α-decay branching ratios for ^{151}Tb, $^{150-153}$Dy, and $^{152-155}$Er[†]

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The isotopes $^{152-155}$Er and ^{151}Tb, $^{150-153}$Dy were produced by bombarding ^{147}Sm and ^{144}Nd, respectively, with ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron. With the use of a gas-jet-capillary transport system α-particle, x-ray, and γ-ray spectra were measured simultaneously and α-decay branching ratios deduced for the above mentioned nuclides. The ratios were determined primarily by measuring 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. In addition, for ^{150,152,153}Dy it was possible to deduce alternate, and thus independent, α-decay branching ratios from γ-ray spectral measurements. Within error limits the two sets of values were found to be in agreement. Because of the essentially equal half-lives of ^{151}Tb and ^{152}Tb the α branch for ^{151}Tb could not be determined from the $K\alpha_1$ ray intensity; instead it was deduced solely on the basis of its known decay to levels in ^{151}Gd. Branches for ^{149}Tb, ^{149}Tb^m, and ^{150}Tb, as well as for the fine structure α decays observed in the case of ^{153}Dy and ^{149,151}Tb, were taken from a survey of published values. These data were combined with our own results and α-decay reduced widths were calculated using the formalism developed by Rasmussen. As is customary, reduced widths for ground-state transitions between even-even nuclei were assumed to represent unhindered decay and then compared with values for the remaining α decays. As we had found earlier for the neighboring odd-Z holmium nuclides these latter reduced widths ranged from values close to those of even-even nuclei down to much smaller ones. This result is examined from the standpoint of what is known about spin assignments for states connected by specific α-decay transitions.

[RADIOACTIVITY ^{151}Tb, ^{150,151,152,153}Dy, ^{152,153,154,155}Er; I_α, I ($K\alpha_1$ x ray), I_γ, E_γ; measured α-decay branching ratios; deduced α-decay rates. ^{150,152}Tb deduced levels, J, π.]

I. INTRODUCTION

In earlier publications[1,2] α-decay branching ratios were reported for various rare earth nuclei. These measurements utilized a helium gas-jet system and a high-resolution Ge(Li) x-ray detector. This combination does away with the necessity of chemical separations and is thus applicable to isotopes with half-lives in the seconds range if a capillary is used to transport the gas jet to a shielded area; α-particle, x-ray, and γ-ray counting can then be made simultaneously.

The technique was tested[1] by measuring ratios for ^{149}Tb^m and ^{150,151}Dy, nuclides for which other determinations[3] were available. Our ^{149}Tb^m and ^{151}Dy ratios agreed with those of Ref. 3. For ^{150}Dy, however, our value of 0.32 was substantially greater than that of 0.18 reported in Ref. 3. Consequences of this discrepancy were discussed with respect to cross sections determined[4] with the lower branching ratio.

The technique was then applied to the high- and low-spin isomers of $^{151-154}$Ho. This represented the first systematic investigation[2] of α-decay rates for a series of isotopes of an odd-Z rare earth element. The study showed, that as in the heavy elements, α decay of odd-A nuclei in the rare earths can proceed at widely varying rates, with reduced widths differing by factors of up to ~25.

In the present paper we report similar measurements for the nearby even-Z nuclides, $^{150-153}$Dy and $^{152-155}$Er. These data are intended to complement the information obtained for the holmium isotopes and to extend, even further, our knowledge of α-decay rates in this mass region. For ^{152,153}Dy only one other set of experimental values has been published,[3] while for the erbium nuclides only estimates are available.[5,6] (Because of the aforementioned discrepancy between Refs. 1 and 3 it was felt than another measurement of the ^{150}Dy ratio was warranted.) As a by-product, the α-decay branching ratio of ^{151}Tb was also determined and combined with values, taken from a literature survey, for ^{149}Tb, ^{149}Tb^{m} and ^{150}Tb. This then provided us with another series of odd-Z α emitters whose α-decay rates could be compared with those of the even-Z dysprosium and erbium isotopes.

II. EXPERIMENTAL METHOD

Two experimental arrangements, both of them based on the well-known helium gas-jet technique,[7] were used in the present investigation. The basic gas-jet assembly, described in Ref. 8, was utilized for the longer-lived dysprosium isotopes whose half-lives range from 7 min to 6 h. Here the radioactivities were collected by placing an aluminum foil directly behind an orifice through which the helium gas and recoil products were pumped out of the gas-jet reaction chamber. After a suitable bombardment time, dependent on the half-life of interest, the catcher was removed for counting while the irradiation and collection cycle was repeated with a new collector foil. To investigate the shorter-lived erbium nuclides, with half-lives ranging from 10 sec to 5 min, a 10-m teflon capillary (i.d. 1.3 mm) was inserted into the orifice. The other end of the capillary tube, situated outside the experimental room, was pumped on to extract the product nuclei into a shielded area. The recoils were actually collected on a catcher foil located in a 500-cm^3 collector chamber (described in Ref. 2). After bombardment, the collector foil could be rotated to a position that allowed α-particle, x-ray, and γ-ray counting to be made at the same time. We should add that the dysprosium measurements were made in the same collection chamber so that counting geometries, wall thicknesses, etc. were the same in both sets of experiments. The absolute efficiencies of the three detectors were determined by calibrating with standard sources of known strengths.

Counting procedures for the determination of half-lives have been described in the earlier paper.[2] Suffice it to say that spectra were accumulated in multichannel analyzers that were interfaced to an in-house computer and each x- and γ-ray spectrum covered the energy ranges 0–120 and 100–1300 keV, respectively.

The dysprosium and erbium activities were produced by bombarding ^{142}Nd and ^{147}Sm, respectively, with ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron. The targets were electrodeposited as rare earth oxide layers (with thicknesses of ~300 μg/cm^2) onto beryllium backing foils. The isotopic enrichments were 97.7% for ^{142}Nd and 97.9% for ^{147}Sm. The primary energy of the carbon beam, 118 MeV, was reduced as needed by the use of additional degrading beryllium foils. For the dysprosium nuclides the excitation-function data of Alexander and Simonoff[4] were used to select the optimum bombarding energy necessary to emphasize the yield of a given radioactive species. Similar information is not available for the ^{147}Sm + ^{12}C system. The α-decay characteristics, however, for the erbium activities are well known[5,8]; α-particle spectra were therefore measured at about 4-MeV intervals and then used to select optimum incident beam energies.

The total number of electron-capture (I_{EC}) and positron ($I_{\beta+}$) decays were obtained primarily by determining the number of $K\alpha_1$ x rays emitted and

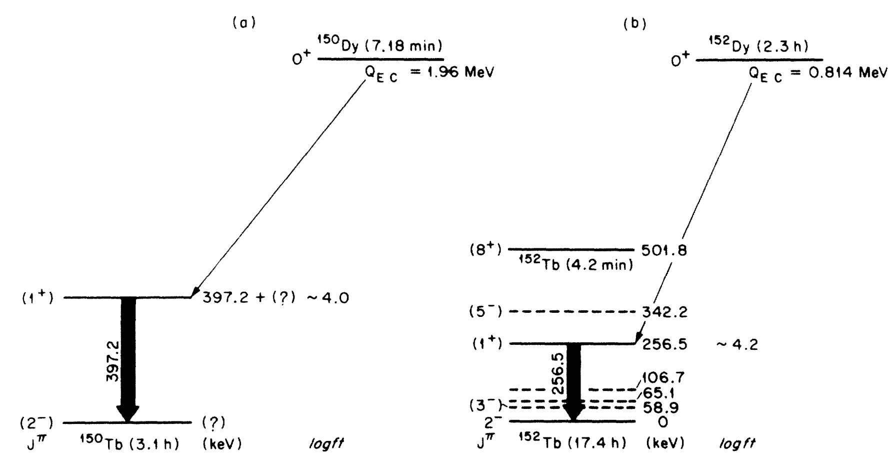

FIG. 1. (a) Proposed electron-capture decay scheme of ^{150}Dy. (b) Proposed electron-capture decay scheme of ^{152}Dy. Levels indicated by dashed lines are populated (Ref. 16) in the decay of the 4.2-min ^{152}Tb high-spin isomer located at an excitation energy of 501.8 keV.

then applying appropriate correction factors. This procedure has been described thoroughly in Refs. 1 and 2. For ^{151}Tb and ^{150,152,153}Dy information is available concerning their decays to ^{151}Gd and ^{150,152,153}Tb. Thus from the γ-ray data it was possible in those instances to obtain the sum $(I_{EC}+I_{\beta^+})$ in an independent manner.

III. RESULTS

A. Dysprosium nuclides

1. ^{150}Dy

From the $K\alpha_1$ x-ray intensity the α-decay branch for ^{150}Dy was deduced to be 0.31 ± 0.03, in good agreement with the value of 0.32 ± 0.05 published in Ref. 1. A careful analysis of the γ-ray spectrum revealed only one intense transition which could be assigned to ^{150}Dy decay. Its energy is 397.2 ±0.3 keV. Similar situations, i.e., only one strong γ ray, are now known to exist in the decays of ^{152}Dy (see below) and of the new isotope, ^{148}Dy (see Ref. 9), to levels in their terbium daughters. By assuming that the 397.2-keV transition represents 100% of all ^{150}Dy decay to ^{150}Tb we arrive at an α-decay branch of 0.36 ± 0.03, a value that agrees with the ones derived from $K\alpha_1$ x-ray intensities.

In Fig. 1(a) we show our proposed scheme for the decay of ^{150}Dy to levels in ^{150}Tb. It is based on the following evidence. Two isomers are known to exist in ^{150}Tb, a 5.8-min high-spin state, probably 9^+ (Ref. 10), and a 3.1-h low-spin state, probably 2^- (Ref. 11). Because no other strong transitions were observed it is essentially a certainty that the 397.2-keV γ-ray cannot be part of a cascade proceeding from a low-spin state (fed in the direct decay of the 0^+ ^{150}Dy ground state) to the 9^+ isomer. A similar argument applies to the 2^- isomer, although in this instance it is conceivable that a low-energy transition could be masked by the intense K x-ray peaks. In the ^{148}Dy decay scheme study,[9] however, the one intense transition (620.2 keV) was found to be coincident only with x rays and annihilation radiation, suggesting that it proceeds directly to one of the isomeric states in ^{148}Tb. Because the high-spin state is once again thought[12] to be 9^+ it has to be excluded and it must be the low-spin isomer that is fed by this transition. We propose a similar set of circumstances for ^{150}Dy, namely an intermediate state in ^{150}Tb at 397.2 keV which deexcites directly to the low-spin isomer. Note that in Fig. 1(a) the excitation energy of this state is indicated by a question mark because it is not known which of the two isomers represents the ground state in ^{150}Tb. If the spin of this state is indeed 2 then one can safely assume that the intermediate level at 397.2 keV receives all of the direct decay from ^{150}Dy. The log ft value calculated on this basis is ~4.0. Then according to the rules recently proposed by Raman and Gove[13] the spin assignment for the 397.2-keV level must be 1^+ because a 0^+ to 0^+ transition is isospin forbidden and would have a log ft value >6.5.

2. ^{151}Dy

Table I summarizes the energies and photon intensities for transitions that we assign to the decay of ^{151}Dy to levels in ^{151}Tb. Since no γ-γ coincidence measurements were made we have not attempted to construct a decay scheme. The information in Table I, however, does represent the most complete γ-ray data available up to now for ^{151}Dy.

By using an electron-capture decay energy[14] of 3.00 MeV and the $K\alpha_1$ x-ray intensity one arrives at an α-decay branching ratio of 0.052. If the decay energy is lowered by ~0.5 MeV to take into account ^{151}Dy decay to excited states in ^{151}Tb then the branching ratio increases to 0.060. (The increase comes about because decreasing the decay energy lowers the calculated β^+ intensity.) Certainly, the large number of γ rays listed in Table I indicates that the ^{151}Dy decay scheme is complex. The value of 0.5 MeV was taken as an estimate by considering the decay[15] of its isotone ^{149}Gd to levels in ^{149}Tb. By taking the average of the two values given above we arrive at an adopted α-decay branch of 0.056 ± 0.004 for ^{151}Dy. This is in agreement with the ratios given in Ref. 1, 0.055 ± 0.008, and in Ref. 3, 0.059 ± 0.006.

TABLE I. γ rays assigned to ^{151}Dy electron-capture decay.

E_γ (keV)	I_γ (% of decay) [a]
22.95 ± 0.05 [b]	2.3 ± 0.2
176.1 ± 0.2	8.7 ± 1.0
386.3 ± 0.3	10.8 ± 1.0
432.9 ± 0.4	2.1 ± 0.5
464.0 ± 0.4	1.6 ± 0.5
477.1 ± 0.3	5.0 ± 1.0
547.1 ± 0.3	9.5 ± 1.0
984.9 ± 0.5	1.0 ± 0.5
1010.8 ± 0.5	1.5 ± 0.5
1096.5 ± 0.5	1.1 ± 0.5
1115.1 ± 0.5	1.9 ± 0.5
1130.9 ± 0.5	1.5 ± 0.5
1143.1 ± 0.5	1.6 ± 0.5

[a] Total number of electron-capture decays determined from $K\alpha_1$ x-ray intensity.

[b] Multipolarity of the transition must be either $E1$ or $M1$. Conversion-electron intensities for other multipolarities sum to more than 100% of all decays.

3. ^{152}Dy

Once again as in the case of ^{150}Dy only one strong transition, 256.5 ± 0.3 keV, could be assigned to the decay of ^{152}Dy. Its electron-capture decay scheme, shown in Fig. 1(b), is proposed on the same set of arguments presented for ^{150}Dy: These will, therefore, not be repeated. Here, however, it is known[16] that the low-spin isomer is the ground state in ^{152}Tb and its spin has been measured[17] to be 2. Thus one is on a firm base to assume that the intermediate state at 256.5 keV receives essentially all of the direct electron-capture decay from ^{152}Dy. The resultant logft value is ~4.2 so that the spin assignment for this level must be 1^+. Levels indicated by dashed lines in Fig. 1(b) at excitation energies of 342.2, 106.7, 65.1, and 58.9 keV are populated[16] in the decay of the 4.2-min isomer located at 501.8 keV.

The α-decay branching ratio deduced from the $K\alpha_1$ intensity is $(0.94 \pm 0.09)\times 10^{-3}$. This is in agreement with the ratio of $(1.08 \pm 0.11)\times 10^{-3}$ derived by assuming that the 256.5-keV transition represents 100% of all ^{152}Dy electron-capture decays. Both numbers are, however, about twice the ratio reported in Ref. 3, i.e., $(5 \pm 1)\times 10^{-4}$.

4. ^{153}Dy

The electron-capture decay scheme of ^{153}Dy is rather well known[18] and in addition, absolute photon intensities are available[19] for several of its transitions. We utilized these absolute intensities for three γ rays observed in our spectra, namely, 80.75, 99.65, and 274.7 keV, to calculate the α-decay ratio for ^{153}Dy. The three values averaged out to $(1.13 \pm 0.17)\times 10^{-4}$. This ratio agrees with that of $(0.83 \pm 0.13)\times 10^{-4}$ which was deduced from the $K\alpha_1$ x-ray intensity. The decay scheme of Harmatz and Handley[18] was used to correct the electron-capture decay energy[14] for population of excited states in ^{153}Tb; their conversion-electron data were also used to determine the contribution to the K x-ray intensity that results from the conversion process. Both ratios are about 3 times larger than the value reported in Ref. 3, i.e., $(3.0 \pm 0.3)\times 10^{-5}$.

B. Erbium nuclides

For several reasons the information from γ-ray spectra obtained during measurements involving the erbium nuclides did not prove useful in determining branching ratios. First, no intense peaks were observed with the half-lives of ^{152,153}Er. As will be seen below this result is consistent with the fact that their α branches appear to be large. Second, the half-lives of ^{154}Er and ^{155}Er are very similar. Third, the (^{12}C, $3n$) product in our investigation is the so far unreported isotope ^{156}Er. A great amount of time would have been needed to sort through carefully the available spectra, as well as obtaining additional ones at other bombarding energies. Because γ-ray spectroscopy was not the primary object of the present study, it was decided to rely solely on x-ray measurements for the determination of the $^{152-155}$Er α-decay branches.

1. ^{152}Er

No $K\alpha_1$ x-rays could be observed with the 10.3-sec half-life of ^{152}Er. If, however, all of the short-lived (~30 sec) component seen in the $K\alpha_1$ x-ray decay curve is assigned to ^{152}Er then a lower limit of 0.53 can be deduced for the nuclide's α-decay branching ratio. Thus the two limits of 1.00 and 0.53 are consistent with the estimate of $(0.90^{+0.05}_{-0.20})$ reported by Macfarlane and Griffioen.[5] It should be noted that our lower limit was determined with an electron-capture decay energy of 3.24 MeV.[14] The decay, if it occurs, must involve excited states in ^{152}Ho because the two isomers in that nucleus have probable spins of 3 and 9 (see Ref. 2). Any lowering in the decay energy will of course decrease the calculated β^+ contribution and therefore increase the α-decay branching ratio. This point coupled with the fact that 36-sec ^{153}Er was known to be present from the α spectrum leads us to believe that the ^{152}Er α-decay branch is closer to the upper rather than the lower limit.

2. ^{153}Er

At the bombarding energy emphasizing the production of ^{153}Er the counting intervals used were 30 sec each. Only the first three points of the decay curve for the $K\alpha_1$ x rays could not be accounted for by the presence of ^{154}Er (see below). By extrapolating these three excess counts to the end of bombardment with the 36-sec half-life of ^{153}Er the α-decay branch for this nuclide was found to be $(0.38^{+0.19}_{-0.07})$. Once again the total electron-capture decay energy of 4.58 MeV[14] was used. The upper limit of 0.57, however, adequately encompasses any reasonable corrections to the decay energy.

Our branch for ^{153}Er is about 2 times lower than the estimate of Macfarlane and Griffioen,[5] i.e., $(0.95^{+0.05}_{-0.20})$. There is evidence from yield-curve data[8] which indicates that the ^{152}Er α-decay branch must be larger than that of ^{153}Er, rather than being equal to it as estimated in Ref. 5. In that study[8] the two nuclides were produced in the following reactions: ^{156}Dy(^{3}He, $6n$)^{153}Er and ^{156}Dy(^{3}He, $7n$)-^{152}Er. The experimental counting rates were corrected for differences in beam intensity, bombardment time, and half-lives; in addition the estimated α-decay branches of Ref. 5 were used. The maximum yield for the (^{3}He, $7n$) reaction leading to ^{152}Er was found to be ~1.25 greater than that for the (^{3}He, $6n$) reaction. This is contrary to what is known for the production of neutron-deficient isotopes which are located far from the line of β stability. Indeed, following the evaporation of four or five neutrons from the compound system, the reaction cross section is expected to decrease substantially for each additional emitted neutron. If the ^{152}Er α-decay branch were ~2 times greater than that of ^{153}Er, as our data indicate, then the measured[8] yields would be more in line with these expectations.

3. ^{154}Er

The α-branching ratio of ^{154}Er was measured from the $K\alpha_1$ x-ray intensity to be $(4.7 \pm 1.3) \times 10^{-3}$. No correction was made for possible decay to excited states in ^{154}Ho. In this instance, however, the electron-capture decay energy[14] is only 2.20 MeV, so that the positron contribution is relatively unimportant. Our ratio is substantially greater than the estimated[6] value of $(1.7 \pm 1.0) \times 10^{-3}$.

4. ^{155}Er

To resolve the ^{155}Er α group, $E_\alpha = 4.012$ MeV, from the one due to ^{151}Dy, $E_\alpha = 4.067$ MeV, it was necessary to utilize a ^{12}C beam with a rather low energy, i.e., ~70 MeV. [The ^{151}Dy α branch is much larger than that of ^{155}Er (see below); thus, even at incident energies where the (^{12}C, $4n$) and (^{12}C, $\alpha 4n$) reaction cross sections are comparable, the ^{151}Dy α peak dominates the nearby ^{155}Er group.] This meant that the (^{12}C, $3n$) product, the so far unreported isotope, ^{156}Er, was undoubtedly produced but its contribution to the $K\alpha_1$ x-ray intensity could not be taken into account. Indeed, the half-life of the $K\alpha_1$ x-ray peak was found to be ~6 min, a value which is somewhat larger than the one determined for ^{155}Er from α spectroscopy, namely, 5.3 ± 0.3 min.[8] Nevertheless, while bearing this caveat in mind, we used the total 6-min contribution to the x-ray intensity and deduced a branching ratio of $(2.2 \pm 0.7) \times 10^{-4}$. We did not attempt to correct for possible decay to excited states in ^{155}Ho, although in this instance the electron-capture decay energy is 3.81 MeV[14] and the calculated positron intensity is about the same as the total K x-ray intensity. Coupling the two problems associated with the present measurement it is fair to say that the ratio given above is almost certainly too small.

C. ^{151}Tb

Many measurements of the ^{151}Tb α-decay branch have been made. The results fall into two groups, the first being in the neighborhood of $\sim 5 \times 10^{-6}$ (refs. 3, 20, and 21), while the second set of values is closer to $\sim 1 \times 10^{-4}$ (Refs. 22 and 23). Radioactivity due to ^{151}Tb was observed in our measurements dealing with ^{151}Dy. It was therefore possible to deduce the ^{151}Tb α-decay branch once all of the ^{151}Dy had decayed. This was done with the idea of deciding which of the previous values were correct.

In the electron-capture decay of ^{151}Tb 3 intense transitions are well characterized, i.e., 108.1 (seen in our x-ray spectra), 251.9 and 287.2 keV (observed in our γ-ray spectra). The conversion-electron data of Ref. 23 were used to supplement our photon information so as to obtain total relative transition intensities. There were in turn converted to intensities per 100 decays by using the decay schemes proposed by Gonsior *et al.*[23] and by Wilski *et al.*[24] The amount of direct decay to the ^{151}Gd ground state is uncertain; it is estimated to be <15% by Wilski *et al.*[24] and <9% by Gonsior *et al.*[23] By assuming 7.5% direct decay (average of the two extremes, 0 and 15%), we arrive at the following values for the transition intensities: 108.1 keV, 70 ± 10%; 251.8 keV, 30 ± 5%; and 287.2 keV, 26 ± 5%. The α-decay branching ratio, as determined by averaging the three intensities, was found to be $(9.5 \pm 1.5) \times 10^{-5}$. This value agrees with those reported in Ref. 22 $(8.3 \pm 2.5) \times 10^{-5}$, and in Ref. 23 $(10 \pm 5) \times 10^{-5}$.

TABLE II. Summary of decay data for dysprosium α emitters.

Nuclide	$T_{1/2}$	E_α (MeV)	α branches (present work) obtained from $K\alpha$ x-ray intensities	Decay schemes
^{150}Dy	7.17 ± 0.05 min [a]	4.232 ± 0.003 [b]	0.31 ± 0.03	0.36 ± 0.03
^{151}Dy	16.9 ± 0.05 min [a]	4.067 ± 0.003 [b]	0.056 ± 0.004	
^{152}Dy	2.3 ± 0.1 h [c]	3.630 ± 0.005 [d]	$(0.94 \pm 0.09) \times 10^{-3}$	$(1.08 \pm 0.11) \times 10^{-3}$
^{153}Dy	6.4 ± 0.2 h [c]	3.464 ± 0.005 [d]	$(0.83 \pm 0.13) \times 10^{-4}$	$(1.13 \pm 0.17) \times 10^{-4}$
		3.305 ± 0.005 [d]	$(1.66 \pm 0.83) \times 10^{-8}$	$(2.26 \pm 1.13) \times 10^{-8}$
^{154}Dy	$(1.0 \pm 0.4) \times 10^7$ yr [d]	2.872 ± 0.005 [d]		
^{154}Dy	$(1.0^{+2.0}_{-0.67}) \times 10^6$ yr [e]	2.85 ± 0.05 [e]		

[a] Reference 1.
[b] Reference 25.
[c] Reference 3.
[d] Reference 26.
[e] Reference 27.

TABLE III. Summary of decay data for erbium α emitters.

Nuclide	$T_{1/2}$	E_α (MeV)	α/K x ray (this work)	α branch (this work)
^{152}Er	10.3 ± 0.5 sec [a, b]	4.799 ± 0.003 [c]	>1.91	$(0.53-1.00)$
^{153}Er	36 ± 1 sec [a, b]	4.671 ± 0.003 [c]	$1.69^{+2.01}_{-0.48}$	$0.38^{+0.19}_{-0.07}$
^{154}Er	3.75 ± 0.50 min [d]	4.166 ± 0.005 [e]	$(5.9 \pm 1.6) \times 10^{-3}$	$(4.7 \pm 1.3) \times 10^{-3}$
^{155}Er	5.3 ± 0.3 min [b]	4.012 ± 0.005 [d]	$(4.9 \pm 1.6) \times 10^{-4}$	$(2.2 \pm 0.7) \times 10^{-4}$

[a] Reference 5.
[b] Reference 8.
[c] Reference 25.
[d] Present investigation.
[e] Reference 6.

IV. SUMMARY OF DATA FOR DYSPROSIUM, ERBIUM, AND TERBIUM α EMITTERS

In Tables II–IV we have listed for all known dysprosium, erbium, and terbium α emitters, respectively, selected data necessary for consideration of their α-decay rates.

Table II summarizes the information for dysprosium nuclides. For $^{150-153}$Dy, half-lives were taken from Refs. 1 and 3, α energies from Bowman, Hyde, and Eppley[25] and from Golovkov *et al.*[26] Branching ratios listed in Table II are the result of the present investigation. Note that fine structure has been reported[26] in the α-decay of ^{153}Dy, with the intensity of the subsidiary peak being $(2 \pm 1) \times 10^{-4}$ times that of the main α group. The α branches given for the less intense group are the result of multiplying that number by the branching ratios determined in this study for the principal ^{153}Dy α peak. We have also included data for long-lived ^{154}Dy, first reported by Macfarlane.[27] It is presumed to be a pure α emitter and its estimated half-lives[26,27] differ by a factor of 10.

Table III summarizes the data for $^{152-155}$Er. The α-decay branches are the result of the present investigation, half-lives are from this study and Refs. 5 and 8, and α energies for $^{152-154}$Er are from Refs. 6 and 25. With the use of these three energies we reexamined α spectra from the investigation reported in Ref. 8 and determined the ^{155}Er α-decay energy to be 4.012 ± 0.005 MeV. This value is more precise than the previously published[8] number of 4.01 ± 0.01 MeV.

A literature survey was made for known terbium α-emitting nuclides and what were considered the most accurate available data are listed in Table IV. Half-lives are from Refs. 1 and 28; α energies, with the exception of ^{149}Tb^m, are those published by Golovkov *et al.*[26] Their ^{149}Tb energy was used in a reexamination of spectra available from the work of Bingham *et al.*[1] and a value of 3.999 ± 0.007 MeV was determined for ^{149}Tb^m. The only previously published[3] number is much less precise, i.e., 3.99 ± 0.03 MeV. Fine structue has been observed[26] in the α decays of ^{149,151}Tb. The α-decay branches for the main groups are from Ref. 29 (^{149}Tb) and the present investigation (^{151}Tb). As before the branches for the subsidiary peaks were obtained by using their intensities[26] relative to the principal groups. The ^{149}Tb^m branching ratio is an average of two values,[1,3] while that of ^{150}Tb is an estimate reported by Golovkov *et al.*[26]

V. DISCUSSION

From the information given in Tables II–IV, α-decay half-lives can be determined and then considered within a theoretical framework so that relative decay probabilities can be obtained after the energy dependence is removed. As in Ref. 2 we have chosen the convenient α-decay formalism developed by Rasmussen.[30] In it an α-decay reduced

TABLE IV. Summary of decay data for terbium α emitters.

Nuclide	$T_{1/2}$	E_α (MeV)	α decay branch
^{149}Tb	4.10 ± 0.05 h [a]	3.967 ± 0.005 [b]	0.226 ± 0.023 [c]
		3.644 ± 0.005 [b]	$(6.8 \pm 2.3) \times 10^{-5}$ [b, c]
^{149}Tb^m	4.16 ± 0.04 min [d]	3.999 ± 0.007 [e]	$(2.25 \pm 0.25) \times 10^{-4}$ [d, f]
^{150}Tb	3.1 ± 0.2 h [a]	3.492 ± 0.005 [b]	$(1.96^{+3.93}_{-1.22}) \times 10^{-6}$ [b]
^{151}Tb	17.5 ± 0.7 h [a]	3.409 ± 0.005 [b]	$(9.5 \pm 1.5) \times 10^{-5}$ [e]
		3.183 ± 0.005 [b]	$(9.5 \pm 1.5) \times 10^{-8}$ [b, e]

[a] Reference 28.
[b] Reference 26.
[c] Reference 29.
[d] Reference 1.
[e] Present investigation.
[f] Reference 3.

TABLE V. α-decay reduced widths (δ^2) for dysprosium and erbium nuclei.

Nuclide	Partial α half-life (sec)	Reduced width (MeV)
^{150}Dy	(1.39×10^{3}) [a]	0.084 ± 0.012
^{150}Dy	(1.20×10^{3}) [b]	0.098 ± 0.012
^{151}Dy	(1.80×10^{4}) [a]	0.062 ± 0.010
^{152}Dy	(8.81×10^{6}) [a]	0.116 ± 0.026
^{152}Dy	(7.67×10^{6}) [b]	0.133 ± 0.035
^{153}Dy	(2.78×10^{8}) [a]	0.068 ± 0.018
^{153}Dy	(2.04×10^{8}) [b]	0.093 ± 0.025
^{153}Dy [c]	(1.39×10^{12}) [a]	$(0.000\,35^{+0.000\,26}_{-0.000\,19})$
^{153}Dy [c]	(1.04×10^{12}) [b]	$(0.000\,47^{+0.000\,35}_{-0.000\,26})$
^{154}Dy	(3.16×10^{14}) [d]	0.016 ± 0.006
^{154}Dy	(3.16×10^{13}) [e]	$(0.16^{+0.380}_{-0.112})$
^{152}Er	(10.3–19.4) [a]	(0.062–0.116)
^{153}Er	$(94.7^{+24.6}_{-33.3})$ [a]	$(0.055^{+0.032}_{-0.013})$
^{154}Er	(4.79×10^{4}) [a]	0.077 ± 0.015
^{155}Er	(1.45×10^{6}) [a]	0.027 ± 0.009

[a] Based on α branch deduced from $K\alpha$ x-ray intensity.
[b] Based on α branch deduced from electron-capture decay scheme.
[c] Fine structure decay.
[d] Estimate from Ref. 26.
[e] Estimate from Ref. 27.

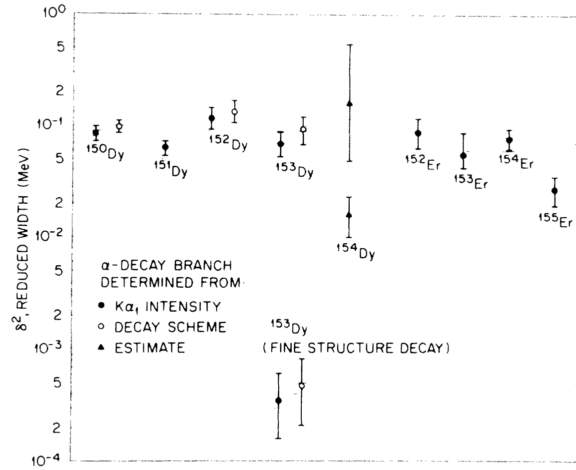

FIG. 2. α-decay reduced widths for $^{150-154}$Dy and $^{152-155}$Er, calculated with $l=0$ α waves. Except for ^{154}Dy and the fine structure decay of ^{153}Dy, the reduced widths are based on α-decay branching ratios measured in this investigation. Closed points indicate branches determined from $K\alpha_1$ x-ray intensities, while the open points for ^{150,152,153}Dy indicate branches deduced from their respective electron-capture decay schemes. Values for ^{154}Dy are based on estimated half-lives reported in Refs. 26 and 27. The branch for the fine structure ^{153}Dy α decay was determined from its intensity (relative to the main ^{153}Dy α group) reported in Ref. 26.

width δ^2 is defined by the equation

$$\lambda = \delta^2 P/h \, , \tag{1}$$

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 by Igo[31] from the analysis of α-particle scattering data. A centrifugal barrier is also included so that an l dependence can be taken into account.

For more convenient discussion and display we will first consider the dysprosium and erbium α emitters, separate from the terbium nuclides. The

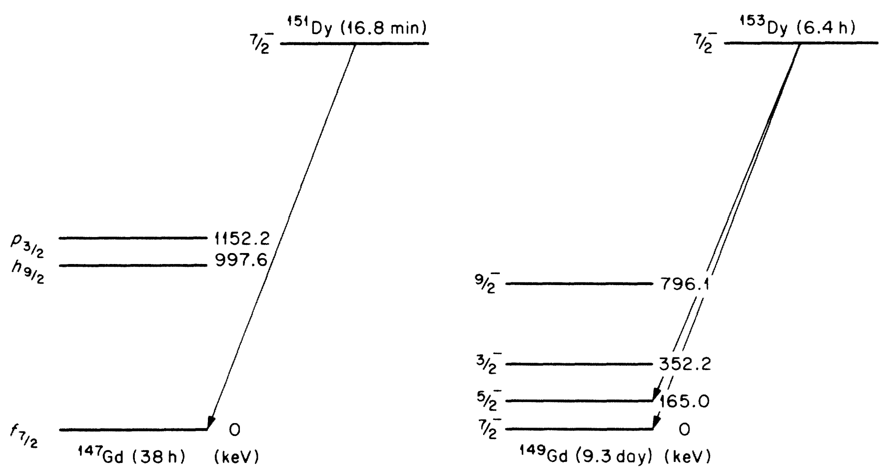

FIG. 3. α-decay schemes for ^{151,153}Dy. The sequence of low-lying levels in their daughters are taken from Ref. 12 (^{147}Gd) and Refs. 35 and 36 (^{149}Gd).

calculated reduced widths for the even-Z nuclei are listed in Table V and are plotted in Fig. 2. Calculations were made in these cases with $l=0$ α waves so that hindrances could be noted. It is customary[32] to assume that α-decay rates for ground to ground-state transitions between even-even nuclei can be taken to represent unhindered α decay. Forgetting for the moment ^{154}Dy and the fine structure ^{153}Dy α group one sees in Fig. 2 that, with the exception of ^{155}Er, all of the other reduced widths are relatively constant. The indication then is that the α-decay rates of the odd-A isotopes, ^{151}Dy, ^{153}Dy, and ^{153}Er, are unhindered, as is possible for instances[32] where the odd-nucleon wave function is the same in the parent and daughter nuclei.

Indeed, the ^{151,153}Dy (Ref. 33) and ^{147,149}Gd (Ref. 34) ground-state spins have all been measured to be $\frac{7}{2}$. The likelihood is that these states are represented by the $f_{7/2}$ odd-neutron orbital, the first one available beyond the $N=82$ closed shell. In Fig. 3 we show the α-decay schemes of ^{151}Dy and ^{153}Dy together with known low-lying excited states in ^{147}Gd (Ref. 12) and ^{149}Gd (Ref. 35 and 36). Because the first excited state in ^{147}Gd is located at 997.6 keV it is clear why no fine structure was observed[26] in the α decay of ^{151}Dy. Keeping in mind that a fair amount of final-state configuration mixing undoubtedly exists, it is still reasonable to describe the first three levels in ^{147}Gd ($N=83$) by the single-neutron orbitals, $f_{7/2}$, $h_{9/2}$, and $p_{3/2}$. In ^{149}Gd, however, two additional states, $\frac{5}{2}^-$ and $\frac{3}{2}^-$, are observed at excitation energies below the $\frac{9}{2}^-$ level. They are interpreted[35] as members of a band ($\frac{3}{2}$ to $\frac{11}{2}$) resulting from the coupling of the single-neutron $f_{7/2}$ state to a quadrupole phonon excitation in the even-even core. The fine structure ^{153}Dy α decay, presumed[26] to proceed to the $\frac{5}{2}^-$ first excited state in ^{149}Gd, has a decay rate which is hindered by a factor of ~200. The introduction of $l=1$ and 2 α waves raises the δ^2 value by factors of only 1.25 and 2.0, respectively, a result which reinforces the well-known[32] fact that for α-particle emission the centrifugal barrier plays a subordinate role. Rather it is α-particle formation that seems to be important and this point will be looked into further when we discuss the terbium reduced widths.

While the ^{153,155}Er spins have not been measured, ^{157,159,161}Er are reported[37] to have spins of $\frac{3}{2}$, the same as for ^{155,157}Dy.[33] These ground states are interpreted[38] as being due to the Nilsson-model [521 $\frac{3}{2}$] configuration, since it is generally agreed that the onset of permanent deformation takes place beyond $N=88$. One might assume then, that as their dysprosium (Ref. 33) and gadolinium (Ref. 34) isotones, ^{153,155}Er also have ground states of $\frac{7}{2}^-$. If such is indeed the case, the slight hindrance, ~3.0, exhibited by the ^{155}Er α decay is probably due to the fact that its measured α branch is too low for reasons discussed in Sec. III.

TABLE VI. α-decay reduced widths (δ^2) for terbium nuclei.

Nuclide	Partial α half-life (sec)	Reduced width (MeV)	
^{149}Tb	(6.53×10^4) [a]	(0.020 ± 0.004)	$l=0$
^{149}Tb (fine structure decay)	(2.17×10^8) [a]	(0.0019 ± 0.0008)	$l=2$
^{149}Tb^m	(1.11×10^6) [b]	(0.0028 ± 0.0006)	$l=3$
^{150}Tb	(5.69×10^9) [c]	$(0.000\,48^{+0.001\,12}_{-0.000\,36})$	$l=0$
^{151}Tb	(6.67×10^8) [d]	(0.018 ± 0.006)	$l=0$
^{151}Tb (fine structure decay)	(6.67×10^{11}) [d]	(0.0029 ± 0.0010)	$l=2$

[a] Based on α branch reported in Ref. 29.

[b] Based on an average of α branches reported in Refs. 1 and 3.

[c] Estimate reported in Ref. 26.

[d] Based on α branch measured in the present investigation.

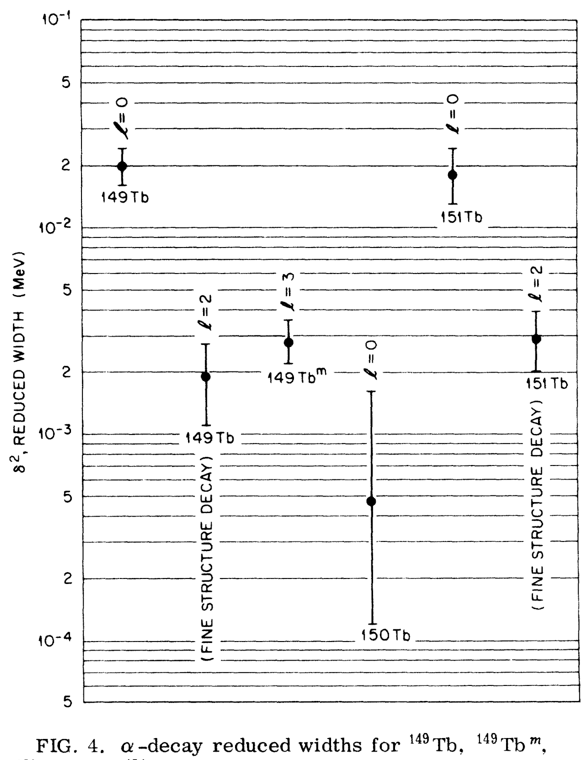

FIG. 4. α-decay reduced widths for ^{149}Tb, ^{149}Tb^m, ^{150}Tb, and ^{151}Tb, calculated with l values as indicated. α-decay branches used in the calculations were obtained as follows: ^{149}Tb (Ref. 29), ^{149}Tb^m (Refs. 1 and 3), ^{150}Tb (Ref. 26), and ^{151}Tb (present investigation). Intensities for the fine structure α groups for ^{149}Tb and ^{151}Tb were taken from Ref. 26.

Before leaving the even-Z nuclei it should be noted that of the two estimated ^{154}Dy half-lives the one reported by Golovkov *et al.*[26] is much too long because it leads to a reduced width which is inconsistent with unhindered α decay (see Fig. 2). Within error limits the half-life reported by Macfarlane[27] spans the unhindered range. It appears, however, that a half-life slightly greater than 10^6 y, rather than lower, is closer to the true value because the resultant reduced width would be more in line with values for the other even-even nuclei.

The terbium reduced widths are listed in Table VI and plotted in Fig. 4. Calculations were made with l values chosen on the basis of available, probable spin assignments, as discussed in the following paragraphs.

Figure 5(a) shows the proposed α-decay schemes for ^{149}Tb and ^{149}Tb^m. Low-lying levels in the $N = 82$ nucleus ^{145}Eu have been interpreted[39] in terms of single-proton orbitals and we have indicated in Fig. 5(a) the shell-model configurations of the first three states. We should add that the assignment for the ^{145}Eu ground state agrees with the measured[34] spin of $\frac{5}{2}$. The presence of isomerism in ^{149}Tb has been suggested by Macfarlane[40] to be the result of the 65th proton being in either the $h_{11/2}$ or $d_{5/2}$ orbitals; he also presented evidence to indicate that the high-spin state is the isomer. (The fact that at $Z = 65$ the $h_{11/2}$ level has dropped below the $g_{7/2}$ state has now been established[12] through the discovery of a 1.9-min high-spin isomer in ^{147}Tb, the $N = 82$ odd-Z nucleus next above ^{145}Eu). We show the ^{149}Tb^m isomer to be located ~32 keV above ground on the assumption that it decays to the ^{145}Eu ground state. From a consideration of $E3$ lifetimes it turns out that if, e.g., the α decay proceeded to the 330.1-keV level then the half-life of the isomeric transition would be ~0.1 sec, i.e., much less than the total half-life of 4.2 min. (A detailed argument has been presented in Ref. 1.) Based on the schemes shown in Fig. 5(a), reduced widths were calculated with $l = 0$ and 2 for the ^{149}Tb α transitions and $l = 3$ for the ^{149}Tb^m α decay.

The proposed ^{151}Tb decay scheme is shown in Fig. 5(b) with spin assignments for the low-lying ^{147}Eu levels taken from Ref. 41. Here once again, the measured[34] spin for ^{147}Eu is $\frac{5}{2}$, in agreement with the decay scheme assignment.[41] The ground state spin of ^{151}Tb has been measured[17] to be $\frac{1}{2}$; however, studies[23,24] of its electron-capture decay are consistent with spin values of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ as indicated in Fig. 5(b). In addition, the ^{149}Tb spin seems to be $\frac{5}{2}$ and the measured values for ^{153}Tb (Ref. 17) as well as for ^{149}Eu (Ref. 34), the isotone of ^{151}Tb, are also $\frac{5}{2}$. We have, therefore, somewhat arbitrarily, assumed a spin in $\frac{5}{2}$ for ^{151}Tb and used $l = 0$ and 2 to calculate reduced widths for the α transitions to the ^{147}Eu ground and first excited states, respectively. The similarity of the ^{149}Tb and ^{151}Tb δ^2 values is perhaps evidence in support of the ^{151}Tb spin being $\frac{5}{2}$.

The spin and parity of 3.1-h ^{150}Tb is probably 2^- (Ref. 11) as indicated earlier in our discussion the ^{150}Dy electron-capture decay scheme. The ^{146}Eu spin has been measured[34] to be 4, a value which is consistent with spin assignments proposed[42] for ^{146}Eu levels populated in ^{146}Gd decay, i.e., 4^-, 3^-, 2^-, and 1^- for states at 0, 115.5, 230.2, and 384.9 keV. Rare earth α-decay systematics show that the measured[26] ^{150}Tb decay energy is anomalously low, prompting the suggestion[8] that the α

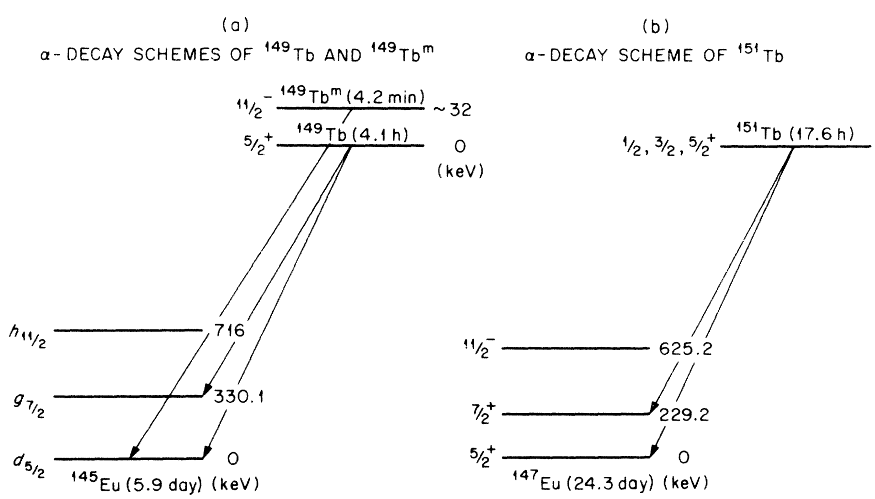

FIG. 5. (a) α-decay schemes for ^{149}Tb and ^{149}Tb^m. Spin assignments for the low-lying levels in ^{145}Eu are taken from Ref. 39. (b) α-decay scheme of ^{151}Tb; spin assignments for levels in ^{147}Eu are from Ref. 41

transition actually proceeds to an excited state in ^{146}Eu. Indeed, if the 2^- level at 230.2 keV is assumed to be the final state then the ^{150}Tb Q_α fits in well with neighboring α-decay energies. For want of other evidence the ^{150}Tb reduced width was calculated with an $l=0$ α wave.

It had been previously[3,20,21] thought that ^{151}Tb α decay was hindered by a factor of $\gtrsim 100$. Our measurement (as well as those of Refs. 22 and 23) indicates the hindrance factor to be only about 3 or 4. In fact, its reduced width, 0.018 ± 0.006, is essentially equal to that of ^{149}Tb, 0.020 ± 0.004, and similar to those of the low-spin (presumably also $d_{5/2}$ states) isomers in ^{151}Ho, 0.0096 ± 0.0053, and ^{153}Ho, 0.031 ± 0.017 (see Ref. 2). If the $d_{5/2}$ proton orbital is involved in all four α transitions, one might wonder why their reduced widths are smaller than those of the odd-A dysprosium and erbium α emitters. There, as we saw above, the initial and final states were represented by the $f_{7/2}$ neutron orbital and the δ^2 values were comparable to those of doubly-even nuclei. Similarly, for the high-spin ^{151,153}Ho isomers where the α transitions involve $h_{11/2}$ proton states, the reduced widths[2] are close to even-even values: (1) 0.052 ± 0.019, ^{151}Ho; and (2) 0.18 ± 0.09, ^{153}Ho. The lower decay rates of ^{149,151}Tb and of the low-spin ^{151,153}Ho isomers may be due to the fact that the $d_{5/2}$ orbital is filled at $Z=64$. This could make α-particle formation from nucleons in this subshell more difficult *vis-à-vis* nucleons in the unfilled $f_{7/2}$ and $h_{11/2}$ orbitals.

By taking into account, as we have done, the effect of orbital angular momentum, one is in a position to obtain a "reduced" hindrance factor for the fine structure α transitions of ^{149,151}Tb and the ^{149}Tb^m α decay. As seen in Table VI and Fig. 4, the three reduced widths are similar in value, between 0.002 and 0.003. The increase in hindrance factors, to about 30 or 40, can be understood in terms of the fact that these α transitions connect states represented by different proton orbitals. The fine structure α decay of ^{153}Dy which also has a low reduced width can be explained in a similar fashion (its δ^2 value can be raised to 0.00092 if an $l=2$ α wave is assumed). In this instance, as we noted above, the final state is interpreted[35] as coupling of the $f_{7/2}$ neutron orbital to a phonon excitation. The small reduced width for ^{150}Tb is not surprising since one would expect α-particle formation involving two odd nucleons to be difficult. One should remember, however, that its α-decay half-life is only an estimate.[26]

VI. CONCLUSION

The present investigation together with the results of our earlier study[2] have substantially increased the number of reliably measured α-decay rates in the rare earth region. Since those nuclei are in the neighborhood of the $N=82$ closed shell, they should be amenable to interpretation in terms of the more sophisticated single-particle α-decay theories. These models (see the review article of Mang[43]) have been successful in describing, for nuclei around the $N=126$ closed shell, the relative behavior of α widths as a function of N and Z and in accounting for observed hindrance factors. The calculations, however, result in absolute decay probabilities which are much smaller than experimental ones. The same is true[43] for calculated α widths in the case of deformed α emitters; these nuclei are, of course, treated in terms of the strong coupling model. Nevertheless, recent attempts of Kadmenskii, Kalechits, and Martynov[44] are promising because they indicate that α-decay probabilities can be greatly increased if allowance is made for superfluid correlations.

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