Nuclear Spectroscopic Studies of Neutron-Deficient Isotopes in the Rare Earth Region*

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The conversion-electron spectra of four neutron-deficient rare earth isotopes are presented and discussed. The four isotopes are Tb^{153}, Tb^{154}, Dy^{155}, and Ho^{160}. Mihelich, Harmatz, and Handley in a recent publication have presented the conversion-electron data of a large number of rare earth isotopes, including all but one (Dy^{155}) of the four above-mentioned activities. The agreement between the two works is good. Some additional conversion lines, not reported by Mihelich *et al.*, have been identified in this work as belonging to the decay of Tb^{153}, Tb^{154}, and Ho^{160}. Decay schemes are proposed for Dy^{155} and Tb^{153}. Tb^{154} and Ho^{160} decay to levels in Gd^{154} and Dy^{160}, respectively. The electron-capture decay data of Tb^{154} and Ho^{160} are compared with data obtained by other workers in the negatron decay of Eu^{154} and Tb^{160} to levels in Gd^{154} and Dy^{160}, respectively, and transitions common to both modes of decay are noted.

INTRODUCTION

IN our studies of rare earth alpha-particle emitters,[1] using scintillation spectrometers, we obtained numerous gamma spectra of neutron-deficient isotopes in this region of the periodic chart. We felt that it would be of great value to supplement the gamma-ray data by using instruments of much higher resolution, namely electron spectrographs. The instruments used to measure the energies of the conversion electrons were permanent-magnet spectrographs. These are 180-degree spectrographs, four of which have been described by Smith.[2] They have been designated *PM* I, *PM* II, *PM* III, and *PM* IV, and their fields are approximately 52, 99, 214, and 340 gauss, respectively. Recently two other spectrographs have been added, *PM* VI and *PM* VII. Their fields are 125 and 150 gauss. Each instrument is especially useful in a particular energy range and each was used at various times during this investigation. Electrons emitted from the source impinge on a photographic plate. By previously calibrating the instruments with electrons of known energies, one may accurately determine the energies of conversion electrons. The momentum resolution of the instruments is about 0.1%. The probable error in electron line energy determinations is generally about $\pm 0.2\%$.

The rare earth samples, in the form of powdered oxides, were bombarded with alpha particles accelerated in the Berkeley 60-inch cyclotron. These samples were several milligrams in weight and were subjected to irradiations ranging up to 100 microampere-hours. The oxides bombarded were:

(a) europium enriched in Eu^{153}, consisting of 5.0% Eu^{151} and 95% Eu^{153};

(b) gadolinium enriched in Gd^{155}, consisting of 0.46% Gd^{152}, 1.23% Gd^{154}, 72.28% Gd^{155}, 17.72% Gd^{156}, 4.60% Gd^{157}, 2.86% Gd^{158}, and 0.81% Gd^{160};

(c) natural terbium consisting of 100% Tb^{159}.

After bombardment, an ion-exchange column was used to separate the rare earths from one another by a method described by Thompson, Harvey, Choppin, and Seaborg.[3] The column used was 12.5 cm in length and 0.6 cm in diameter and was enclosed in a glass jacket that was heated to 87°C by trichloroethylene vapor. It was packed with Dowex-50, 4% cross-linked cation-exchange resin. The eluting agent was 0.4*M* α-hydroxyisobutyric acid buffered with ammonium hydroxide to a *p*H that was varied according to what elements were being eluted. The more basic the eluant, the faster the activity is eluted from the column. The *p*H in this research was varied between 3.9 and 4.3. Separations of the rare earths were very satisfactory.

After ion-exchange separation of the target material, the drops of α-hydroxyisobutyric acid solution containing the rare earth activity were combined and made 0.1*N* in HCl. This solution was placed on a resin column of 4% cross-linked Dowex-50. The size of this column was varied according to the amount of solution present. Half-normal HCl was passed through until all the α-hydroxyisobutyric acid was removed and the activity was then stripped off with 6*N* HCl. The hydrochloric acid solution was brought to dryness taken up in water and evaporated to dryness again to remove all excess HCl. The activity was then plated onto a 10-mil-diameter platinum wire from a solution of 0.1*M* ammonium bisulfate at a *p*H of 3.6. The procedure used was similar to that of Harvey in which the wire is made the cathode of an electrolytic cell.[4] Because the hydroxide ion concentration is high around the cathode, the rare earths are deposited on the wire as hydroxides. The wire was held in a Bunsen burner flame for a few

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
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[1] K. S. Toth and J. O. Rasmussen, Phys. Rev. **109**, 121 (1958).
[2] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).
[3] Thompson, Harvey, Choppin, and Seaborg, J. Am. Chem. Soc. **76**, 6229 (1954).
[4] Bernard G. Harvey, University of California Radiation Laboratory (unpublished).

seconds before being placed in the spectrograph. The plating yield varied but averaged about 50%.

The nuclides studied were Tb^{153}, Tb^{154}, Tb^{155}, Dy^{155}, Dy^{157}, Dy^{159}, and Ho^{160}. Mihelich, Harmatz, and Handley, in a recent publication,[5] have presented results concerning the conversion lines of a large number of rare earth isotopes, including all but one (Dy^{155}) of the activities that we studied. The agreement between the two works is good. We have seen some additional conversion lines that were not reported by Mihelich *et al.*

A careful examination of some of the data from experiments reported by us here led us to suspect the existence of unreported Tb^{152} with a half-life nearly the same as Tb^{151} and Tb^{154}. Further confirmatory experiments substantiated this idea, and they are reported in the paper following this.[6]

We discuss here four of the above-mentioned nuclides —Tb^{153}, Tb^{154}, Dy^{155}, and Ho^{160}—stating our results, comparing them with the other work, discussing the assignment of new lines, and then drawing some conclusions. Gamma spectra that have been obtained for the same isotopes are also presented and correlated with the conversion-electron data. These gamma spectra were obtained with the use of a 100-channel gamma pulse-height analyzer. Results are summarized in tables; electron lines not reported by Mihelich, Harmatz, and Handley bear asterisks. A nine-step visual-intensity scale is employed, designated by the symbols vvw, vw, w, wm, m, ms, s, vs, vvs, where v stands for very, w for weak, m for moderate, and s for strong.

Terbium-153

Terbium-153 was made by bombarding Eu^{153} with 48-Mev alpha particles. In this bombardment Tb^{154} also was produced by an $(\alpha,3n)$ reaction on Eu^{153}. Only one experiment of this nature was carried out. In order to differentiate between the transitions following the decay of the two isotopes two exposures were made. The first lasted a little less than 60 hr (the half-life of Tb^{153}) and the second about 8 days. The reason for choice of these times of exposure was as follows: By the time 60 hours had elapsed most of the 17-hr Tb^{154} would have decayed and its lines would not appear in so high an intensity on the second exposure. The transitions following Tb^{153} decay would seem to be almost as intense on the second exposure as on the first. By the end of the first exposure somewhat less than 50% of Tb^{153} would have decayed. By the end of another 8 days Tb^{153} would have decayed for three more half-lives, and this would have accounted for about another 44% of Tb^{153}. Thus the transitions in Gd^{153} should have been about as intense on the second exposure as on the first. More refined half-lives could have been determined for the electron lines; however, as only Tb^{153} and Tb^{154} would have been made in any large amount, and as we were looking for the less intense lines belonging to them, it was necessary only to differentiate between these two isotopes. Terbium-151 lines had been previously determined by Mihelich *et al.* Only the more prominent of the lines of Tb^{151} would appear, and these could easily be noticed. Terbium-155 had been thoroughly studied by Mihelich *et al.*, and its lines, also, could be easily subtracted out. On such a basis lines were assigned to Tb^{153} and are listed in Table I. All the lines listed in the table satisfy the condition that the intensities of the lines were equal in both exposures. The lines are divided into two groups:

(a) Those whose assignment is more certain—that is, either they were seen by Mihelich *et al.*[5] and by us, or they fit into a proposed decay scheme (see below), or both K and L lines were seen for the transitions.

(b) Those which were assigned to Tb^{153} simply because they satisfy the exposure-intensity criterion. No statements can definitely be made on whether they are K or L lines.

A decay scheme is proposed on the basis of sums and differences and is shown in Fig. 1. The proposal is quite tentative. The 109.9-kev gamma transition may be analogous to the 108.1-kev one in Gd^{151} and to the 105.4-kev transition in Gd^{155}; the 109.9-kev transition is therefore postulated to go directly to the ground state in our scheme. The 87.61-kev photon is also supposed to de-excite to the ground state, in analogy to the 86.7-kev gamma in Gd^{155} (see Mihelich's decay scheme in the

TABLE I. Conversion electron lines from Tb^{153} decay.[a]

Electron energy (kev)	Visual intensity	Conversion shell	Apparent transition energy (kev)	Transition energy (best value) (kev)
		Group *a* (assigned lines)		
33.28	m	L_{I}	41.66	41.68
34.40	mw	L_{III}	41.65	
39.82	m	M	41.71	
41.33	mw	N	41.72	
43.45	w	L_{I}	51.84	51.84
37.44	mw	K	87.67	87.61
79.17	mw	L_{I}	87.55	
52.03	m	K	102.26	102.3
59.60	s	K	109.82	109.9
101.62	m	L_{I}	109.99	
74.30*	w	K	124.51	124.5
91.20*	w	K	141.43	141.5
133.17*	vw	L_{I}	141.55	
120.42*	mw	K	170.65	170.6
124.24	vw	K	174.47	174.5
144.95	w	K	195.18	195.2
162.23	m	K	212.46	212.3
203.24	vvw	L_{I}	212.22	
199.43	vw	K	249.66	249.7
		Group *b* (unassigned lines)		
81.26*	mw			
86.79*	w			
95.37*	w			

[a] Electron lines not reported by Mihelich, Harmatz, and Handley are indicated with asterisks in the first column.

[5] Mihelich, Harmatz, and Handley, Phys. Rev. **108**, 989 (1957).
[6] Toth, Faler, and Rasmussen, following paper [Phys. Rev. **115**, 158 (1959)].

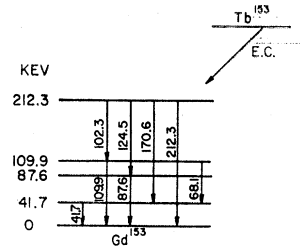

FIG. 1. Proposed decay scheme of Tb^{153}.

reference given[7]). Mihelich *et al.* saw a weak 68.1-kev transition which we were unable to observe. It fits very well as the difference between 109.9 and 41.68 kev. Rather than postulate a state at 68.1 kev, again in analogy to a 60.1-kev transition in Gd^{155}, we propose a state at 41.68 kev because the latter transition seems to be so much stronger than the 68.1-kev one. The 212.3-kev transition is proposed because gamma rays have been identified which fit well as the differences between this state and the other three already proposed. No spins can be assigned to any of the levels at this time.

A gamma spectrum was not obtained for Tb^{153}.

Terbium-154

Terbium-154 was produced by the method described in the preceding section. The lines belonging to it were assigned as described previously, and are listed in Table II.

The gamma spectrum of Tb^{154} is shown in Fig. 2. This was obtained in a bombardment on Eu^{153} below the $(\alpha,4n)$ threshold, so that very little Tb^{151} or Tb^{153} should have been present. The half-lives of all the peaks seem to be about 17 or 18 hours. The 123.2-kev photon

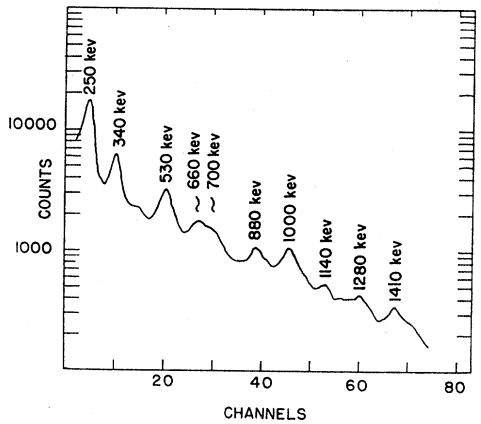

FIG. 2. Gamma-ray spectrum of Tb^{154}. The activity was produced by means of a 37-Mev helium-ion bombardment on Eu^{153} and was chemically separated by ion-exchange chromatography. The detector was a 1.5×1 inch NaI(Tl) scintillation crystal. Other terbium activities would be negligible at the time this spectrum was obtained.

[7] Mihelich, Ward, Jacob, Harmatz, and Handley, Bull. Am. Phys. Soc. **2**, No. 5, p. 259, B4 (1957).

is not shown (owing to the energy setting of the scintillation spectrometer), but one can readily see peaks at 250 and 340 kev. These peaks presumably represent the transitions of 248.1 and 347.1 kev listed in Table II. The Eu^{154} gamma spectrum obtained by Stephens is shown in Fig. 3,[8] so that the differences and similarities of the two spectra can be noted. The 340-kev peak is absent in Eu^{154} decay. The high-energy portions of the two spectra resemble each other. In each there are there gamma rays, whose energies are about 880, 1000, and 1280 kev. Stephens' spectrum also shows two peaks at 600 and 750 kev. In the same region of our spectrum there is a broad peak which undoubtedly encompasses several transitions. The latter could include, in addition to the gamma rays at 600 and 750 kev, the two transitions seen by us whose electron lines are listed in Table II with electron energies of 626.3 and 641.5 kev. The peak at approximately 530 kev in our spectrum is probably due to annihilation radiation from positrons (positron radiation from Tb^{154} was detected in a previous beta-spectroscopic study[9]). In addition there are peaks at 1140 and 1410 kev in our spectrum which are not observed in the other. The possibility was considered that these peaks might be the stack-up peaks of the following gamma rays in coincidence:

(a) 1008 and 123, adding up to 1131 kev;
(b) 1280 and 123, summing to 1403 kev.

The energies of the 1008- and 1280-kev gamma rays were taken from the conversion-electron data on Eu^{154} decay of Juliano and Stephens.[10] It is most likely that the 1131-kev peak is a stack-up peak and not a true gamma ray since for spectra taken at different distances

TABLE II. Conversion electron lines from Tb^{154} decay.[a]

Electron energy (kev)	Visual intensity	Conversion shell	Apparent transition energy (kev)	Transition energy (best value) (kev)
72.78	vvs	K	123.01	123.2
114.77	ms	L_{I}	123.15	
115.14	ms	L_{II}	123.08	
115.85	ms	L_{III}	123.10	
121.45	ms	M	123.34	
122.79	mw	N	123.18	
197.75	s	K	247.98	248.1
		L_{I}[b]		
240.21	ms			
		L_{II}[b]		
246.33	mw	M	248.21	
296.84	m	K	347.1	347.1
626.33*	w	K?		
641.54*	w	K	691.77	691.8

[a] Electron lines not observed by Mihelich, Harmatz, and Handley are indicated with asterisks in the first column.
[b] Unresolved.

[8] Frank S. Stephens, Jr., thesis, University of California Radiation Laboratory Report UCRL-2970, June, 1955 (unpublished).
[9] M. A. Rollier and J. O. Rasmussen, Jr., Rend. accad. nazl. Lincei **14**, 526 (1953).
[10] J. O. Juliano and F. S. Stephens, Jr., Phys. Rev. **108**, 341 (1957).

from the crystal the intensity of this peak was seen to diminish relative to the 1000-kev peak as the geometry was decreased. This is not true of the 1410-kev peak, since its intensity remained approximately unchanged relative to the 1280-kev gamma ray as the geometry was varied. Perhaps the 1410-kev peak is a gamma ray that does not belong to the decay of Tb^{154}.

The 123.2- and 248.1-kev transitions in Gd^{154} agree closely in energy with transition energies measured in the decay of Eu^{154} by Juliano and Stephens.[10] Their decay scheme is shown in Fig. 4. The two gamma rays represent the first excited state and a transition between that state and the second excited state, respectively. The spin and parity assignments of the two levels are 2+ and 4+, and the levels form a rotational band based on the ground state. The transitions are therefore of an $E2$ nature. The 347.1-kev transition was not excited in the decay of Eu^{154}, since the transition was not seen in either the conversion-electron spectrum or the gamma spectrum of Eu^{154}. Mihelich *et al.*,[5] who did observe the transition in their conversion-electron spectra of Tb^{154}, proposed that it could be an $E2$ transition to the 4+ state from the next member of the rotational band, whose spin and parity would be 6+.

The 691.8-kev transition must belong to a level in Gd^{154} because it was seen by Juliano in Eu^{154} decay.[10] This fact was established by placing one of his photographic plates exposed in the same permanent-magnet spectrograph side by side with our plate on which the transition was seen. By lining up the two strong transitions of 123 and 248 kev on both plates, we determined that our 691.8-kev gamma ray was the same as one of his high-energy gamma rays. However, he lists the energy of the K conversion-electron line as 643.6 kev, yielding a transition in gadolinium of 693.8 kev. As a difference of more than 2 kev is outside the scope of experimental error, his electron-line energy was recalculated and found to be in error. He also lists an L_I line for the same transition. We were unable to see this L_I line on any of his plates exposed in the permanent-magnet spectrograph in question. Presumably he must have been able to identify the line on a spectrograph with a higher field (*PM* IV) and used the field calibration of that spectrograph to calculate the energy of the transition. The use of energy calibrations from two different spectrographs could account for the difference in the calculated energies for the same transition. We believe our transition energy to be the more correct one, since the calibration of *PM* IV is not so accurate as that of *PM* III. He does not place this transition in the Eu^{154} decay scheme. Cork and co-workers have also studied the decay of Eu^{154}.[11] Their decay scheme is in agreement with that of Juliano and Stephens except that a level has been added at 1824 kev. The level is depopulated by a transition of 694 kev to the 1130-kev state common to both decay schemes. The 694-kev transition is undoubtedly the 691.8-kev one seen by us in Tb^{154} decay. Although the 694-kev transition has been observed by us, the remainder of the gamma rays reported by Juliano and Stephens and by Cork *et al.* with comparable energies (725, 759, and 592 kev) were not observed by us in the Tb^{154} decay. The explanation must be that the 1824-kev level proposed by Cork *et al.* is more heavily populated in the electron-capture decay of Tb^{154}, than in the negatron Eu^{154} decay. Though our wire sample was intense enough to enable us to observe the 694-kev transition it was insufficiently intense for us to observe the two gamma rays, 759 and 1008 kev, which depopulate the 1130-kev state.

It is not known where the transition whose electron line is at 626.3 kev fits. It is certain that it must belong to Tb^{154} decay because the only other isotopes made in

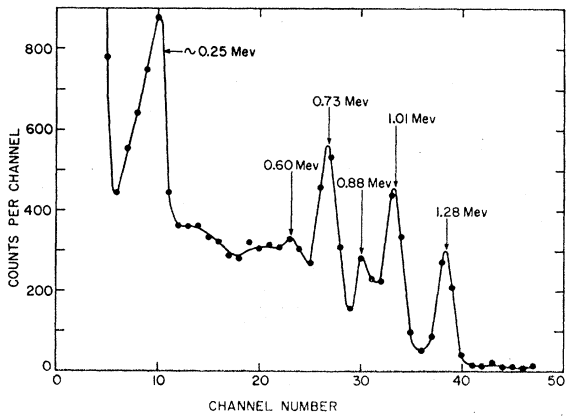

FIG. 3. Gamma spectrum of Eu^{154} as obtained by Stephens[8] using a $1\frac{1}{2}\times 1$ inch NaI(Tl) scintillation spectrometer.

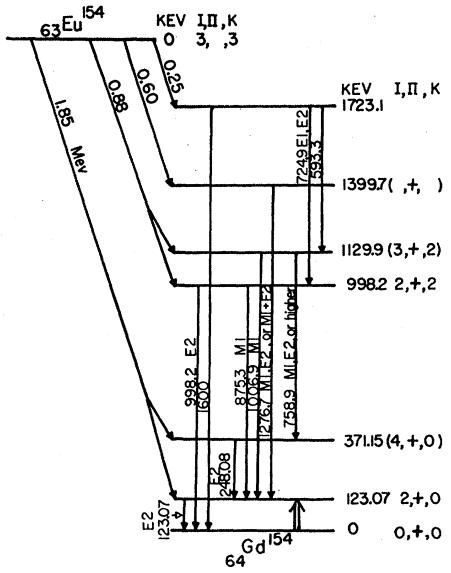

FIG. 4. Decay scheme of Eu^{154}, as proposed by Juliano and Stephens.[10]

[11] Cork, Brice, Helmer, and Sarason, Phys. Rev. **107**, 1621 (1957).

any quantity in the bombardment were Tb^{153} and Tb^{155}. The half-lives of the latter two nuclides are 60 hr and 5 days, respectively. If the transition were in the decay of either of the two isotopes it would have appeared in the second and longer exposure in which the conversion-electron lines of Tb^{153} were identified.

Some of the other gamma rays reported by Juliano and Stephens[10] have been observed by us in scintillation spectra. As mentioned previously the gamma-ray peaks at 880, 1000, and 1280 kev are seen in both Figs. 2 and 3. The energies of the gamma rays as reported by Juliano and Stephens from their conversion-electron data are 875, 998, 1007, and 1278 kev. The 1000-kev peak in both scintillation spectra evidently includes both the 998- and 1007-kev gamma rays.

TABLE III. Conversion-electron lines from Dy^{155} decay.[a,b]

Electron energy (kev)	Visual intensity	Conversion shell	Apparent transition energy (kev)	Transition energy (best value) (kev)
Part (a)				
56.70*	vs	L_I	65.41	65.43
57.18*	vw	L_{II}	65.43	
57.85*	w	L_{III}	65.37	
63.42*	ms	M	65.39	
65.13*	m	N	65.53	
38.29*	s	K	90.29	90.38
81.68*	ms	L_I	90.39	
88.42*	mw	M	90.39	
90.04*	vw	N	90.44	
obscured by another line		K		115.4
106.65*	vvw	L_I	115.36	
103.87*	mw	K	155.87	155.8
147.38*	vw	L_{II}	156.09	
148.34*	vw	L_{III}	155.86	
109.45*	m	K	161.45	161.4
obscured by another line		L_I		
153.587*	vw	K	205.59	205.7
197.12*	vvw	L_I	205.83	
175.13*	vvs	K	227.13	227.0
218.30*	mw	L_I	227.02	
225.02*	vw	M	226.99	
226.65*	vvw	N	227.05	
219.20*	w	K	271.20	271.4
262.84*	vvw	L_I	271.55	
Part (b)				
34.398*	s	L_I	43.11	43.09
34.82*	s	L_{II}	43.08	
35.54*	s	L_{III}	43.06	
41.51*	ms	M?		
42.74*	ms	N	43.14	
36.02*	s	K?	88.02	88.03
79.313*	vw	L_I?	88.03	
132.62*	m	K?	184.62	184.6
247.67*	vvw			
266.02*	vvw			
319.23*	vvw			
381.22*	vw			
432.12*	vw			
446.14*	vw			
455.95*	vw			

[a] Electron lines not observed by Mihelich, Harmatz, and Handley are indicated with asterisks in the first column.
[b] Part (a) lists the electron lines that seem certain to belong to Dy^{155}; part (b) lists the rest of the lines, which cannot be assigned with any certainty to either Dy^{155} or Dy^{157}.

Thus out of the ten gamma rays that comprise the disintegration scheme of Eu^{154}, seven are also found in the decay of Tb^{154}. There are also two gamma rays following Tb^{154} decay which are absent in Eu^{154} decay. They are the 347.1-kev gamma ray and the transition whose conversion-electron line appears at 626.3 kev.

Dysprosium-155

Dysprosium-155 was made by bombarding Gd^{155} with 48-Mev alpha particles. In the process a large amount of Dy^{157} was also made. The problem was to resolve the lines of Dy^{155}, of Dy^{157}, and of Tb^{155}, the 5.6-day daughter of Dy^{155}. (The daughter of Dy^{157}, Tb^{157}, has never been seen; Mihelich *et al.* prepared an intense source of Dy^{157}, but were unable to find any indication of activity due to Tb^{157}.[5] Two exposures of the same sample were taken. The first was for about 30 hours, by which time most of the Dy^{155} and Dy^{157} (half-lives of 10 and 8 hours, respectively) would have decayed out. The second exposure lasted for about a week, so that the lines due to Tb^{155} would be identified. Mihelich *et al.* have studied the levels in Gd^{155} following the decay of Tb^{155}.[5] We were able to identify most of the lines they reported for Tb^{155} by studying the photographic plate resulting from the second exposure. Any lines that agreed in energy in both exposures and that decayed in intensity, or else were completely absent in the second exposure, were assigned to Dy^{155} and Dy^{157}. Mihelich *et al.* have reported some lines for Dy^{157} decay.[5] These were also identified by us. Table III lists the remainder of the electron lines that fulfilled the requirement that their intensities should have decreased in the second exposure. The table is divided into two sections. The first portion lists the electron lines that seem certain to belong to Dy^{155}. The second portion lists the rest of the lines, which cannot be assigned with any certainty to either Dy^{155} or Dy^{157}.

The electrons in part (a) of Table III were assigned to Dy^{155} for two reasons. The first is that lines of such intensities, if they belonged to Dy^{157}, would have been seen by Mihelich *et al.* The second is that they fit into a disintegration scheme constructed in analogy to neighboring isotopes. The decay scheme is shown in Fig. 5. It is readily seen that the first two excited states (65.43 and 155.8 kev) can be proposed as members of a rotational band with the ground state used as a base. The spin assignments of the three levels would be $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. A similar scheme can be found in the decay of Dy^{157}, Dy^{159}, and Tb^{155}. The parity of all three states would then be even. The 271.4-kev level was placed in the scheme because two transitions could be found that would match well the differences between this level and the first and second excited states. The 227.0-kev transition was made to go directly to ground because of its intensity. Also a gamma ray was found that seems to be the transition between the 227-kev level and the 65.43-kev level. It is interesting to note that

the 9/2 state of the rotational band should have, by the simple $I(I+1)$ dependence, an energy of about 275 kev, in good agreement with the 271.4 kev observed.

The 43.09-, 88.02-, and 184.6-kev transitions probably belong to Dy^{155} and not to Dy^{157}, because of their intensities. The 43.09-kev gamma ray could be the transition between a 108.5-kev level and the 65.43-kev level. However, no such crossover of 108.5 kev to the ground state has been seen, and no photons can be identified decaying to the 108.5-kev level from a higher one. The 88.02-kev photon could be a transition proceeding to ground. No gamma rays have been seen decaying to such a state from higher levels. Of the remainder of the electron lines very little can be said except that some of them probably belong to Dy^{157}.

The gamma spectrum obtained in the bombardment clearly showed the 225-kev gamma ray together with the 325-kev one belonging to Dy^{157} decay. Small peaks were visible in the vicinity of 70 and 95 kev, representing no doubt the 65.43- and 90.38-kev gamma rays. Several peaks were seen between 100 and 200 kev which were probably due to weak gamma rays and the back-

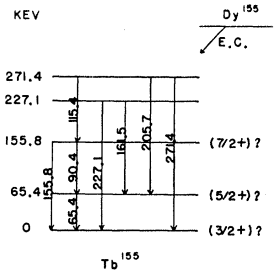

FIG. 5. Proposed decay scheme of Dy^{155}.

scatter peaks of the two prominent 225- and 325-kev transitions. In addition there were peaks at about 645, 890, and 1080 kev. It could not be determined whether these latter gamma rays were to be assigned to Dy^{155} or Dy^{157}. Relative gamma intensities were not calculated because of the difficulty that would have been involved in the resolution of the low-energy gamma rays mentioned above. By inspection, however, it could be easily observed that the 225-kev photon was by far the most prominent following the decay of Dy^{157}. Because of this it is almost certain that the 225-kev gamma ray does proceed to ground as indicated in the decay scheme.

The decay scheme proposed here in Fig. 5 for Dy^{155} was constructed on the basis of energy sums and differences of the various transitions identified in the conversion-electron spectra, with the similar decay schemes of neighboring isotopes kept in mind. However, some corroborating evidence for the decay scheme can be found in the intensities of the L-conversion lines of the 65.43-, 90.38-, and 155.8-kev gamma rays.

(a) For the 65.43-kev transition ($\frac{5}{2}+$ to $\frac{3}{2}+$) the L_I line is much more intense than either the L_{II} or the L_{III} line. The numerical ratio of the intensities is $L_I:L_{II}:L_{III}$ or $\sim 10:1:1$. The sequence of L-subshell intensities indicates the multipolarity of the transition to be an $M1+E2$ mixture.

(b) For the 90.38-kev transition ($\frac{7}{2}+$ to $\frac{5}{2}+$) only the L_I is visible; the other two L lines are presumably too weak to be observed. An $M1$ transition is indicated.

(c) For the 155.8-kev transition ($\frac{7}{2}+$ to $\frac{3}{2}+$) two L lines have been identified. They are the L_{II} and L_{III} lines. Their intensities seem to be equal, so that the multipolarity of the transition is indicated to be $E2$.

The multipolarities of the transitions thus seem to be in agreement with the spin and parity assignments of the levels in Fig. 5.

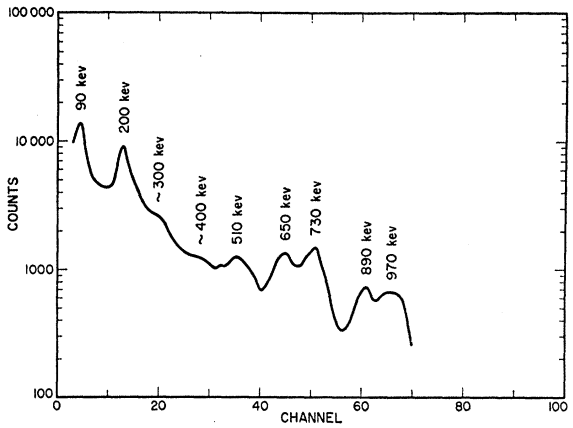

FIG. 6. Gamma spectrum of Ho^{160}, obtained in a 37-Mev alpha-particle bombardment on terbium. The detector was a 1.5×1 inch NaI(Tl) scintillation crystal. The holmium activity was chemically purified by ion-exchange chromatography. Other holmium activities would have made a negligible contribution at the time this spectrum was obtained.

Holmium-160

Holmium-160 was made by bombarding Tb^{159} with 48-Mev alpha particles. Terbium is a monoisotopic element and therefore, at the bombarding energy, the isotopes that would be produced in any quantity are Ho^{159}, Ho^{160}, and Ho^{161}. By the time a wire source could be prepared most of the Ho^{159} (33-min half-life) had decayed, so that this nuclide offered no obstacles in determining the Ho^{160} electron lines. Two experiments were carried out. In the second experiment the sample that was prepared was much more intense than in the first bombardment. As a consequence the less intense sample was placed in a permanent-magnet spectrograph with a low magnetic field in a search for the lower-energy lines already reported by Mihelich *et al.*[5] The more intense wire sample was placed in the permanent-magnet spectrograph whose field is about 340 gauss, in order to observe the high-energy gamma rays that were known to follow the decay of Ho^{160} from the gamma spectrum (see Fig. 6). The electron lines seen in the two experiments are listed separately in Tables IV and V. The main reason for the separation is that the disagreement between the energies of two gamma rays as

TABLE IV. Conversion-electron lines of Ho^{160}, Experiment 1.

Electron energy (kev)	Visual intensity	Conversion shell	Apparent transition energy (kev)	Transition energy (best value) (kev)
50.85	m	*L*	59.77	59.78
51.75	m	*L*	59.83	
57.98	mw	*M*	60.11	
59.32	vw	*N*	59.75	
77.98	m	*L*	86.57	86.58
78.79	m	*L*	86.58	
84.85	mw	*M*	86.69	
86.17	vw	*N*	86.59	
142.84	w	*K*	196.61	196.6

determined in the two experiments is somewhat greater than the range of experimental error, probably owing to an incorrect calibration of the 340-gauss spectrograph. Another reason is that the two Ho^{160} sources were very different in their total activities and that the two spectrographs used covered quite dissimilar energy ranges. If the lines were combined into one group a meaningful relative-intensity scale would be rather difficult to construct.

All the lines in Table IV were seen by Mihelich *et al.*[5] and assigned to the decay of Ho^{160}, including the 59.78-kev transition, which is an isomeric transition in Ho^{160} reported previously by the same workers. No half-life determinations were made on any of the electron lines seen in the second experiment. Because of the shortness of the half-life of Ho^{160} (5 hr) it was felt that if the weak high-energy gamma rays were to be observed then it would be necessary to have an exposure that would extend as long as any of the activity would last. Thus no interruptions were made to determine the electron-line half-lives. It is possible that some of the gamma rays in Table V may belong to the decay of either Ho^{161} or Ho^{162}. This is improbable because the half-lives of the latter two isotopes are rather short (2.5 hr and 67 min). Also, none of the electron lines reported for the two isotopes by Mihelich *et al.*[5] has been identified by us. If the more prominent transitions of the two nuclides were not observed, then there is no reason why some of the less intense transitions (not reported by Mihelich *et al.*) should have been. Therefore we would prefer to assign tentatively all the transitions in Table V to Ho^{160}.

TABLE V. Conversion-electron lines of Ho^{160}, Experiment 2.[a]

Electron energy (kev)	Visual intensity	Conversion shell	Apparent transition energy (kev)	Transition energy (best value) (kev)
79.64	vvs	*L*	87.44	87.44
85.62	vs	*M*	87.66	
86.84	ms	*N*	87.26	
119.59*	vw	?		
143.83	s	*K*	197.60	197.7
189.31	ms	*L*	197.90	
196.31	mw	*M*	198.35	
176.10*	vw	*K*	229.87	229.9
200.07*	w	?		
244.81	w	*K*	298.58	298.6
256.51*	w	*K*	310.28	310.3
275.38*	w	*K*	329.11	329.1
318.85*	vw	*K*	372.62	372.6
486.70*	vvw	*K*	540.47	540.5
505.42*	vvw	*K*	559.19	559.2
593.69*	vw	*K*	647.46	647.5
676.06*	vw	*K*	729.83	729.8
826.19*	vvw	*K*	879.96	880.0

[a] Electron lines not observed by Mihelich, Harmatz, and Handley are denoted with asterisks in the first column.

The gamma-ray spectrum of Ho^{160} is shown in Fig. 6. Gamma rays are evident at energies of 90, 200, 650, 730, 890, and 970 kev. All except the 970-kev photon have been identified by their conversion electrons in Table V. There is a slight rise in the spectrum in the vicinity of 400 kev, which may indicate the presence of a 395-kev gamma ray reported by others in the decay of Ho^{160}.[12]

Although a complete decay scheme for Ho^{160} cannot be proposed at this time, a start can be made if the decay scheme of Tb^{160} as proposed by Nathan[13] is considered and gamma rays common to both decays are noted. Transitions common to both decays and seen by us in our conversion-electron spectrum are 87.4, 197.7, 298.6, and 880.0 kev. The first two are the cascade transitions depopulating the first two excited states of an even-even rotational band with a ground state of 0+ in Dy^{160}. According to Nathan's work on Tb^{160} the 970-kev peak seen in our gamma spectrum consists of two gamma rays, one of 960 and the other of 964 kev. In addition Nathan reports a gamma ray of 395 kev that he was able to observe only in his gamma spectra. The transition is presumably the same as the one seen in Ho^{160} decay. Thus a total of seven gamma rays are common to both Ho^{160} and Tb^{160} decay to Dy^{160}.

There are two levels in Nathan's Tb^{160} decay scheme,[13] one at 964 and the other at 1047 kev, which prove to be interesting. The energy difference between them is 83 kev, which is very similar to the difference between two transitions listed in Table V, 729.8 and 647.5 kev. We should like to propose a level at 1698 kev populated in the electron-capture decay of Ho^{160}, and de-excited by the emission of the two gamma rays, 729.8 and 647.5 kev, to the levels at 964 and 1047 kev, respectively. This state is probably not populated in the beta decay of Tb^{160}, since neither of the two transitions has been reported. The level at 1698 kev is proposed in preference to one at 320.5 kev, because neither a gamma ray of 320.5 kev nor any other that could be construed as de-exciting the level has been identified in either Ho^{160} or Tb^{160} decay.

Little can be said about the remainder of the conversion-electron lines in Table V except that the large number of them indicates the decay scheme of Ho^{160} to be a complex one.

[12] W. E. Nervik and G. T. Seaborg, Phys. Rev. **97**, 1092 (1955).
[13] O. Nathan, Nuclear Phys. **4**, 125 (1957).

CONCLUSION

To conclude, we should like to discuss the change in excited-state energies of the isotopes studied in this work as the neutron number of these nuclei is increased. Thus, in the discussion of the decay of Tb^{154} it was pointed out that the first excited level in Gd^{154} (90 neutrons) was 123 kev. This is to be contrasted with the first excited level in Gd^{152} (88 neutrons), which has an energy of 344 kev. The large difference in energies is attributed to the fact that the transition into the strong-coupling region, where the Bohr-Mottelson spheroidal nuclear model is applicable, probably occurs between 88 and 90 neutrons. The value of 123 kev is still somewhat high, indicating that this particular nucleus is on what may be termed the fringe of the spheroidally deformed region. Dysprosium-160, another even-even nucleus which we have studied in the decay of Ho^{160}, has 94 neutrons and should be definitely inside the deformed region. That this is so is indicated by the first-excited-state energy of Dy^{160}, which is 87 kev above the ground state, a value very similar to the energies of first excited states in other neighboring even-even nuclei: Gd^{156} (92 neutrons), 89 kev; Dy^{162} (96 neutrons), 81 kev. An energy of about 85 kev seems to be the standard value for the 2+ member (first excited level) of even-even rotational bands in this portion of the periodic chart.

Turning to odd-mass nuclei, let us consider the three isotopes Dy^{155}, Dy^{157}, and Dy^{159}, decaying to Tb^{155} (90 neutrons), Tb^{157} (92 neutrons), and Tb^{159} (94 neutrons), respectively. The decay scheme of Dy^{155} was constructed in analogy to those of Dy^{157} and Dy^{159}, assuming a rotational sequence of $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ for the spins of the first three levels. If the proposed Dy^{155} scheme is correct, then a regular variation is noticed in the level energies of the three nuclei, as follows:

	Isotope	First excited level (kev)	Second excited level (kev)
(a)	Tb^{155}	65.4	156
(b)	Tb^{157}	60.8	144
(c)	Tb^{159}	58.0	138

Terbium-155 with 90 neutrons is presumably on the edge of the spheroidal region. However, as previously presented, its first two excited levels together with the ground state form a rotational band and follow the simple $I(I+1)$ formula quite well. Levels in Gd^{155} (91 neutrons) have been studied extensively from the decays of both Eu^{155} and Tb^{155}. The ground-state spin of the nucleus has been found to be $\frac{3}{2}$, just as in the three terbium nuclei already discussed. The energies of the first two excited levels in Gd^{155} are 60.1 and 146 kev, numbers which fit well into the sequence of the terbium nuclei.

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