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ABSTRACT

The photon and conversion electron spectra following electron-capture decay of Gd^{151} were studied. Transitions of 21.59 (M1), 153.7, 175.0 (M2), 243.8 (E1), and 308.4 keV seen in these spectra and a very weak transition of 155 ± 5 keV seen in coincidence with the 153.7-keV transition were assigned to the decay of Gd^{151} . Relative photon, conversion-electron, and transition intensities were determined for some of the transitions, and coincidence measurements were made at resolving times of 4 and 40 microseconds. The 175.0-keV transition was observed to depopulate a metastable state with a half-life of 58 ± 10 microseconds. A level scheme is proposed for Eu^{151} including the levels populated by Coulomb excitation, β^- decay of Sm^{151} , and electron-capture decay of Gd^{151} .

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INTRODUCTION

Gd^{151} , which decays by electron-capture with a half-life of 150 days,¹ is an isotope of special interest because it lies in a region where nuclear properties change abruptly. Brix and Kopfermann have noted that in going from 88- to 90-neutron isotopes, sharp breaks in isotope shifts occur,² and, in the stable europium isotopes,³ that quadrupole moments change abruptly. In Coulomb excitation work, Heydenburg and Temmer⁴ and later Class and Meyer-Berkhout⁵ found a well-developed rotational band in Eu^{153} but a level pattern not readily interpretable in terms of a rotational structure in Eu^{151} . Information on the levels in Eu^{151} populated by the electron-capture decay of Gd^{151} was obtained in this work by studying the conversion-electron and photon spectra of Gd^{151} . A recent study on the decay scheme of Gd^{151} is that by Bisi, Germagnoli, and Zappa.⁶ Recent work of W. T. Achor *et al.* on the beta decay of Sm^{151} yields information on the lowest two levels in Eu^{151} .⁷

EXPERIMENTAL PROCEDURES

The Gd^{151} for these experiments was produced in the Berkeley 60-inch cyclotron by 17-Mev deuteron and 12-Mev proton bombardments of europium oxide. When natural europium (47.77% Eu^{151} and 52.23% Eu^{153})¹ was bombarded, Gd^{151} and Gd^{153} were made in approximately equal amounts, and when europium enriched⁸ in Eu^{151} (91.9% Eu^{151} and 8.1% Eu^{153}) was bombarded, greater amounts of Gd^{151} were produced. Transitions arising from the decays of Gd^{151} and Gd^{153} were distinguished by comparing the relative abundances of the gamma-rays in the two mixtures of Gd^{151} and Gd^{153} . Other gadolinium isotopes produced did not

interfere because they were either stable or very long- or short-lived. The target assemblies and radiochemical procedures used have been described in an earlier paper.⁹

The conversion-electron spectrum of Gd^{151} was measured with the Berkeley permanent-magnet electron spectrographs. These are 180° -focusing instruments which record electrons photographically with a momentum resolution of about 0.12%. The four spectrographs used in this work have fields of about 50, 100, 200, and 350 gauss. Their calibration and operation have been described by Smith and Hollander.¹⁰ The relative intensities of the conversion electrons were obtained from densitometer traces of the spectrograph plates. The photon energies and relative intensities were measured with a scintillation spectrometer using a sodium iodide (thallium-activated) crystal 1.5 in. in diameter by 1 in. thick, a Dumont 6292 photomultiplier tube, a double-differentiating linear amplifier, and a Penco¹¹ 100-channel pulse-height analyzer. This equipment operated at 8.5% energy resolution on the 662-keV gamma ray of Cs^{137} .

CONVERSION-ELECTRON SPECTRUM OF GADOLINIUM-151

Table I lists the transitions assigned to the decay of Gd^{151} , with the conversion-electron lines seen for each. The intensities given for the electron lines are visual estimates of the degree of darkening of the permanent-magnet spectrograph plates, and the electron energies listed are weighted averages of values obtained from several plates. Internal energy standards were not incorporated in the gadolinium activity, but the calibrated energy scale used was checked internally by the energies of electrons from three intense transitions in Gd^{153} decay. The transition energies, 69.7, 97.5, and 103.2 keV, are in agreement with values of 69.4, 97.3, and 103.1 keV reported in Gd^{153} decay by Church and Goldhaber,¹² of 69.1 and 102.7 keV reported in Sm^{153} decay by Lee and Katz,¹³ and of 69.0 and 102.5 keV reported in Sm^{153} decay by Graham and Walker.¹⁴ We estimate that the relative Gd^{151} transition energies are good to within 0.1% and the absolute energies to within 0.5%.

Table I. Conversion-electron lines observed in the decay of Gd^{151}

Transition energy (kev)	Conversion-electron line	Conversion-electron energy (kev)	Visual intensity estimate ^a	Remarks
21.59	L_I	13.54	S	
	L_{II}	13.96	W-M	
	M_I	19.77	M-S	
	M_{II}	19.96	W	N_I line is masked by K line of Gd^{153} 69.7-kev transition
153.7	K	105.31	VS	
	L_I	145.81	M	
	M_I	152.16	W-M	
	N_I	153.52	VVW	
175.0	K	126.59	VVS	
	L_I	167.12	S	
	L_{III}	167.98	VVW	
	M_I	173.23	M	
243.8	N_I	174.75	VW	
	K	195.15	W-M	
	L_I or L_{II}	235.54	VW	L_I and L_{II} lines are difficult to distinguish in high-field spectrographs.
308.4	K	259.70	W	
	L_I or L_{II}	308.62	VVW	L_I and L_{II} lines are difficult to distinguish in high-field spectrographs.
		58.01	W	
		75.97	W-M	
		76.78	VVW	
		79.34	VVW	Gd^{151} or Gd^{153} conversion electrons not assigned to a transition. ^b
		81.14	VVW	
		111.30	W	
		315.15	VVW	

^a S = strong, M = moderate, W = weak, V = very.

^b These electron lines were not assigned to a Gd^{151} or Gd^{153} transition either because they were weak and seen only once or because they were obviously the only lines seen for a given transition.

PHOTON SPECTRUM OF GADOLINIUM-151

Figure 1 shows the low-energy sodium iodide scintillation gamma spectrum of a Gd^{151} and Gd^{153} sample that contained mostly Gd^{151} ; and Fig. 2 shows the total sodium iodide scintillation gamma spectra of two Gd^{151} and Gd^{153} samples, one with mostly Gd^{151} and one with approximately equal amounts of Gd^{151} and Gd^{153} .

RELATIVE PHOTON AND ELECTRON INTENSITIES; CONVERSION COEFFICIENTS

Table II gives the relative photon and electron intensities for the Gd^{151} transitions. In obtaining the relative photon intensities varying thicknesses of lead absorbers were used, and several sets of relative intensities were calculated and averaged. The values of Davisson and Evans¹⁵ were used in correcting for absorption through lead absorbers, and curves from Kalkstein and Hollander¹⁶ were used to obtain NaI crystal counting efficiencies. Table II also lists the relative photon intensities given by Bisi *et al.*⁶ These values have been normalized to give our figure of 80.6 to the K x-ray intensity. As mentioned before, the relative electron intensities of the stronger lines were obtained from densitometer traces of the permanent-magnet spectrograph plates. We put the photon and electron intensities onto the same relative scale by assuming the theoretical (Sliv¹⁷) value for the K-conversion coefficient of the 175.0-keV transition. From its K/L ratio, L-subshell intensities, and K/M ratio, this transition appears to be either magnetic dipole or magnetic quadrupole. A measurement of its half-life, which is discussed later, essentially establishes the M2 multipolarity as the correct choice. K-conversion coefficients calculated by Sliv¹⁷ and L- and M-conversion coefficients calculated by Rose¹⁸ were used in assigning multiplicities to the Gd^{151} transitions. In addition, Rose's K-conversion coefficients were used for calculating theoretical K/L and K/M ratios.

Table III gives the experimental K-conversion coefficients for the Gd^{151} transitions along with the Sliv theoretical K-conversion coefficients for E1, E2, M1, and M2 transitions ($Z = 63$).

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Fig. 1. Low-energy sodium iodide scintillation gamma spectrum for a Gd^{151} and Gd^{153} sample containing mostly Gd^{151} : Peak A, K x-ray escape peak; Peak B, 21.5-kev photopeak; Peak C, K x-ray peak.

Fig. 2. Sodium iodide scintillation gamma spectra for Gd^{151} and Gd^{153} samples containing mostly Gd^{151} (Curve A) and approximately equal amounts of Gd^{151} and Gd^{153} (Curve B). The small peak between the 41.5- and 103-kev peaks in curve A is due to x-rays from the platinum sample backing.

Table II. Relative electron, photon, and transition intensities
for Gd^{151} transitions

Gamma ray energy (kev)	Line	Electron intensity	Photon ^a intensity (this work)	Photon ^b intensity (Bisi et al. ⁶)	Transition intensity
21.59			4.4	3.7	~ 30
	L_I	~ 22			
	M_I	~ 4			
41.5 (K x-ray)			80.6	(80.6) ^b	
153.7			6.0	4.8	9.4
	K	2.7			
	L_I	0.41			
	M_I	0.31			
155 ± 5 ^c			very weak		
175.0			2.7		9.0
	K	4.9			
	L_I	1.0			
	M_I	0.36			
243.8			4.5	3.2	4.6
	K	0.10			
308.4			0.79	0.24	~ 0.88
	K	~ 0.085			

^a Intensities are in arbitrary units, but the photon and electron intensity scales were normalized to give the Sliv theoretical M2 K-conversion coefficient of 1.8 to the 175.0-kev transition.

^b Intensity values have been normalized to give the figure obtained in this work (80.6) to the K x-ray intensity.

^c Gamma ray was seen only in coincidence with the 153.7-kev gamma ray.

Table III

K-conversion coefficients for Gd^{151} transitions

Gamma ray energy (kev)	Experimental conversion coefficient	Sliv theoretical conversion coefficient			
		E1	E2	M1	M2
153.7	0.45	0.080	0.35	0.50	2.9
175.0	(1.8) ^a	0.057	0.24	0.34	1.8
243.8	0.022	0.023	0.084	0.13	0.61
308.4	~0.1	0.012	0.044	0.072	0.28

^a Parentheses indicate that the relative photon and electron intensities have been normalized to give the theoretical M2 conversion coefficient for this transition.

MULTIPOLARITY ASSIGNMENTS

21.6-kev Transition

The 21.6-kev transition seen in the decay of Gd^{151} has also been seen in the decay of Sm^{151} ,^{1,7,19} and is believed to be the transition from first excited state to ground state in Eu^{151} .¹ From its L- and M-subshell ratios and L_I -conversion coefficient this transition appears to be magnetic dipole. An M2 assignment was ruled out because of the lack of observable conversion in the L_{III} subshell and because the measured L_I -conversion coefficient ($\alpha L_I \sim 5$) was low. This conversion coefficient is perhaps in error by as much as a factor of 5 because the electron lines were so strong and were riding on such a high scattering continuum that intensity values obtained from the densitometer traces were uncertain. The theoretical L_I -conversion coefficients for M1 and M2 transitions are 22 for M1 and 1900 for M2. The half-life of this transition should be barely measurable if it were an M1 transition and very long if it were an M2. McGowan looked at the radiation from a sample of Sm^{151} and was able to set an upper limit of 1×10^{-8} sec for the half-life of any transitions he saw.²⁰ We also looked at a sample of Sm^{151} in a fast-coincidence setup employing a time-to-height converter,²¹ and were able to determine that any gamma ray half-lives in the sample would have

to be $< 4 \times 10^{-9}$ sec or $> 10^{-7}$ sec. In both McGowan's work and our own, however, there exists the possibility that the 21.6-keV gamma ray was not detected at all. An E1-M2 mixture assignment was ruled out because the amount of E1 mixing (99.8%) necessary to bring the L_I -conversion coefficient down to the experimental value gives theoretical subshell ratios that do not agree with the experimental ones. Achor *et al.*¹⁹ have obtained a conversion coefficient of 12 for this transition as seen in the decay of Sm^{151} , in rough agreement with our value of 5. We therefore feel that an M1 assignment (with an upper limit of 0.05% E2 mixing set by the lack of L_{III} conversion) is very reasonable.

154-keV Transition

The 154-keV transition has a K-conversion coefficient of 0.45 and a half-life of < 1 millimicrosecond (discussed later). From its subshell ratios and K-conversion coefficient, it appears to be an M1 transition (see Table III). E2 mixing, if present, would have to be extremely small, because a rather strong L_I line was seen, but no L_{II} or L_{III} . Another possible assignment for this transition is an 87% E1 - 13% M2 mixture. Such a mixture gives a reasonable K-conversion coefficient and subshell ratios.

175-keV Transition

This transition has already been mentioned as being the one used to normalize the electron and photon intensities to the same relative scale. From its K/L ratio, L-subshell ratios, and K/M ratio it appears to be either magnetic dipole or magnetic quadrupole, and a measurement of its half-life essentially established it as an M2 transition. The theoretical half-life for an M2 transition of 175 keV in a nuclide with $A = 151$ was calculated, by use of Moszkowski's formula,²² to be 0.4 microsecond. We measured the half-life of this transition to be 58 ± 10 microseconds by an oscilloscope technique described by Hyde, Florence, and Larsh.²³

244-keV Transition

This transition has a half-life of < 1 millimicrosecond (discussed later) and an experimental K-conversion coefficient in good agreement with the theoretical K-conversion coefficient for an E1 transition (see Table III). We therefore give this transition an E1 assignment. K/L and L-subshell ratios could not be used in making the assignment because no experimental values were determined for these ratios.

308-keV Transition

This transition has a half-life of < 1 millimicrosecond (discussed later) and an experimental K-conversion coefficient leading roughly to an M1 or E1-M2 mixture assignment (see Table III). As with the 244-keV transition, K/L and L-subshell ratios did not enable us to choose between the above alternative assignments.

COINCIDENCE MEASUREMENTS

By use of slow-coincidence techniques²⁴ (resolving time 4 microseconds), gamma-gamma coincidence measurements were made on a Gd¹⁵¹ sample. The 308-, 244-, composite 154-175-keV, and K x-ray peaks were selected for the "gate", and coincidence spectra were measured up to 400 keV. With the available apparatus, it was not possible to detect and gate on the 21.6-keV photons.

A very weak coincidence was seen between the composite 154-175-keV peak and a gamma ray of 155 ± 5 keV. By gating on various parts of the 154-175-keV peak and observing the change in the coincidence counting rate, we determined that the weak gamma ray was in coincidence with the 154- rather than with the 175-keV peak. When the two crystal detectors were placed at right angles to each other with shielding between them, the coincidences were still seen, which indicated that they were real and not due to Compton-degraded photons from the 308-keV gamma rays. Bisi *et al.*⁶ saw a weak coincidence between the 154-keV photon and a gamma ray of about 144 keV. We feel that these are the same coincidences as we saw and that the energy agreement is poor because of the poor counting conditions involved.

Further very weak coincidences were observed between all the gate peaks and a gamma ray of about 100 kev. With the 154-175-kev peak, these coincidences could be due in part to Compton-degraded photons from the 244-kev peak, since they almost completely disappeared when the two crystals were placed at right angles. In the other cases they could be due to the strong 103-kev gamma ray seen in Gd^{153} decay or to some other contaminant. Bisi et al.⁶ did not report these coincidences.

When the K x-ray peak was used as the gate energy, all the Gd^{151} photons except the 175-kev gamma ray were seen in the coincidence spectrum. The lack of coincidences between K x-rays and 175-kev gamma rays at a resolving time of 4 microseconds suggested that the 175-kev gamma ray arises from a metastable state. The half-life of the state emitting this gamma ray was then measured to be 58 ± 10 microseconds by an oscilloscope technique, as mentioned in an earlier section.

By use of fast-coincidence techniques²⁴ (resolving time ~ 40 millimicroseconds), the 308-, 244-, and 154-kev gamma rays were studied for possibly measurable delays. From these measurements upper limits on half-lives of the 308-, 244-, and 154-kev gamma rays were set at < 1 millimicrosecond. With the fast-coincidence equipment, as with the slow, it was not possible to detect the 22-kev gamma ray.

DISCUSSION

Except for a transition of 80 kev reported by Bisi et al.,⁶ the transitions we assign to Gd^{151} decay are the same as those reported previously.⁶ Their 80-kev transition was assigned on the basis of a single conversion-electron line. Bisi et al. said that this line (electron energy 72.5 kev) was probably due to the L+M- conversion of a transition of 80 kev, whose K-conversion line was not seen because of Geiger-Mueller window distortion and because it occurs in the same spectral region as the Auger lines. We saw an electron line of 76 kev, which we left unassigned. If this is the same line as Bisi et al. saw, we feel that an L-shell assignment is questionable, because a transition with an L-line of that strength would have a K-conversion line easily seen with our spectrographs.

In trying to formulate a decay scheme for the electron-capture decay of Gd^{151} , the question arises whether or not the 308-keV transition seen in Gd^{151} decay is the same as the 304-keV transition seen in the Coulomb excitation of Eu^{151} .^{4,5} Class and Meyer-Berkhout⁵ state that the 304-keV transition is of predominantly M1 character, an assignment we listed as possible for the 308-keV transition (see section on Multipolarity Assignments). However, if the two transitions were the same, the Gd^{151} spectrum should include the other two transitions (111 and 284 keV), which Class and Meyer-Berkhout⁵ say depopulate the 304-keV state. We see an electron line of 58 keV which we have not assigned to a transition and which could possibly be the K-conversion line for the 111-keV transition. However, the K-conversion line for this transition should have an energy of about 62.5 keV, and the 58 - 62.5 energy discrepancy, besides being large, is in the opposite direction from the 308-304 discrepancy. We therefore feel that the 58-keV electron line is probably not the K line for the 111-keV transition. We see no electron lines that could possibly be assigned to the 284-keV transition. When the intensities of the conversion lines seen in the Gd^{151} decay and Eu^{151} Coulomb excitation spectra were compared, it was obvious that the K-lines of both the 111- and 284-keV transitions, if present, should have been seen in the Gd^{151} decay spectrum. We therefore feel that the 308-keV transition seen in Gd^{151} decay is probably not the same as the 304-keV transition seen in the Coulomb excitation of Eu^{151} ,^{4,5} although our evidence for making this decision is not too conclusive.

Figure 3 shows the proposed level scheme for Eu^{151} . Among the five gamma transitions observed in the conversion-electron spectrum for the decay of Gd^{151} , only one energy-sum relationship was found ($21.59 + 153.7 = 175.0$). This relationship could not be incorporated in the decay scheme, however, because it requires that the 154-keV (half-life < 1 millimicrosecond) and 175-keV (half-life 58 ± 10 microseconds) transitions depopulate the same state. Coincidence measurements have shown that none of the four highest-energy transitions are in coincidence with one another, but a weak coincidence with the 154-keV transition was found of energy 155 ± 5 keV (144 according to Bisi *et al.*⁶). Within the uncertainty of the energy measurement, the weak 155-keV - 154-keV cascade may issue from the same level as the 308-keV

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Fig. 3. Proposed level scheme for Eu^{151} . The dotted levels and transitions are those obtained in the Coulomb excitation of Eu^{151} .^{4,5} The solid levels and transitions are those seen in the beta decay of Sm^{151} ,^{1,7,21} and in the electron-capture decay of Gd^{151} . (See text for an explanation of the double energy assignments given to some of the states.)

transition and is tentatively so placed in the decay scheme. Our available coincidence equipment as that of Bisi et al.,⁶ was incapable of testing for coincidences with the transition from the 21.6-kev first excited state to the ground state. Thus, in the proposed decay scheme there is a choice of energies for the four upper levels, depending on whether or not the transitions depopulating them go to the ground state or the first excited state.

From the abundance of K x-rays and the transition intensities of Table II (and arbitrarily assuming about 10% L + M capture), we would calculate that about a third of the primary decay occurs to the ground state, a third to the first excited state, and the remainder to the higher states. The proportion of decay to the ground state is quite uncertain, as it depends solely on the apparent excess of K x-rays over those accountable by decay to excited states. It is possible, within the experimental limits of error, that no decay occurs to the ground state, though this possibility does not seem likely.

The ground-state spin of Eu^{151} is well known as $5/2$.¹ Nilsson and Mottelson²⁵ have associated this state with the odd-proton orbital ($\Omega = 5/2$) correlating to $h_{11/2}$ in the spherical limit, hence, with odd parity. With the spin and parity of the ground state of Eu^{151} fixed, the first excited state (B) can have spins $3/2$, $5/2$, or $7/2$ and odd parity. States C and F would then have odd parity and D and E even. Since it is not known whether the transitions from states C, D, E, and F go to the ground state (A) or to state B, it is not possible to make spin assignments to C, D, E, or F.

We may set limits for the $\log ft$ values of decay to states A and B, since observance of a 308-kev transition requires at least that much total decay energy: $\log ft_A > 7.3$ and $\log ft_B > 7.3$. It is not safe to conclude that the decay is first-forbidden, as many cases of allowed, hindered transitions have been assigned with comparable $\log ft$ values by Alaga.²⁶

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