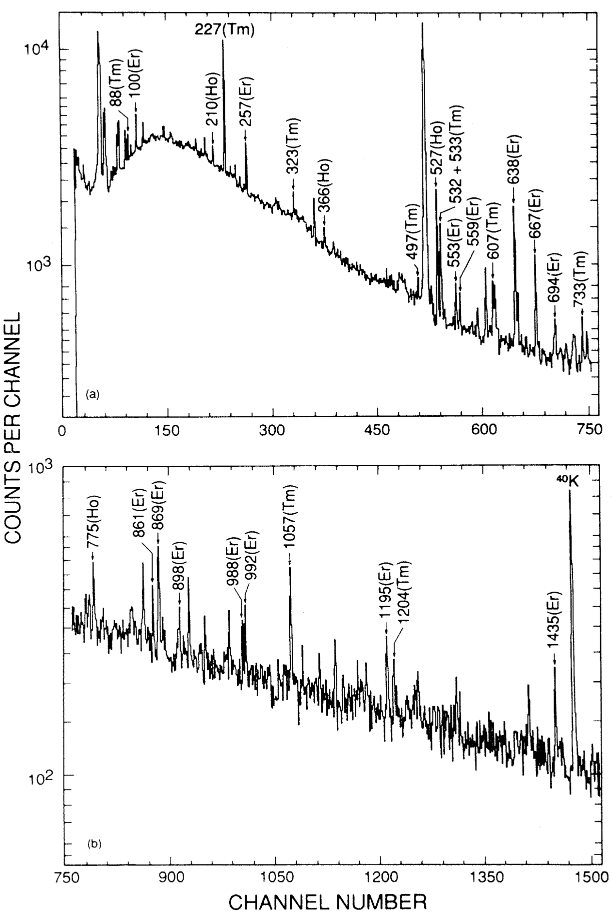

FIG. 7. High-energy singles γ-ray spectrum recorded by the 24.3% n-type Ge detector during the 40-s counting cycles. Intense transitions assigned to ^{155}Tm, ^{151}Er, and ^{151}Ho are identified by energy and elemental symbol.

multipolarities based on the conversion-electron measurements of Aguer *et al.* [18].

In Ref. [18], a total of 42 ^{155}Tm transitions were reported, but only 16 of them were placed in the proposed decay scheme. We observe 18 of the 42 transitions (including all of those placed in the scheme) together with five new γ rays. Most of the 24 transitions that we did not detect are weak. In Table II we group our γ rays in two sets, one associated primarily with the $h_{11/2}$ ground state and the other with the $s_{1/2}$ isomer. Relative photon intensities for those in the first set agree well with values in Ref. [18], while those in the second set are generally lower by about a factor of 2. We believe that, since the intensities being considered are normalized to that of the 226.5-keV γ ray (associated with the $h_{11/2}$ ground state), the discrepancy arises as a result of the two different ways used to produce ^{155}Tm. In Ref. [18] the isotope was made in proton bombardments of natural erbium so that there would have been a relatively greater amount of the $s_{1/2}$ isomer produced than in our heavy-ion irradiations.

Our proposed decay scheme (Fig. 8) for ^{155}Tm was constructed by using the information in Table II, γ-γ coincidence relationships (some of which are shown in Fig. 9) and results from in-beam γ-ray experiments [11]. The excitation energy of the $s_{1/2}$ isomer, indicated to be about

TABLE II. Energies and photon intensities of γ rays observed in ^{155}Tm (EC+β^+) decay. Transitions grouped in the upper half of the table are associated with the $h_{11/2}$ ground state, while those listed in the lower half follow the decay of the $s_{1/2}$ isomer.

E_γ (keV)	I_γ (relative)[a]	Multipolarity[b]
31.5(1)	5(1)	
226.5(1)	100	$M1+E2$
304.3(2)	~1	
380.1(2)	~1	
518.4(2)	4(1)	
531.7(2)	23(3)	
533.4(2)	5(1)	
606.5(2)	11(2)	
732.9(3)[c]	7(1)	
830.0(3)[c]	2.2(6)	
1057.2(3)[c]	13(3)	
1204.2(3)[c]	4(1)	
63.5(1)	1.5(5)	$M1+E2$
88.1(1)	10.0(7)	$M1+E2$
151.6(1)	2.2(5)	$E2$
171.5(2)	1.6(6)	$E2+M1$
247.0(2)	2.8(5)	$E2+M1$
315.2(2)	1.0(5)	$E2+M1$
323.2(2)	6.5(7)	$M1+E2$
379.1(2)	~1	$M1+E2$
432.7(2)	1.0(2)	
496.7(3)	0.8(5)	
507.0(4)[c]	~4	

[a]Normalized to a value of 100 for the 226.5-keV transition.
[b]Taken from Ref. [18].
[c]Transition not observed in Ref. [18].

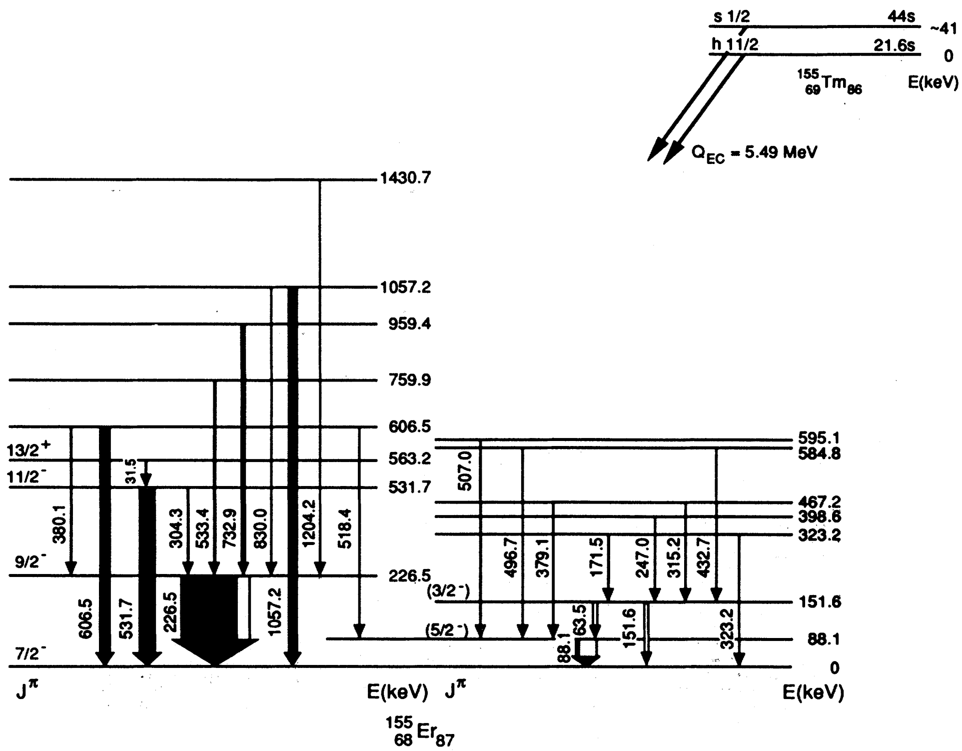

FIG. 8. Decay schemes proposed for the ^{155}Tm $s_{1/2}$ isomeric and $h_{11/2}$ ground states. The $s_{1/2}$ isomer is estimated (see text) to be at an excitation energy of ~41 keV.

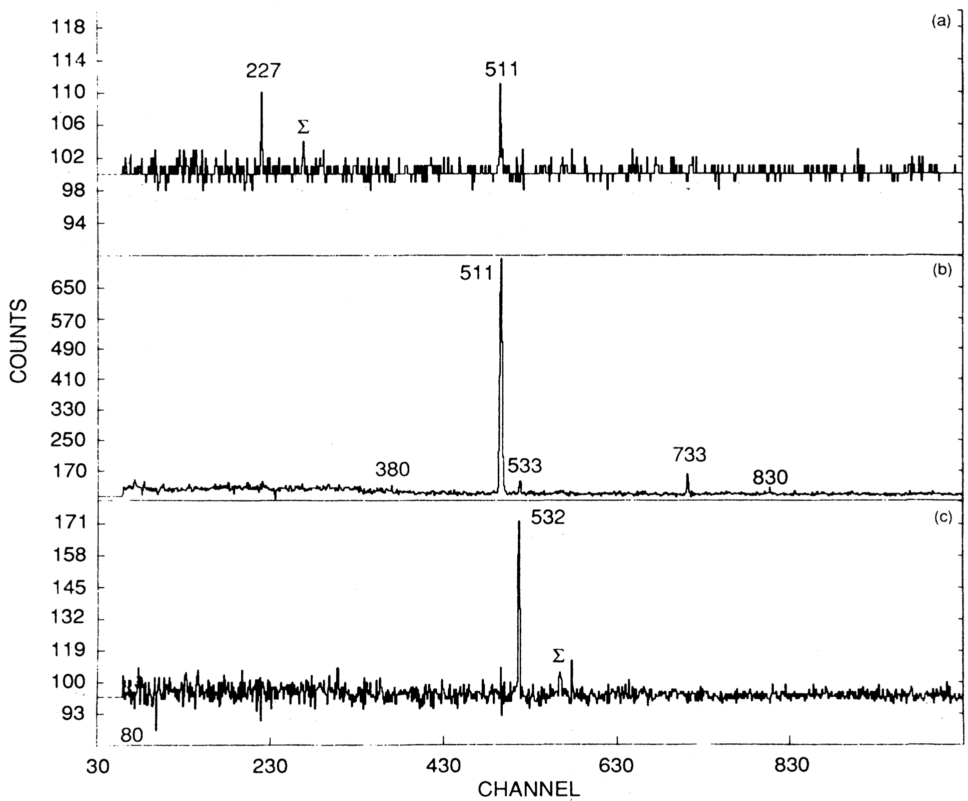

FIG. 9. Spectra recorded by the 52.3% n-type Ge detector during the 40-s counting cycles in coincidence with the following gates: 533.4-keV [part (a)], 226.5-keV [part (b)], and 31.5-keV [part (c)] γ rays assigned to the decay of the $h_{11/2}$ ground state of ^{155}Tm. Gates for parts (b) and (c) were set with the hyperpure Ge detector, while for part (a) the 24.3% n-type Ge detector was utilized. Σ indicate sum peaks.

41 keV, is based on the assumption (discussed above) that the 4.45-MeV ^{155}Tm α group is a doublet and the two α transitions, which originate from the $s_{1/2}$ and $h_{11/2}$ states in ^{155}Tm, feed the corresponding single-proton states in ^{151}Ho. The ^{151}Ho $s_{1/2}$ isomer has been established to be 41.4 (Ref. [21]) and 41.1 keV (see Sec. II D) above the $h_{11/2}$ ground state. If the two ^{155}Tm α transitions are approximately equal in energy, then the $s_{1/2}$ isomer is also $\sim$41 keV above the ^{155}Tm ground state.

The decay scheme in Fig. 8 is similar to that of Aguer *et al.* [18] except that we have added six states (563.2, 595.1, 759.9, 959.4, 1057.2, and 1430.7 keV) to their nine excited levels (88.1, 151.6, 226.5, 323.2, 398.6, 467.2, 531.7, 584.8, and 606.5 keV). Also, for a better visual presentation, we have divided the levels into high- and low-spin groupings. Figure 9 shows some of the coincidence data that indicate the presence of the additional states. The spectrum in Fig. 9(c) is gated by the 31.5-keV γ ray (Fig. 6), which was seen in Ref. [18] but not placed in the ^{155}Tm decay scheme. This low-energy transition has been observed [11] in-beam and has been suggested to feed the 531.7-keV level. The 531.7-keV γ ray is clearly seen in Fig. 9(c). Its close-lying neighbor of 533.4 keV was also reported by Aguer *et al.* [18] but not placed in their scheme. Figure 9(a) shows that the 533.4-keV γ ray is in coincidence with the intense 226.5-keV transition so that a new state at 759.9 keV is proposed. The 533.4-keV transition can be seen in Fig. 9(b), which displays coincidences with the 226.5-keV γ ray. Transitions of 732.9 and 830.0 keV are also seen in Fig. 9(b); these coincidences tentatively establish the existence of the new levels at 959.4 and 1057.2 keV, respectively. In addition, weak coincidences involving the new 507.0- and 1204.2-keV γ rays with 88.1- and 226.5-keV transitions, respectively, suggest the presence of excited levels at 595.1 and 1430.7 keV.

As in the case of ^{155}Yb and ^{151}Er, we propose a $\frac{7}{2}^-$ assignment for the ^{155}Er ground state. The same spin and parity are also suggested in Nuclear Data Sheets [11] based on the assignments for two other $N=87$ isotones, ^{153}Dy and ^{151}Gd. A logft value of 4.7 for β-decay to the 226.5-keV level can be calculated with a Q_{EC} value of 5.49 MeV [16]. The allowed character of this transition from an $\frac{11}{2}^-$ parent and the $M1+E2$ multipolarity [18] of the deexciting γ ray are strong evidence for a $\frac{9}{2}^-$ assignment for the 226.5-keV state. It is, most probably, the $\nu h_{9/2}$ state, since its excitation energy fits well into the systematics (see Ref. [22] for a recent update) of this neutron orbital. The 563.2-keV level, based on lifetime and g-factor measurements from in-beam γ-ray studies [11], is suggested to have a $\frac{13}{2}^+$ assignment. Its energy also fits into the systematics [22] for this positive-parity state, which is either the $\nu i_{13/2}$ orbital, the result of coupling the $\nu h_{9/2}$ and $\nu f_{7/2}$ orbitals to the 3^- core excitation, or a mixture of both possibilities. Some mixing of the core excitation with the $\nu i_{13/2}$ orbital is likely. While the energies of the $\frac{13}{2}^+$ levels vary smoothly as a function of both Z and N, their behavior [22] is different from the trends exhibited by the other single-neutron orbitals available after the $N=82$ shell. The $\frac{11}{2}^-$ assignment for the 531.7-keV level is based [11] upon the stretched $E2$ character of the transition to the ground state.

As suggested by Aguer *et al.* [18], the $M1+E2$ multipolarities of the 88.1- and 63.5-keV transitions and the $E2$ character of the 151.6-keV transition make $\frac{5}{2}^-$ and $\frac{3}{2}^-$ the preferred assignments for the 88.1- and 151.6-keV levels. A spin of $\frac{5}{2}$ for the 88.1-keV level is consistent with its feeding from the 606.5-keV level, which also deexcites to $\frac{9}{2}^-$ and $\frac{7}{2}^-$ states. It should be noted that half of the deexciting intensities from the 88.1- and 151.6-keV levels are unaccounted for by incoming γ-ray strengths. One is therefore left with a situation where $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states are being directly fed by $\frac{1}{2}^+$ and $\frac{11}{2}^-$ parents. However, the large number of unplaced γ rays mentioned earlier make the ^{155}Tm decay scheme in our work (and in Ref. [18]) only a partial one and imbalances

TABLE III. Energies and photon intensities of γ rays assigned to the decay of ^{151}Er.

E_γ (keV)	I_γ (relative)[a]
100.1(1)	27(5)[b]
230.7(2)	3.2(4)
256.5(1)	52(5)[b]
302.4(2)	6.5(5)
455.0(2)	5.8(4)
462.0(2)	4.9(4)
537.0(2)	5.3(16)
553.0(1)	17.2(15)
558.8(1)	12.6(12)
638.3(1)	100
641.5(1)	17(2)
667.2(1)	51(3)
694.4(1)[c]	14.4(16)
720.6(2)[c]	9.8(20)
739.5(1)[c]	12.6(20)
768.9(2)[c]	8.2(10)
860.5(1)[c]	13.3(18)
868.9(1)	33(3)
874.4(2)[c]	6.0(17)
898.0(2)[c]	8.9(15)
987.9(2)	12.8(18)
992.0(2)	16.1(20)
1061.0(4)[c]	$\sim$2.5
1194.5(2)	17.8(20)
1435.2(2)[c]	17.7(13)
1549.3(3)	9.7(15)
1935.1(3)[c,d]	11(2)
2133.7(3)[c,d]	4.0(10)

[a]Normalized to a value of 100 for the 638.3-keV transition. To obtain intensities per 100 ^{151}Er decays, these relative values should be multiplied by 0.35. This normalization factor was arrived at by requiring that the intensity sum for the 100.1-, 638.3-, 667.2-, and 868.9-keV transitions be equal to 100% of all ^{151}Er decays; the intensities of the internal-conversion electrons of the $M1$ 100.1-keV transition are included in this intensity sum.

[b]Multipolarity of this transition is $M1$ (see Ref. [25]).

[c]Transition not observed in Ref. [25].

[d]Transition not placed in decay scheme.

at all levels, except the one at 226.5 keV, should probably be considered as upper limits.

D. Decay of $^{151}_{68}Er_{83}$ to levels in $^{151}_{67}Ho_{84}$

The decay of 23.5-s ^{151}Er was first identified [23] from an observed growth period in the decay curve of the low-spin ^{151}Ho α-particle group. Subsequently, two γ-ray transitions that follow ^{151}Er decay were reported [24] and, more recently, a decay scheme has been presented [25].

In Table III we list the energies and photon intensities of γ rays, which we assign to ^{151}Er, while in Fig. 10 we display spectra observed in coincidence with the three most intense transitions, namely, 100.1 [part (a)], 256.5 [part (b)], and 638.3 [part (c)]. These and other coincidence data, together with the singles information in Table III, allowed us to construct the ^{151}Er (EC+β^+)-decay scheme shown in Fig. 11. It is similar to, but more complete than, the one reported by Barden *et al.* [25]. Our scheme incorporates 17 additional transitions together with 11 new (861.8, 910.1, 934.7, 1001.7, 1129.1, 1202.2, 1377.8, 1541.6, 1563.5, 1860.9, and 1947.0 keV) and nine previously known (41.1, 141.2, 397.7, 638.3, 667.2, 700.0, 868.8, 1279.8, and 1832.8 keV) excited states. Of the 18 γ rays reported in Ref. [25], we observe all but one, namely, 1073.0 keV. Nine of the 18 γ rays in Ref. [25] were unplaced in the ^{151}Ho level scheme; with the exception of the 1073.0-keV γ ray, all of these transitions are placed in our scheme. Also, as indicated in Table III, we have detected ten new transitions of which only two are unplaced. The estimated Q_{EC} value of 5.20 MeV shown in Fig. 11 is from Ref. [16].

We suggest the ^{151}Er ground-state spin and parity to be $\frac{7}{2}^-$, since the $f_{7/2}$ single-neutron orbital is the first one available after the 83-neutron shell closure. This was noted earlier in our discussion of the ^{155}Yb unhindered α decay, where we pointed out that the ^{155}Yb and ^{151}Er ground states probably have similar configurations. The ^{151}Er $\frac{7}{2}^-$ ground state is expected to decay *via* Gamow-Teller allowed transitions to $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$ levels, which then should deexcite to the ^{151}Ho $s_{1/2}$ and $h_{11/2}$ (single-proton) low-lying isomer and ground state, respectively. This is indeed the picture that is apparent in Fig. 11. One set of levels is built upon the $s_{1/2}$ isomer, the other on the $h_{11/2}$ ground state. The 1832.8- and 1129.1-keV levels feed both sets of states. Thus we were able to establish the excitation energy of the $s_{1/2}$ isomer to be 41.1 ± 0.2 keV, a value in agreement with, but more precise than, the (41.4 ± 0.9)-keV value [21], which is based on an analysis of fine structure in ^{151}Ho α decay.

The 141.2- and 397.7-keV levels, deexcited by the intense 100.1- and 256.5-keV transitions, are suggested to

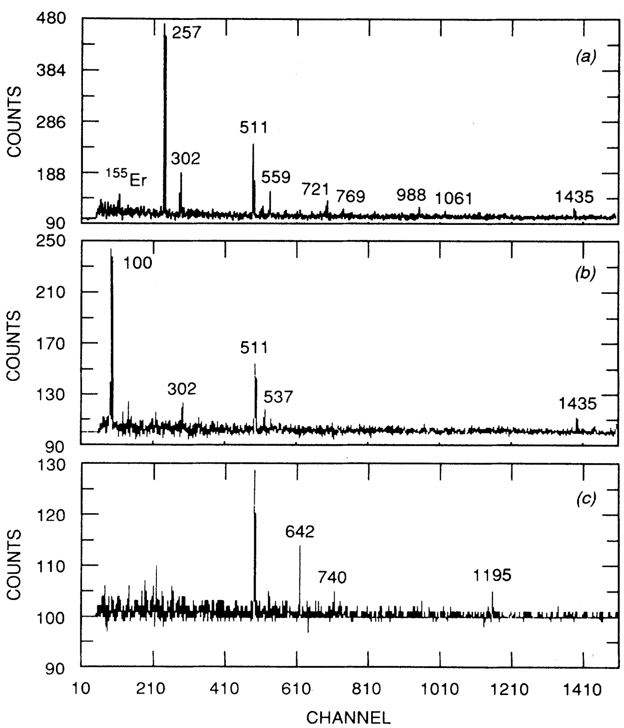

FIG. 10. Spectra recorded by the 52.3% n-type Ge detector during the 40-s counting cycles in coincidence with the following gates: 100.1-keV [part (a)], 256.5-keV [part (b)], and 638.3-keV [part (c)] γ rays assigned to ^{151}Er decay. Gates for parts (a) and (b) were set with the hyperpure Ge detector, while for part (c) the 24.3% n-type Ge detector was utilized.

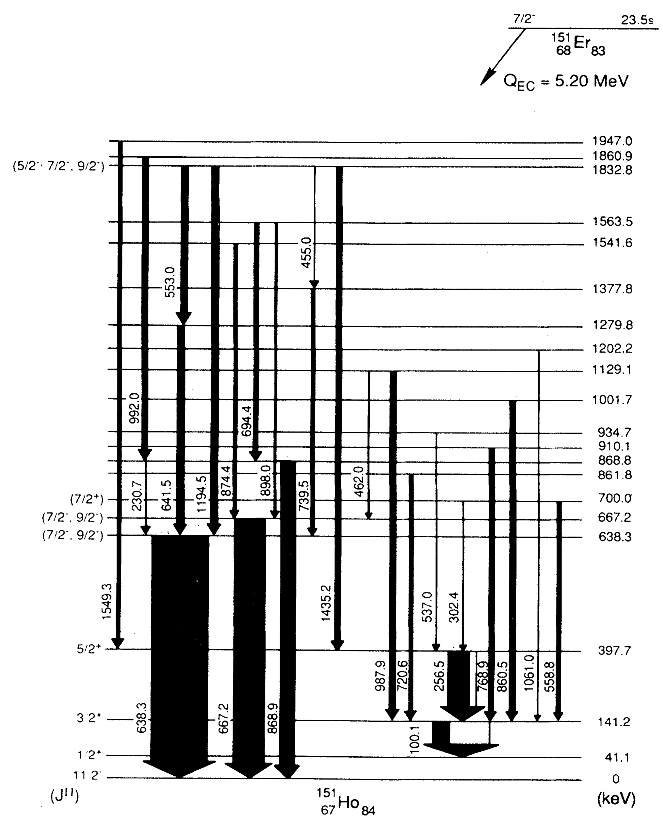

FIG. 11. Decay scheme proposed for ^{151}Er.

be the $d_{3/2}$ and $d_{5/2}$ proton states in ^{151}Ho. A candidate for the $g_{7/2}$ proton state is the 700.0-keV level, which is deexcited by 302.4- and 558.8-keV γ rays to the 397.7- and 141.2-keV levels, respectively. Our proposed assignments are based on the energies of known single-proton states in neighboring odd-Z nuclei with $Z \geq 65$. These energy systematics for $N=82$ and 84 nuclei are shown in Fig. 12 and one sees that the ^{151}Ho levels fit well into the overall trends. Because of the strong 638.3-, 667.2-, and 868.9-keV transitions to the $\frac{11}{2}^-$ ground state, the levels that they depopulate have possible spins that range from $\frac{7}{2}$ to $\frac{15}{2}$. The parent spin of $\frac{7}{2}^-$ and γ-ray intensity imbalances (all three states have $\log ft$ values of ~ 5.1) indicate $\frac{7}{2}^-$ or $\frac{9}{2}^-$ as the probable spin assignments for these levels.

E. The α-decay branches of ^{151}Ho and ^{151}Ho^m

The isotope ^{151}Ho was first identified by Macfarlane and Griffioen [26] who observed two α-decay groups associated with the nuclide. Based on differences between the maxima of ^{16}O$+^{141}$Pr excitation functions for the two α groups, they concluded that 4.51-meV α particles were emitted by the $\pi h_{11/2}$ ground state, while 4.60-MeV α particles were emitted by a low-spin isomer, which, originally thought [26] to be the $\pi d_{5/2}$ state, is now established to be the $\pi s_{1/2}$ state. Subsequent ^{151}Ho α- and (EC$+\beta^+$)-decay studies and in-beam γ-ray investigations of ^{151}Dy levels are summarized in Ref. [10].

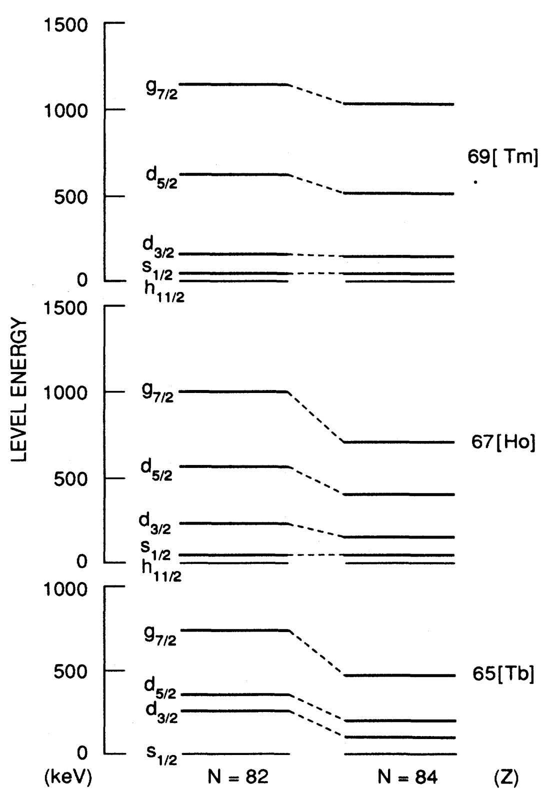

FIG. 12. Systematics of excitation energies for the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ proton states in Tb, Ho, and Tm nuclei with $N=82$ and 84.

In our study, ^{151}Ho is produced primarily *via* the decay chain $^{155}\text{Yb} \xrightarrow{\alpha} {}^{151}\text{ER} \xrightarrow{EC} {}^{151}\text{Ho}$ with a much smaller amount arising from the α decay of ^{155}Tm, whose α branching is estimated to be $\sim 1\%$ if the α reduced width is in the unhindered range. We observed both α groups (Figs. 2 and 5) and most of the intense γ rays that have been reported [10] to follow the nuclide's (EC$+\beta^+$) decay. However, our data did not yield any new information concerning ^{151}Ho decay to ^{151}Dy levels partly because the relatively short 40-s counting time was not optimized for the half-lives of the two ^{151}Ho states [35.2 s ($h_{11/2}$) and 47.2 s ($s_{1/2}$)], which were still further increased by feeding from 23.5-s ^{151}Er. Nevertheless, we were able to deduce α branches for both ^{151}Ho α emitters.

By comparing the intensity of the 4.517-Mev α group with the sum of the intensities of the only three γ rays (527.3, 775.4, and 1549.3 keV) known [10] to proceed directly to ground, an α branch of $28\pm7\%$ was determined for the $h_{11/2}$ ground state. This value is somewhat higher than previously measured ones [10] which range from $18\pm5\%$ to $22\pm3\%$. It results in an α reduced width of 0.096 MeV and is a clear indication of an allowed α transition [note that even a branching as low as 18% still leads to a reduced width (0.062 MeV) large enough for an allowed α decay] so that the initial and final levels are the $\pi h_{11/2}$ states in ^{151}Ho and ^{147}Tb.

In contrast to the general agreement found for the variously determined α branches of the ^{151}Ho ground state, there exists a wide range of values for ^{151}Ho^m, namely, from 13% (Ref. [27]) to an estimate of 28% (Ref. [26]) to a limit of $>40\%$ (Ref. [28]). Since γ rays belonging to the (EC$+\beta^+$) decay of ^{151}Ho^m have not been observed [10], we could not determine the α branch from a comparison α-particle and γ-ray intensities. However, as noted earlier, in our sources, the bulk of ^{151}Ho is produced from ^{151}Er decay, which, according to γ-ray intensities in Table III and the decay scheme in Fig. 11, should yield 1.87 times more of the $\frac{11}{2}^-$ ground state than of the $\frac{1}{2}^+$ isomer. Since both α-particle intensities and the $\frac{11}{2}^-$ (EC$+\beta^+$) strength are known, the $\frac{1}{2}^+$ (EC$+\beta^+$)-decay intensity can be deduced. In this way the ^{151}Ho^m α branching was determined to be $(80^{+15}_{-20})\%$. The resultant α reduced width of 0.069 MeV provides the first definitive evidence that this is an allowed α transition, which connects the $\pi s_{1/2}$ isomer in ^{151}Ho with the $\pi s_{1/2}$ ground state in ^{147}Tb (see the discussion in Ref. [21]). It also clears up the problem raised in Ref. [27], where the calculated reduced width of ~ 0.01 MeV for ^{151}Ho^m indicated a hindered decay, whereas the expectation was that the α transition proceeded between levels with the same configuration (assumed to be $\pi d_{5/2}$ at the time). We conclude by pointing out that the recent $\pi s_{1/2}$ assignments for the low-spin states in Tb and Ho nuclei near $N=82$ explain the lower α reduced widths (~ 0.02 MeV) for the ^{149}Tb and ^{151}Tb ground states. It is now clear that these α decays, originally thought [29] to be

$\pi d_{5/2} \rightarrow \pi d_{5/2}$ transitions, are in reality $\pi s_{1/2} \rightarrow \pi d_{5/2}$ transitions.

ACKNOWLEDGMENTS

The assistance of L. F. Archambault, R. M. Chasteler, R. B. Firestone, A. A. Shihab-Eldin, A. A. Wydler, and the SuperHILAC staff during this experiment is gratefully acknowledged. Oak Ridge National Laboratory is managed by Martin Marietta Energy systems, Inc. for the U. S. Department of Energy under Contract No. DE-AC05-84OR21400. Work at the Lawrence Berkeley Laboratory was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Support was also provided by the U. S. Department of Energy through Contract No. DE-FG05-84ER4-0159 with Louisiana State University.

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