α-decay branching ratios for high- and low-spin isomers in ^{151,152,153,154}Ho[†]

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α-decay branching ratios were obtained for high- and low-spin isomers in ^{151,152,153,154}Ho. These activities were produced by bombarding ^{144,147}Sm with ^{11,10}B ions, respectively, accelerated in the Oak Ridge isochronous cyclotron. With the use of a gas-jet-capillary transport system it was possible to do α-particle, x-ray, and γ-ray counting simultaneously. Branching ratios were deduced in the main by determining the number of $K\alpha_1$ x rays emitted and then applying appropriate correction factors to obtain the total number of electron-capture and positron decays. For ^{152,154}Ho, where the γ-ray spectral measurements could be used to extract information concerning their decay to ^{152,154}Dy, it was possible to deduce alternate, and thus independent, α-decay branching ratios. (Incidentally, our results confirm those of Ward and Neiman for the decay of the high-spin ^{154}Ho isomer to levels in ^{154}Dy.) Within error limits the two sets of ratios for ^{152,154}Ho were found to be in agreement. For the two cases, i.e., 35.6-sec ^{151}Ho and 9.3-min ^{153}Ho, where experimental α-decay branches had been previously measured our data agree with the earlier results. α-decay reduced widths were calculated by using the formalism developed by Rasmussen and compared with values for neighboring even-even nuclei, which can be taken to represent unhindered α decay. The present study is the first systematic investigation of α-decay rates for a series of isotopes of an odd-Z element in the rare earth region. It was found that, as for odd-A isotopes in the heavy-element region, the α-decay reduced widths range from those of even-even nuclei down to much smaller values.

[RADIOACTIVITY ^{151,152,153,154}Ho; I_α, $I_{(K\alpha\ \text{x ray})}$, I_γ, E_γ; measured α-decay branching ratios; deduced α-decay rates. ^{152,154}Dy deduced levels, J, π.]

I. INTRODUCTION

In an earlier paper[1] the feasibility of measuring α-decay branching ratios by combining the helium gas-jet technique[2] with the use of high-resolution Ge(Li) x-ray detectors was demonstrated. Because this combination does away with the necessity of chemical separations it can be used to measure branching ratios for isotopes with half-lives in the seconds range if a capillary is used to transport the gas jet to a shielded area. This then allows α-particle, x-ray, and γ-ray counting to be made simultaneously. In the present investigation we utilized just such a transport system to measure α-decay branching ratios for the isomers of $^{151-154}$Ho whose half-lives range from ~36 sec to ~12 min.

Experimental branching ratios are lacking for a large number of α-emitters in the mass region below bismuth. As noted in the previous publication[1] these are important not only for comparison with α-decay theories but also because they can be used to determine absolute cross sections for reactions in which products have been identified by means of characteristic α-particle groups.

II. EXPERIMENTAL METHOD

The holmium activities were produced by bombarding ^{144}Sm and ^{147}Sm with ^{11}B and ^{10}B ions accelerated in the Oak Ridge isochronous cyclotron (ORIC). The experimental assembly utilized the gas-jet technique,[2] the basis for which is that recoil product nuclei ejected from thin targets by the incident beam are stopped in helium gas and then swept out together with the gas through an orifice. In this particular setup a 9-m Teflon capillary (i.d. 1.3 mm) was inserted through the orifice into the reaction chamber. The other end of the capillary, situated outside the experimental room, was pumped on to extract the product nuclei into a shielded area. The recoils were collected on a catcher foil located in a 500-cm^3 collector chamber (shown schematically in Fig. 1). After a suitable bombardment time, the collector foil was rotated to a location in front of the α-particle and Ge(Li) x-ray detectors. The Ge(Li) γ-ray detector [with an efficiency of ~19% relative to a 7.5 × 7.5-cm NaI(Tl) crystal] was located 2.5 cm from the collected sample. The transport of product recoils from heavy-ion-induced reactions through capillaries has been investigated[3] extensively at the Oak Ridge National Laboratory and the apparatus used in the present study was assembled with that experience in mind.

The x- and γ-ray spectra were stored simultaneously in a 4096-channel analyzer which is interfaced to an in-house computer. The analyzer was programmed to go automatically through cycles of counting for a preset time, of transferring the accumulated data to the computer, and finally of restarting the analyzer whose memory had in the meantime been automatically cleared. Each x- and γ-ray spectrum contained 2048 channels, covering the energy ranges 0–220, and 150–1300 keV, respectively. The α-particle spectra were stored in a second analyzer, also interfaced to the computer. For permanent storage and later data reduction, all information was transferred onto magnetic tapes. Computer codes were used to obtain peak positions and areas and to convert these into energies and intensities, respectively. The absolute efficiencies of the three detectors were determined for the particular geometries used by calibrating with standard sources of known strengths.

The samarium targets were electrodeposited as oxide layers (with thicknesses of ~300 $\mu g/cm^2$)

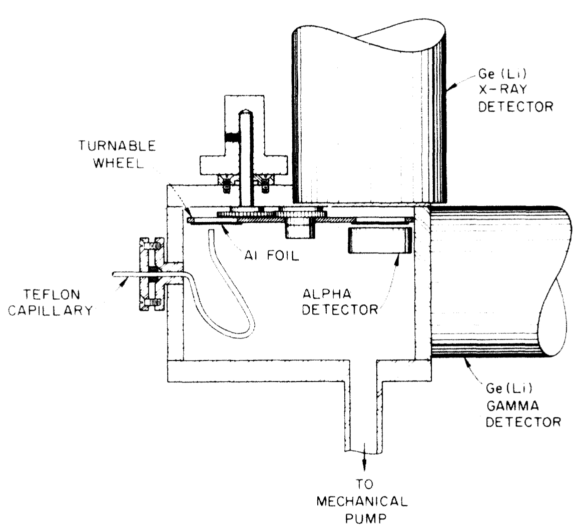

FIG. 1. Schematic drawing showing the collection end of the gas-jet-capillary system used in this investigation. The figure also shows the positions in which the α-particle, x-ray, and γ-ray detectors were located with respect to one another.

onto beryllium backing foils. The isotopic enrichments of the samarium oxides were 96% for ^{144}Sm and 98% for ^{147}Sm. The primary energies of the boron beams, 74 MeV for ^{11}B and 81 MeV for ^{10}B, were reduced as needed by the use of additional degrading beryllium foils.

The main procedure used for deducing α-decay branching ratios in this study will now be described. Because the α-decay characteristics of the holmium activities are well known, α-particle spectra were measured at about 4-MeV intervals to determine the optimum incident beam energy for a particular nuclear species. Once the bombarding energy was selected the irradiation and collection of activity was begun, terminated, and the counting cycles started. The determination of the amount of α activity I_α, presented essentially no problems because each holmium isomer had a distinct α group. The intensities of the other modes of decay were determined as follows. The dysprosium $K\alpha_1$ x-ray peaks were found to be well resolved from neighboring x-ray groups. From decay-curve analyses of these $K\alpha_1$ lines, intensities for the holmium activities of interest were extracted and the total number of K x rays calculated.[4] The intensities of γ rays assigned to the particular activity were then used to correct for the number of K x rays produced in internal conversion processes.[5] Finally, by using tabulated P_K values[6] and fluorescence yields[4] the number of electron capture decays I_{EC} was then calculated. For the determination of the number of positron decays the number of observed annihilation quanta could not be used. First, their detection efficiency is different from that for γ-ray quanta of the same energy since only a fraction of the annihilation takes place in the collector foil. Second, the analysis of the decay curve for the annihilation radiation is extremely complicated because no Z selection of the components is provided. Third, the contribution of positrons from recoils produced by reactions in the target backing and in the admixture to the transport gas, could not be excluded. Therefore, the number of positron decays $I_{\beta+}$ was calculated by using Q values from the 1971 Mass Tables[7] and theoretical electron capture to positron ratios[8] for allowed or first forbidden nonunique decays. From the three intensities, I_α, I_{EC}, and $I_{\beta+}$, the α-decay branching ratios were then deduced.

In the case of ^{152}Ho and ^{154}Ho some information is available concerning their decays to ^{152}Dy and ^{154}Dy, respectively. Thus from the γ-ray data obtained with the Ge(Li) detector it was possible to obtain the sum of I_{EC} and $I_{\beta+}$ and thus deduce branching ratios in a manner independent from the one described in the previous paragraph.

Holmium $K\alpha$ x rays were not observed. Typically, the upper limits for their intensities were less than 5% of those for the corresponding dysprosium x rays. This was taken to mean that the intensities of the isomeric transitions were quite weak. Supporting evidence is also available from α-decay studies. When the holmium α emitters have been produced directly (i.e. not from the decay of isotopes with higher atomic numbers) no initial growth periods have been observed in the decay curves of the individual α groups (see Refs. 9–11).

III. SUMMARY OF PREVIOUS WORK

The holmium activities being considered, with the exception of 3.25-min ^{154}Ho, were discovered[9-11] by the observation of characteristic α groups. The high-spin isomer of ^{154}Ho was first reported by Ward and Neiman[12] who investigated its decay to levels in ^{154}Dy. Published information concerning the electron capture and positron decay modes for the remaining radioactivities is extremely sparse, though preliminary results have appeared in annual reports[13] for the ^{152}Ho high-spin isomer. The half-lives and α-decay energies of the $^{151-154}$Ho isomers, taken from Refs. 9–12 and 14, 15 are summarized in Table I.

Experimentally determined α-decay branching ratios are available only for the ^{151}Ho high-spin,[9] and ^{153}Ho low-spin[10] isomers. Estimates based on assumed reaction cross sections have been reported[9,14] for the ^{152}Ho high-spin isomer and for the $^{151-154}$Ho low-spin isomers. These previously available ratios will be discussed when they are compared with the present measurements.

TABLE I. Previous results on α-decay energies and total half-lives for the holmium isomers.

Isomer	Energy of α group (MeV)	Half-life $T_{1/2}$
^{151}Ho low spin	4.60 ± 0.01 [a]	47 ± 2 sec [a]
^{151}Ho high spin	4.52 ± 0.01 [a]	35.6 ± 0.4 sec [b]
^{152}Ho low spin	4.38 ± 0.01 [a]	2.36 ± 0.16 min [b]
^{152}Ho high spin	4.46 ± 0.01 [a]	52.3 ± 0.5 sec [b]
^{153}Ho low spin	4.010 ± 0.005 [c]	9.3 ± 0.5 min [d]
^{153}Ho high spin	3.91 ± 0.01 [e]	2.0 ± 0.1 min [e]
^{154}Ho low spin	3.933 ± 0.005 [c]	11.8 ± 1.0 min [d]
^{154}Ho high spin	3.72 ± 0.01 [e]	3.25 ± 0.10 min [f]

[a] Reference 15.
[b] Reference 9.
[c] Reference 14.
[d] Reference 10.
[e] Reference 11.
[f] From γ decay (Ref. 12).

IV. RESULTS

A. ^{154}Ho isomers

The ^{154}Ho isomers were produced in the ^{147}Sm(^{10}B, $3n$) reaction at incident energies of 41 and 45 MeV. The low-spin isomer α group was observed at both energies; that of the 3.25-min high-spin species was seen at neither energy. The dysprosium $K\alpha_1$ x-ray line, however, was found to have a decay component with a ~3-min half-life at each bombarding energy. The interfering presence of the ^{153}Ho 2.0-min isomer did not have to be considered because its α-particle peak was not seen at either 41 or 45 MeV. A small amount of the 9.3-min ^{153}Ho low-spin isomer was seen in the α spectrum measured at 45 MeV. It was absent at 41 MeV; at this energy it was then assumed that the 10–12-min component of the $K\alpha_1$ line was due only to the decay of 11.8-min ^{154}Ho. By using the number of counts in its α peak at the two incident energies it was possible to obtain a value for its $K\alpha_1$ intensity at 45 MeV as well.

Energies and intensities for γ rays assigned to ^{154}Ho decay are listed in Table II where they are compared with the data of Ward and Neiman[12] for the 3.25-min isomer. The two sets of data are in reasonable agreement, the one major exception being the intense 295.8-keV γ ray which appears to belong to the decay of 2.0-min ^{153}Ho (see below). Also, we tentatively assign a new 911-keV γ ray to 3.25-min ^{154}Ho, which fits well into the decay scheme (shown in Fig. 2) proposed by Ward and Neiman.[12] We might add that they did not place the 295.8-keV transition in that decay scheme. Five γ rays are proposed to belong to the decay of 11.8-min ^{154}Ho. Its decay scheme is included in Fig. 2.

The total number of electron capture and positron decays of the ^{154}Ho high-spin isomer was obtained from the intensities of the two ground state transitions of 334.5 and 906 keV. The spin of 11.8-min ^{154}Ho is known[16] to be 1. Therefore, to estimate the number of electron capture and positron decays for the low-spin isomer it was assumed that the direct feeds to the ground and first excited states in ^{154}Dy are equally intense. From these intensities the α-decay branching ratio for 11.8-min isomer was deduced to be $(2.8 \pm 0.9) \times 10^{-4}$ and a limit of $<1 \times 10^{-5}$ was set for that of the 3.25-min isomer. With the use of the experimental $K\alpha_1$ x-ray intensity and of the procedure described in Sec. II the ratio for the low-spin isomer was determined to be $(1.4 \pm 0.3) \times 10^{-4}$ This particular value utilizes a Q_{EC} of 5.76 MeV; if the decay energy is modified to 5.43 MeV by taking into account population of excited states in

TABLE II. Transition energies and photon intensities for ^{154}Ho isomers.

Ward and Neiman[12] 3.25-min isomer E_γ (keV)	I_γ (%)	Present work 3.25-min isomer E_γ (keV)	I_γ (%)	Present work 11.8-min isomer E_γ (keV)	I_γ (%)
157.8 ± 0.2	3.9 ± 0.3	158	<3	158 ± 1	20 ± 10
289.2 ± 0.2	4.3 ± 0.3	289 [a]	<3		
295.8 ± 0.2	12.8 ± 0.5				
310.3 ± 0.25	3.0 ± 0.3	310 [a]	<2		
334.7 ± 0.25	100	334.5 ± 0.1	100	334.4 ± 0.1	100
346.5 ± 0.3	12.5 ± 1.0	346.4 ± 0.2	13 ± 2		
407.0 ± 0.3	24.5 ± 1.0	406.8 ± 0.1	18 ± 1		
412.5 ± 0.3	84 ± 4	412.3 ± 0.1	74 ± 3	412.2 ± 0.1	25 ± 6
434.9 ± 0.4	2.5 ± 0.3	435.3 ± 1.0	2 ± 1		
444.2 ± 0.4	5.1 ± 0.5	443.4 ± 0.3	5 ± 1		
471.9 ± 0.6	2.5 ± 0.4	472 [a]	<2		
477.4 ± 0.4	56 ± 2	477.1 ± 0.1	52 ± 3		
505.2 ± 0.4	16.2 ± 0.7	505.1 ± 0.2	25 ± 4		
523.8 ± 0.4	16.0 ± 0.7	523.9 ± 0.2	22 ± 3		
570.6 ± 0.5	10 ± 2	570.8 ± 0.1	12 ± 1	570.7 ± 0.2	16 ± 4
726.5 ± 0.7	13 ± 2	725.6 ± 0.1	14 ± 2		
815 ± 0.7	13 ± 3	814.9 ± 0.3	12 ± 2		
906 ± 1	1.5 ± 0.5	906 ± 1	3 ± 1	906 ± 1.0	5 ± 3
		911 ± 1	<1		
1249.5 ± 1	16 ± 2	1250.5 ± 0.1	19 ± 3		

[a] Not included in decay scheme.

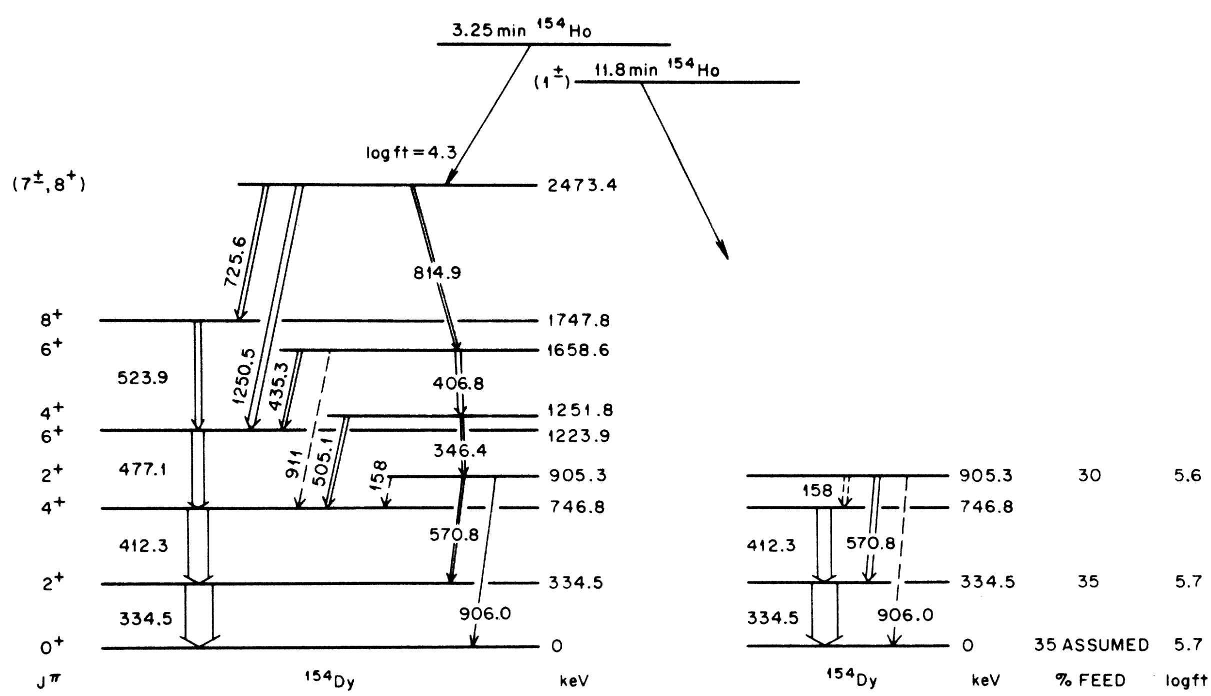

FIG. 2. Levels in ^{154}Dy populated in the decay of the ^{154}Ho isomers. For the 3.25-min isomer the decay scheme is the one reported in Ref. 12. That information and our γ-ray spectral measurements allowed us to propose the decay scheme shown for the 11.8-min isomer (its spin is known to be 1 from Ref. 16).

^{154}Dy (Fig. 2) then the ratio becomes $(1.7 \pm 0.4) \times 10^{-4}$. Within error limits it is seen that the 11.8-min ^{154}Ho branching ratios deduced from the proposed decay scheme and from the dysprosium $K\alpha_1$ x-ray intensity are in agreement. They are also in agreement with the only value available in the literature,[14] $(4.2 \pm 2.4) \times 10^{-4}$, which is based on predicted cross sections for spallation reactions induced by 660-MeV protons incident on tantalum. Finally, the limit for 3.25-min ^{154}Ho as determined from the $K\alpha_1$ x rays is $<2 \times 10^{-5}$.

B. ^{153}Ho isomers

Bombarding energies of 45 and 53 MeV were used for the production of ^{153}Ho isomers in the ^{147}Sm(^{10}B, $4n$) reaction. As mentioned in the previous subsection, the α spectrum at 45 MeV showed the presence of the ^{153}Ho low-spin isomer. To obtain its $K\alpha_1$ dysprosium x-ray intensity a normalized contribution from the 11.8-min ^{154}Ho decay was subtracted, again as discussed above. At 53-MeV bombarding energy, the α-particle spectrum showed α groups due to both ^{153}Ho isomers and the low-spin isomers of ^{152,154}Ho. At this incident energy the decay curve measured for the $K\alpha_1$ peak was resolved into two components with half-lives of 2.7 and 10 min. Each component was known to include contributions from two activities, namely (1) 2.0-min ^{153}Ho and 3.25-min ^{154}Ho, and (2) 9.3-min ^{153}Ho and 11.8-min ^{154}Ho. The division of each component between the two contributing activities was estimated, and a 40% error was ascribed to the intensities of the $K\alpha_1$ dysprosium x rays emitted in the decays of the ^{153}Ho isomers. Based on the number of α particles observed at 45 and 53 MeV the relative intensities of the $K\alpha_1$ rays assigned to the decay of the ^{153}Ho low-spin isomer were found to agree with one another. Because of its much larger α-decay branch the presence of the ^{152}Ho α group required at most a 4% correction to the 2.0-min ^{153}Ho x-ray component.

In Table III we list energies and γ-ray intensities for transitions that we propose to follow the decay of the ^{153}Ho isomers. Their γ-ray spectra have not been investigated previously. We base our assignments on half-lives and the variation of intensities with bombarding energy. No attempt was made to place the γ rays in a decay scheme; the information in Table III, however, was used to estimate corrections to the x-ray intensities resulting from internal conversion processes.

The ^{153}Ho α-decay branching ratios were deduced from the $K\alpha_1$ x-ray intensities as outlined in Sec. II. The Q_{EC}, 4.26 MeV, was taken from the 1971 Atomic Mass Tables.[7] To take into account direct feeding to excited states in ^{153}Dy a reduced Q_{EC} of 3.46 MeV was also used, the decrease being based on an analogy with the known decay scheme[17] of the isotone, ^{151}Tb. The two decay energies lead to α-decay branches for the ^{153}Ho low-spin isomer of $(1.2 \pm 0.5) \times 10^{-3}$ and $(1.8 \pm 0.8) \times 10^{-3}$. These have to be compared with a previously reported[10] experimental value of $(1.2 \pm 0.7) \times 10^{-3}$ and estimated values of $(3 \pm 2) \times 10^{-3}$ (Ref. 9) and $(0.8 \pm 0.5) \times 10^{-3}$ (Ref. 14). For the high-spin isomer the two decay energies lead to α-decay branching ratios of $(3.4 \pm 1.7) \times 10^{-4}$ and $(5.1 \pm 2.5) \times 10^{-4}$.

TABLE III. Transition energies and relative photon intensities for ^{153}Ho isomers.

Low-spin isomer 9.3 min		High-spin isomer 2.0 min	
E_γ (keV)	I_γ (%)	E_γ (keV)	I_γ (%)
109 ± 0.5	6 ± 4	109 ± 0.5	2 ± 1
162 ± 0.5	20 ± 7	162 ± 0.5	3 ± 2
295.8 ± 0.1	13 ± 6	295.8 ± 0.1	100
334.6 ± 0.1	40 ± 15	334.6 ± 0.1	45 ± 10
343.0 ± 0.2	40 ± 3		
366.1 ± 0.1	13 ± 5	366.1 ± 0.1	4 ± 1
438.1 ± 0.1	22 ± 5	438.1 ± 0.1	16 ± 2
455.8 ± 0.2	15 ± 3		
566.8 ± 0.2	33 ± 3		
638.3 ± 0.1	100	638.3 ± 0.1	29 ± 5
648.5 ± 0.2	20 ± 4		
		1087.2 ± 0.2	5 ± 2
		1277 ± 1 [a]	10 ± 3

[a] Doublet.

C. ^{152}Ho isomers

The ^{152}Ho isomers were produced in the reaction ^{144}Sm(^{11}B, $3n$) at a bombarding energy of 46 MeV. The most prominent α groups observed were those that belong to the two isomers of ^{152}Ho. The α groups due to ^{151}Ho were about one hundred times less intense. The decay curve of the Dy

TABLE IV. Transition energies and relative photon intensities for ^{152}Ho isomers.

Bowman *et al.*, Ref. 13 High-spin isomer 52.3 sec		Present work High-spin isomer 52.3 sec		Present work Low-spin isomer 2.36 min	
E_γ (keV)	I_γ (%)	E_γ (keV)	I_γ (%)	E_γ (keV)	I_γ (%)
491	60	492.8 ± 0.1	70 ± 5		
613	100	614.0 ± 0.1	100	614.0 ± 0.1	100
647	94	647.6 ± 0.1	104 ± 6	647.6 ± 0.1	16 ± 4
683	81	683.8 ± 0.1	102 ± 6		
		759.3 ± 0.3	15 ± 4		

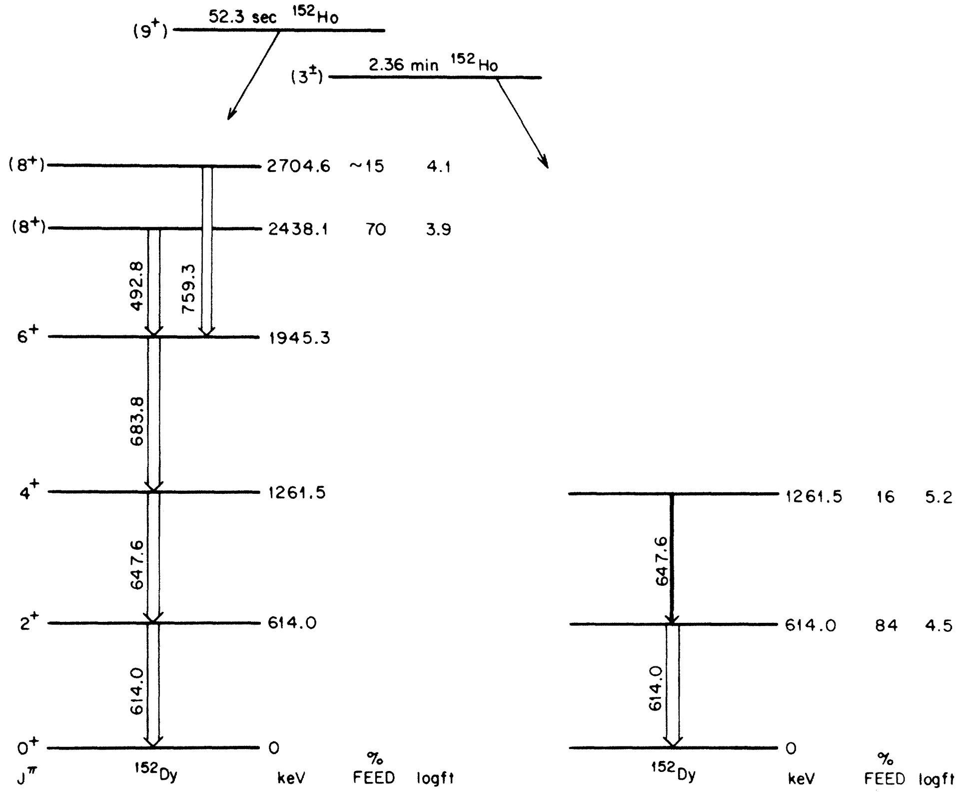

FIG. 3. Levels in ^{152}Dy populated in the decay of the ^{152}Ho isomers. The decay schemes were arrived at on the basis of our γ-ray measurements and on a survey (see Ref. 13) of available data for high-spin isomers in neighboring doubly odd nuclei.

$K\alpha_1$ x rays was separated into a 2.4-min and a 52-sec component.

The assignment of γ rays to the decay of ^{152}Ho was based once again on the measurement of half-lives and excitation functions. These γ rays and their intensities are listed in Table IV together with the preliminary results of Bowman, Haenni, and Sugihara[13] who investigated the decay of the ^{152}Ho high-spin isomer. Based on a survey of neighboring high-spin isomers they proposed a decay scheme for 52.3-sec ^{152}Ho which consisted of a cascade of four γ rays depopulating ^{152}Dy states in the following sequence, $8^+ \to 6^+ \to 4^+ \to 2^+ \to 0^+$. Our data for both isomers confirm their proposal and Fig. 3 shows the two decay schemes. We would like to discuss our confirming points in some detail. Since the 614.0-keV transition shows up strongly in the decay of both isomers it must represent the $2^+ \to 0^+$ transition in ^{152}Dy. The 647.6-keV transition which again shows up in both decays but with a smaller intensity in the case of the low-spin isomer is therefore the $4^+ \to 2^+$ transition. In the decay of ^{152}Ho high-spin isomer, the 492.8-keV γ ray has smaller intensity than the 683.8-keV γ ray. Thus the latter γ ray must represent the $6^+ \to 4^+$ transition while the 492.8-keV transition deexcites the 8^+ level at 2438.1 keV which is strongly fed in the electron capture and positron decay of the high-spin isomer. This is consistent with the suggestion of Bowman, Haenni, and Sugihara[13] that the ^{152}Ho high-spin isomer can be described as the coupling of the $h_{11/2}$ orbital for the odd proton and $f_{7/2}$ orbital for the odd neutron to form a 9^+ state. If this is indeed the case then the fact that the 492.8-keV γ ray is less intense than the 683.8-keV γ ray means that there is a transition that populates the 6^+ state from a level at a higher excitation energy in ^{152}Dy. We tentatively propose that the new 759.3-keV γ ray assigned to ^{152}Ho decay is this particular transition and that it proceeds from a level at 2704.6 keV. The direct feeding of the 4^+ and 2^+ states in the decay of the ^{152}Ho low-spin isomer suggests that its spin is probably 3.

From the decay schemes shown in Fig. 3 the α-decay branching ratios were deduced to be $4.0 \pm 1.0\%$ and $3.0 \pm 1.0\%$ for the high- and low-spin isomers, respectively. From the $K\alpha_1$ x-ray intensity and with the use of the decay schemes to obtain corrected Q_{EC} values the branching ratios were calculated to be 6.4 ± 1.3% and 1.7 ± 0.3% for the high- and low-spin isomers once again. These ratios are much smaller than the estimated ones published[9] in the literature, namely, 19 ± 5% for the high-spin state and 30 ± 15% for the low-spin isomer. From an earlier investigation[18] of thulium α emitters, decay data were available that demonstrated a parent-daughter relationship between ^{156}Tm and 2.36-min ^{152}Ho. By assuming no independent production of the daughter it was then possible to derive an upper limit of <7% for the α-decay branch of the low-spin ^{152}Ho isomer.

D. ^{151}Ho isomers

The ^{151}Ho isomers were produced in the reaction ^{144}Sm(^{11}B, $4n$) at bombarding energies of 61 and 68 MeV. At both bombarding energies, the α group of the ^{151}Ho high-spin isomer was the most intense one observed. The intensity of the ^{151}Ho low-spin isomer α group at 68- and 61-MeV bombarding energy was 7% and 13%, respectively, relative to that of the high-spin isomer. The α groups of ^{152}Ho were also present, and the decay curves of the Dy $K\alpha_1$ x rays, therefore, had to be corrected for the contributions from the 52.3-sec ^{152}Ho decays. The remainder of the short-lived portions of the decay curves were then tentatively separated into 36- and 47-sec components, bearing in mind the relative intensities of the two α groups at 61 and 68 MeV.

γ-ray spectra were measured at both bombarding energies. Because of the similarity of half-lives only tentative assignments could be made for the low- and high-spin isomeric decays. These γ rays are listed in Table V. No attempt was made to derive decay schemes; the γ rays instead were used to obtain corrections for internal conversion processes.

The decay energy for ^{151}Ho is given at 5.05 MeV

TABLE V. Transition energies and relative photon intensities for ^{151}Ho isomers.

E_γ (keV)	I_γ (%)
210.2 ± 0.2 [a]	5.6 ± 1.0
488.9 ± 0.4 [a]	4.8 ± 1.6
694.8 ± 0.2 [a]	5.4 ± 1.1
776.2 ± 0.1 [a]	17 ± 2
352.2 ± 0.4 [b]	4.2 ± 1.6
527.4 ± 0.1 [b]	100
551.0 ± 0.1 [b]	13 ± 2
653.8 ± 0.1 [b]	13 ± 2
804.4 ± 0.1 [b]	22 ± 2
1047.1 ± 0.1 [b]	4.6 ± 0.9

[a] Probably low-spin isomer.
[b] Probably high-spin isomer.

in the Mass Tables.[7] This value of Q_{EC} and another one decreased by 0.8 MeV (in analogy with the decay scheme[19] of the isotone ^{149}Tb) were used to derive branching ratios. For the high-spin isomer the two α-decay ratios were 13 ± 5% and 18 ± 6%. Both values are in excellent agreement with the previously reported[9] experimental ratio of 20 ± 5%. For the low-spin isomers the ratios were calculated to be 9 ± 4% and 13 ± 4%. These numbers are smaller than the estimated ratio of 28 ± 14%, reported previously.[9] Once again from the available data[18] for ^{155}Tm α decay to the low-spin isomer of ^{151}Ho it was possible to deduce an upper limit of <11% for the holmium daughter.

V. DISCUSSION

Our α-decay branching ratios are summarized in Table VI and compared with previously reported values. It is seen that for the two cases, i.e., 35.6-sec ^{151}Ho and 9.3-min ^{153}Ho, where experimental values had been measured our data agree with the earlier results. Also, the estimated branching ratios for 9.3-min ^{153}Ho and 11.8-min ^{154}Ho are in agreement with our measurements. The agreement is less good in the case of 47-sec ^{151}Ho, and discrepancies appear for 52.3-sec ^{152}Ho and 2.36-min ^{152}Ho. There the estimated values are much larger than ours. Because the main features of the decay of the ^{152}Ho isomers to ^{152}Dy now seem to be fairly well established (see Fig. 3) we feel that, within the quoted error limits, our data are correct.

From the branching ratios α-decay half-lives can be determined and then considered within the framework of some α-decay-rate theory. In this manner relative decay probabilities can be obtained after the energy dependence is removed. One convenient α-decay formalism has been developed by Rasmussen.[20] In it an α-decay reduced width, δ^2, is defined by the equation

$$\lambda = \delta^2 P/h , \quad (1)$$

where λ is the decay constant, h is Planck's constant, and P is the penetrability factor calculated for a barrier that includes an optical-model potential derived from the analysis of α-particle scattering data,

$$V(r) = -1100 \exp\{-[(r - 1.17A^{1/3})/0.574]\} \text{ MeV} . \quad (2)$$

A centrifugal barrier is also included so that an l dependence can be taken into account.

The sensitive dependence of half-lives on α-decay energies can be minimized by using the most accurate energies available. Until recently, only the magnetic spectrograph measurements[14] for the

TABLE VI. α-decay branching ratios.

Isomer	Present work from X rays	Present work from Decay scheme	Present work from Parent-daughter relationship	Previous work
^{151}Ho low spin	0.09 ± 0.04		<0.11	0.24 ± 0.14 [a]
	0.13 ± 0.04			
^{151}Ho high spin	0.13 ± 0.05			0.20 ± 0.05 [a]
	0.18 ± 0.05			
^{152}Ho low spin	0.017 ± 0.003	0.03 ± 0.01	<0.07	0.30 ± 0.15 [a]
^{152}Ho high spin	0.064 ± 0.013	0.04 ± 0.01		0.19 ± 0.05 [a]
^{153}Ho low spin	$(1.2 \pm 0.5)\times 10^{-3}$			$(3 \pm 2) \times 10^{-3}$ [a]
	$(1.8 \pm 0.8)\times 10^{-3}$			$(1.2 \pm 0.7)\times 10^{-3}$ [b]
				$(0.8 \pm 0.5)\times 10^{-3}$ [c]
^{153}Ho high spin	$(3.4 \pm 1.7)\times 10^{-4}$			
	$(5.1 \pm 2.5)\times 10^{-4}$			
^{154}Ho low spin	$(1.7 \pm 0.4)\times 10^{-4}$	$(2.8 \pm 0.9)\times 10^{-4}$		$(4.2 \pm 2.4)\times 10^{-4}$ [c]
^{154}Ho high spin	$<2\times 10^{-5}$	$<10^{-5}$		

[a] Reference 9.
[b] Reference 10.
[c] Reference 14.

low-spin isomers of ^{153,154}Ho quoted errors of ±5 keV. For the remaining holmium activities the error limits were ±10 (Refs. 10 and 11) and ±20 keV (Ref. 9). Bowman, Hyde, and Eppley[21] have now made available a list of more accurate energies for 40 α emitters. Many of the rare earths, including ^{151,152}Ho, now have quoted errors of ±3 keV. We have utilized this list to reexamine our earlier spectral data[11] for the holmium α emitters and have calculated new decay energies for ^{153,154}Ho. These new values, good to ±5 keV, compare with previous numbers (enclosed in parentheses) as follows: (1) 2.0-min ^{153}Ho, 3.910 (3.91 ± 0.10) MeV; (2) 9.3-min ^{153}Ho, 4.011 (4.010 ± 0.005) MeV; (3) 3.25-min ^{154}Ho, 3.721 (3.72 ± 0.01) MeV; and (4) 11.8-min ^{154}Ho, 3.937 (3.933 ± 0.005) MeV.

Table VII summarizes the reduced widths calcu-

TABLE VII. α-decay reduced widths (δ^2).

Isomer	E_α (MeV)	Partial α half-life (sec)	Reduced widths (MeV)
^{151}Ho low spin	4.607 ± 0.003	(5.22×10^{2}) [a]	0.0066 ± 0.0039
		(3.62×10^{2}) [b]	0.0096 ± 0.0053
		$(>4.3 \times 10^{2})$ [c]	<0.0081
^{151}Ho high spin	4.517 ± 0.003	(2.74×10^{2}) [a]	0.038 ± 0.016
		(1.98×10^{2}) [b]	0.052 ± 0.019
^{152}Ho low spin	4.387 ± 0.003	(0.83×10^{4}) [b]	0.0062 ± 0.0015
		(0.47×10^{4}) [d]	0.011 ± 0.004
		$(>0.2 \times 10^{4})$ [c]	<0.029
^{152}Ho high spin	4.453 ± 0.003	(0.82×10^{3}) [b]	0.030 ± 0.008
		(1.31×10^{3}) [d]	0.0174 ± 0.0053
^{153}Ho low spin	4.011 ± 0.005	(4.65×10^{5}) [a]	0.021 ± 0.010
		(3.10×10^{5}) [b]	0.031 ± 0.017
^{153}Ho high spin	3.910 ± 0.005	(3.53×10^{5}) [a]	0.125 ± 0.065
		(2.36×10^{5}) [b]	0.18 ± 0.09
^{154}Ho low spin	3.937 ± 0.005	(4.17×10^{6}) [b]	0.0067 ± 0.0020
		(2.53×10^{6}) [d]	0.0110 ± 0.0044
^{154}Ho high spin	3.721 ± 0.005	$(>9.7 \times 10^{6})$ [b]	<0.08
		$(>1.95\times 10^{7})$ [d]	<0.04

[a] From x rays, decay energy from 1971 Mass Tables.
[b] From x rays, decay energy corrected for direct feeding of excited states in dysprosium daughters.
[c] From parent-daughter relationship.
[d] From decay scheme.

lated with the above energies for ^{153,154}Ho and those of Ref. 21 for ^{151,152}Ho and by using α half-lives derived from the various branching ratios given in Table VI. The calculations were for $l=0$ α waves so that hindrances could be noted. In Fig. 4 we have plotted these reduced widths and have indicated a band of values which, because they encompass δ^2's for even-even rare earth α emitters,[1,22] can be taken to represent unhindered α decay. The figure shows, as has been known from studies in the heavy elements, that for odd-A nuclei reduced widths range from those of even-even nuclei down to much smaller values. The introduction of an α wave other than zero

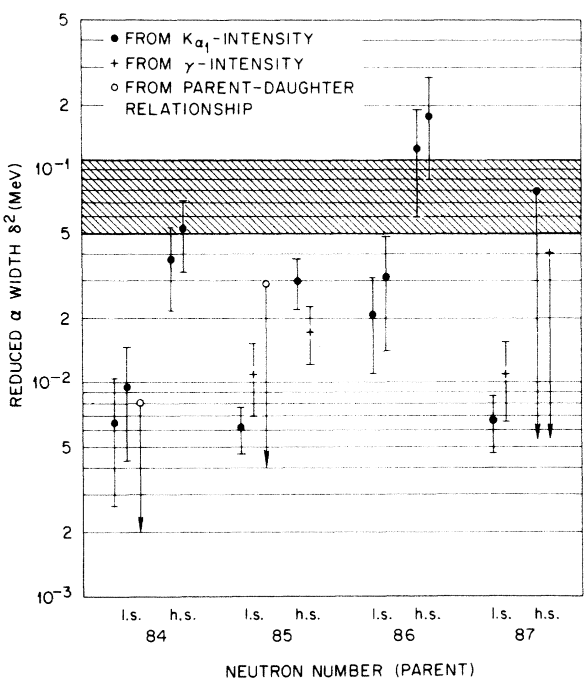

FIG. 4. α-decay reduced widths for the holmium isomers investigated in the present study. These isomers are identified by neutron number, e.g., ^{151}Ho has 84 neutrons, and by the letters l.s. (low-spin) and h.s. (high-spin). The cross-hatched band encompasses reduced widths for doubly even rare earth nuclei, values that can be considered to represent unhindered α decay. Closed and open points and crosses identify the method by which a given α decay branching ratio was determined. Details of these methods and of the reduced width calculations are presented in the text. The actual values of these reduced widths are listed in Table VII. For the isomers of ^{151}Ho($N=84$) and ^{153}Ho($N=86$) two sets of closed points are indicated. The lower values are calculated by using electron-capture decay energies from the 1971 Mass Tables[8]. The higher set of values are obtained by using decay energies that have been decreased to take into account direct feeding to excited states in their dysprosium daughters.

does raise the reduced width value but for the emission of α particles the centrifugal barrier plays only a subordinate role. It has been pointed out[23] that instead of changes in multipolarities, it may be the necessity of forming an α particle from unpaired nucleons that slows down the α-decay rate of an odd-A nucleus; for cases where the odd-nucleon wave function remains unchanged α decay may proceed at an unhindered rate.

The ^{152,154}Ho isomers, each with two unpaired nucleons, as might be expected, appear to have hindered α decays. Aside from the fact (see Refs. 24 and 25) that the two terbium daughters have high- and low-spin isomers as well, nothing is known about their level structures. Thus one can say little about the states involved in the α decays of the ^{152,154}Ho isomers.

The ^{153}Ho isomers, presumably due to the 67th proton being in the $h_{11/2}$ and $d_{5/2}$ orbitals, have reduced widths in the unhindered range. This suggests that their α decays proceed to states in ^{149}Tb represented by the same proton orbitals. Macfarlane[26] indeed proposed that the α-decaying ^{149}Tb isomers were due to $h_{11/2}$ and $d_{5/2}$ proton orbitals. He also had evidence to indicate that the $h_{11/2}$ state was the isomer and was located ~40 keV above the $d_{5/2}$ ground state. In Fig. 5 we show α-decay schemes for the ^{153}Ho isomers that are consistent with unhindered α-decay rates.

When the ^{151}Ho isomers were discovered[9] the proposal was that their α-decay schemes were as shown in Fig. 5 for the ^{153}Ho pair. (At that time the $d_{5/2}$ and $h_{11/2}$ isomers in ^{147}Tb had not been observed, though their existence has now been established.[24]) As in the case of ^{153}Ho the reduced width for the high-spin ^{151}Ho isomer is in the unhindered range and the indication here again is that the α decay involves states represented by the $h_{11/2}$ proton orbital. The α decay of the low-spin ^{151}Ho isomer, however, seems to be hindered, and thus raises the question as to whether the $d_{5/2}$ orbital is involved in both the initial and final states. In fact if an $l=3$ α wave (assuming that the decay proceeds to the $h_{11/2}$ state) is used, then the calculated reduced width is in the unhindered range. From a recent study[24] it appears that, as in the case of ^{149}Tb, the ground state of ^{147}Tb (96 min) is represented by the $d_{5/2}$ orbital while the $h_{11/2}$ state (1.9 min) is located at some unknown higher excitation energy. Thus the suggestion that the $d_{5/2}$ ^{151}Ho state decays to the $h_{11/2}$ ^{147}Tb level despite an unfavorable spin change is made even more unlikely by the greater decay energy available for the transition to the $d_{5/2}$ ground state. It is therefore not clear why, in contrast to the case in ^{153}Ho, the ^{151}Ho low-spin isomer α decay should exhibit hindrance. Interestingly, however,

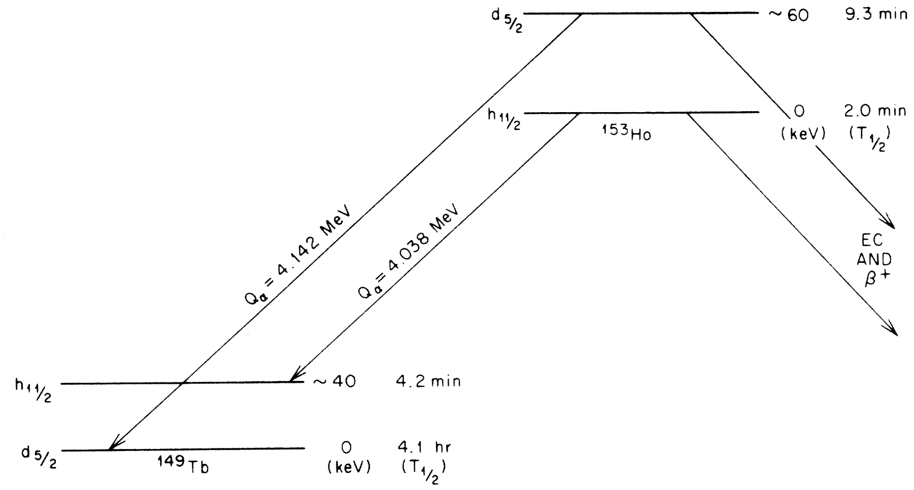

FIG. 5. Proposed α-decay schemes for the ^{153}Ho isomers. If the $h_{11/2}$ state in ^{149}Tb is ~40 keV above the $d_{5/2}$ ground state (see Ref. 26) then the indication is that in ^{153}Ho the situation is reversed with the $d_{5/2}$ state lying ~60 keV above the $h_{11/2}$ state.

the ratio of δ^2 for the high-spin to that of the low-spin isomer is ~5 for both ^{151}Ho and ^{153}Ho.

VI. CONCLUSION

It appears that the technique described in Ref. 1 and used in this study does provide one with a simple method of determining α-decay branching ratios. The largest error is introduced by having to rely on theoretical K capture/positron ratios and on predicted decay energies. The use of an on-line isotope separator would not only simplify the analysis of the x-ray spectra but would also make the information available from the annihilation radiation peak much more useful. Nevertheless, it is encouraging that ratios determined for ^{152,154}Ho from their decays to levels in ^{152,154}Dy agree within error limits with those determined from $K\alpha_1$ x-ray intensities.

The present study represents the first attempt at determining experimental α-decay branching ratios for a series of isotopes of an odd-Z element in the rare earths. It was intended primarily to extend our knowledge of α-decay rates in this mass region. Our study shows that as in the heavy elements, α decay for odd-A nuclei can proceed at widely varying rates, with reduced widths differing by factors of up to ~25.

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