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DECAY SCHEME STUDIES OF SOME LIGHT GADOLINIUM ISOTOPES

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ABSTRACT

Information on the excited levels in $Eu^{147,149,151}$, and 153 was obtained by studying the photon and conversion electron spectra of gadolinium activities produced by alpha particle bombardments on samarium and deuteron bombardments on europium. A new isotope decaying by electron capture with a 29 hour half-life was found and characterized as Gd^{147}. Sixteen gamma transitions were found for Gd^{147}, of which the strongest are ones of 229.49 and 396.21 kev. Of sixteen transitions found for Gd^{149}, the strongest occur at 149.86, 298.79, and 346.70 kev. Nine transitions were found for Gd^{151} and Gd^{153} combined, seven for a probable isomer of one of the isotopes, and eight for europium daughters. Relative photon and electron intensities were determined for some of the transitions, coincidence measurements were made, and accurate transition energies were measured. Multipolarities for a few of the transitions are assigned and a tentative decay scheme for Gd^{149} is suggested.

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I. INTRODUCTION

Little work on the decay schemes of the neutron deficient gadolinium isotopes has been done before. Church and Goldhaber[1] have reported finding levels of 69.4, 97.3, and 103.1 kev in Eu^{153} populated by the decay of Gd^{153}. In coulomb excitation work, Heydenberg and Temmer[2] have found levels of 82 and 187 kev for Eu^{153}. In addition, they have tentatively assigned a level of 310 kev to Eu^{151}. Bhattacherjie and Raman[3] have reported levels of 72 ± 8 and 100 ± 4 kev resulting from the decay of Gd^{153}; and in absorption work, Hein and Voigt[4] have attributed a 265-kev transition to the decay of Gd^{151}. Wilson and Lewis[5] have seen a level of 20 kev for Eu^{151} resulting from the beta decay of Sm^{151}.

The region around the light gadolinium isotopes is of special interest because of the many breaks in nuclear properties seen in passing between 88 and 90 neutrons. In optical spectroscopic work, Brix and Kopferman[6] have called attention to sharp isotope shift breaks in going from 88- to 90- neutron isotopes. They have also observed[7] breaks in the quadrupole moments of the europium isotopes. The large deformation approximation of the Bohr-Mottelson model[8] has been successful in describing nuclei at $N \geq 90$, where rotational bands generally occur. The energies of the first members of these bands are usually low, and the failure to find such low-lying levels below this region indicates the inapplicability or, at best, limited applicability of the model there.

Information on the excited levels in $Eu^{147,149,151,}$ and 153 was obtained by studying the photon and conversion electron spectra of gadolinium activities produced by alpha particle bombardments on samarium and deuteron bombardments on europium. A new isotope decaying by electron capture with a 29 hour half-life was found and characterized as Gd^{147}. Sixteen gamma transitions were found for Gd^{147}, of which the strongest

are ones of 229.49 and 396.21 kev. Of sixteen transitions found for Gd^{149}, the strongest occur at 149.86, 298.79, and 346.70 kev. Nine transitions were found for Gd^{151} and Gd^{153} combined, seven for a probable isomer of one of the isotopes, and eight for europium daughters. Relative photon and electron intensities were determined for some of the transitions, coincidence measurements were made, and accurate transition energies were measured. Multipolarities for a few of the transitions are assigned and a tentative decay scheme for Gd^{149} is suggested.

II. EXPERIMENTAL PROCEDURES

A. Experiments I and II

1. Accelerator

The accelerator used in both experiments was the Berkeley 60-inch cyclotron. In experiment I, alpha particles were accelerated to 48 Mev and in experiment II, deuterons to 24 Mev.

2. Target Assembly

The target materials used to prepare gadolinium isotopes were samarium and europium, both in the oxide form. The rare earth oxide was placed in a "boat" stamped in 10-mil platinum foil, and a piece of 1/4-mil platinum foil was used to cover the top. The dimensions of the boat are approximately 2 cm x 0.5 cm x 0.32 cm. The boat fits into a standard target assembly and is cooled by a stream of water directed at the back of the target.

3. Chemistry

The platinum boat containing the irradiated rare earth oxides was placed in hot 8N hydrochloric acid until the oxides dissolved. The platinum was then removed and ammonia was passed into the acid solution until the rare earths precipitated as hydroxides. The precipitate was removed by centrifugation, washed, and dissolved in a minimum amount of 8N HCl. The gadolinium produced was separated from the remaining rare earths by an ion exchange method identical to that described by Thompson, Harvey, Choppin and Seaborg.[9] The column was 3 mm in diameter, 5 cm in length and was heated to 87°C by a trichloroethylene vapor jacket. The eluting agent was 0.4 M alpha-hydroxyisobutyric acid buffered to a pH of

3.93 with ammonium hydroxide, and the resin was Dowex-50 spherical resin, 200-400 mesh size, 12% cross-linked. Since the maximum capacity of the column was ~ 10 mg of rare earths, it was necessary to remove the bulk of the target material by another method. A sodium amalgum reduction method, which depends on a rate and not equilibrium separation was used. Sodium amalgam is capable of reducing +3 rare earth ions to the metal and amalgamating them; and since both samarium and europium have +2 states to act as intermediate states, the reduction of Sm^{+++} and Eu^{+++} is much faster than that of Gd^{+++}. This made the separation of gadolinium from both the samarium and europium targets quite easy. The rare earths dissolved in a minimum amount of 8N HCl were transferred to a separatory funnel, and 10 ml of water and 8 drops of glacial acetic acid (to maintain the hydrogen ion concentration) were added. 0.3 percent sodium amalgam (15 ml for 150 mg rare earths) was added and the mixture shaken for 10 seconds. After the amalgam layer was removed, the remaining aqueous layer seemed to retain about 10% of the original target material. The procedure was repeated three more times in order to be sure that the total rare earth mass retained was under 10 mg. Ammonia was passed into the final aqueous layer until the rare earths precipitated as hydroxides. After washing, the precipitate was dissolved in a minimum amount of 1 N HCl. The previously mentioned column procedure was then carried out.

4. Instruments

a. Nucleometer:[10]

This is a methane-filled, windowless proportional counter, which was used for following the activity of the gadolinium isotopes decaying by electron capture. It has a relatively high counting efficiency for electron capture.

b. Alpha Counter:

The alpha counter used is an argon flow-type ionization chamber developed at the University of California Radiation Laboratory. It has a counting efficiency of 100% for thin samples and a geometry of 52% of 4π (including a correction for backscattering of alpha particles.)

c. Lens Spectrometer:[11]

The lens spectrometer is a ring-focusing, solenoidal beta ray

spectrometer using an anthracene scintillation detector and giving about three percent resolution. Resolution is defined as the width ($\Delta H\rho$) of a peak at half of the total peak height divided by the $H\rho$ value for the peak, where $H\rho$ is a measure of the electron momentum for a given energy electron. This spectrometer was useful in early survey work because of its high transmission.

d. Permanent Magnet Spectrographs:

These four instruments described by Smith[12] are 180° spectrographs with fields of approximately 52, 99, 214, and 340 gauss. They are designated as PM I, PM II, PM III, and PM IV respectively. Electrons emitted from the source impinge on a photographic plate; and by previously calibrating the instruments with electrons of known energies, one may accurately determine the energies of conversion electrons. The resolution of the instruments is about 0.15%, and each one is especially useful in a particular energy range. In this work, these instruments were used to measure the energies of conversion electrons.

e. Densitometer:

This instrument, commonly used in optical spectroscopy, was used to measure the relative intensities of electron lines in permanent magnet spectrograph plates. A light source and photo cell measure blackening as a function of plate position, and an automatic recorder transfers this to paper. The instrument is calibrated to record from zero to infinite blackening, and hence the peak heights must be put on a linear scale before relative intensities can be determined. This is done by using a D vs E curve where D is the photographic density ($\log I_o/I$) and E is the exposure in arbitrary, linear units. The D vs E curve used was determined in this laboratory.[12] The relative intensity of an electron line is given by $I = A\rho/y$ where A is the area of the densitometer peak, ρ is the radius of curvature of the electron and y is the blackening efficiency. This efficiency was determined as a function of electron energy by Cranberg and Halpern[13] and Dudley.[14] A is determined by approximating the peak as a rectangle with height, $E_{top} - E_{bottom}$, and width, the width of the peak in mm at E_{middle}. This method of measuring intensities was taken in part from Slätis.[15]

f. Double-Focusing Spectrometer:[16]

The double-focusing spectrometer in this laboratory is a shaped-

field, 256°, prismatic spectrometer with about 0.3% resolution. It was not used for energy determinations; but good values for relative electron intensities were obtained by integrating peaks for given lines.

g. 100-Channel Gamma Analyzer:[17]

The 100-channel gamma analyzer is a gamma pulse height analyzer used with a scintillation counter with a 1" x 1-1/2" sodium iodide crystal and photomultiplier tube. It records data by means of a magnetic core matrix memory, and is able to record at relatively high counting rates. It has about 9% resolution and was used for measuring gamma ray energies and intensities.

5. Sample Preparation

After completing the ion exchange separation of the target material, the drops of alpha-hydroxyisobutyric acid solution containing the gadolinium activity were combined in a tube and made 0.5 - 1 M in HCl. This solution was placed on a Dowex-50, 4% cross-linked, 3 mm x 5 cm column at room temperature. 0.5 M HCl was passed through until all of the alpha-hydroxyisobutyric acid was removed, and the activity was then stripped off with 8 M HCl. Samples for the nucleometer, alpha counter, lens spectrometer, and double-focusing spectrometer were prepared by evaporating the HCl solution down on appropriate sample holders. For the permanent magnet spectrographs, the HCl solution was evaporated down to dryness, brought up in water, and evaporated down again to remove all excess HCl. The activity was then plated onto a 10-mil platinum wire from a solution of 0.1 M ammonium bisulfate at a pH of 3.6. The procedure used was that suggested by Harvey[18] in which the wire is made the cathode of an electrolysis cell. Since the hydroxide ion concentration around the cathode is high, the rare earths are deposited onto the wire as hydroxides. The wire was held in a bunsen burner flame for a few seconds before placing it in the spectrograph. A plating yield of about 45% was obtained in most cases.

B. Experiment III

1. Accelerator

The Berkeley 60-inch cyclotron, with alpha particles accelerated to 48.2 Mev, was used with a Faraday cup assembly.

2. Target Assembly

In this experiment, a stacked foil technique was used to determine excitation functions. Samarium oxide suspended in amyl acetate was painted onto 2 mil aluminum foil discs one inch in diameter (the area painted was 1.8 cm in diameter). In order to assure uniformity, the painting was done in about 100 layers, with time allowed in between for the plates to dry. Eight plates, with an average thickness of 0.62 mg Sm_2O_3/cm^2, were prepared and stacked with other aluminum foils to give target energies from 48 to 20 Mev in 4 Mev stages.

3. Chemistry

The targets with their aluminum backings were dissolved in 8N HCl so that any gadolinium atoms recoiling into the aluminum would not be lost. Sodium hydroxide was then added until the solution was about 10 M in NaOH. In this step the rare earths precipitated as hydroxides, the aluminum went into solution as sodium aluminate, and any sodium activities produced from aluminum remained in the supernatant solution. The precipitate was finally washed twice with 10 M NaOH and four times with water.

4. Instruments

The nucleometer, alpha counter, and 100-channel gamma analyzer were used in this experiment.

5. Sample Preparation

The rare earth hydroxides were semi-quantitavely transferred to weighed platinum plates in slurry form. After drying, the plates were flamed to convert the rare earths to the oxide form and reweighed. These samples were used in all three counters.

III. RESULTS

A. Conversion Electron Spectra of Gd^{147}, Gd^{149}, $Gd^{151-153}$, and $Eu^{147-149}$

In bombarding natural samarium (3.16% Sm^{144}, 15.07% Sm^{147}, 11.27% Sm^{148}, 13.84% Sm^{149}, 7.47% Sm^{150}, 26.63% Sm^{152}, and 22.53% Sm^{154})

with alpha particles, one would expect to make a variety of gadolinium isotopes. Among the unstable of these are Gd^{148} (140 year alpha),[19] Gd^{149} (9 day electron capture - alpha),[20] Gd^{151} (150 day electron capture),[20] and Gd^{153} (236 day electron capture).[20] In addition, one may possibly expect to produce the unreported isotope, Gd^{147}, by the reactions Sm^{144} (α,n) Gd^{147}, and Sm^{147} $(\alpha,4n)$ Gd^{147}. In the first bombardment of this type, enough activity was made for survey work on the lens spectrometer. Using europium binding energies to determine the gamma energies for given electron lines, the following spectrum, which is shown in Figure 1, was seen:

Table I

Lens Spectrometer Spectrum of Gd^{147} - Gd^{149}

Gamma Energy (kev)	Shell	Approximate Relative Intensity	Half-life
115	K	very weak	?
150	K	strong	9 day
150	L	moderate	9 day
229	K	moderate	2 day
261	K	weak	?
299	K	moderate	9 day
347	K	moderate-strong	9 day
347	L	moderate	9 day
396	K	weak	2 day

The two gammas with a 2 day half-life were tentatively assigned to Gd^{147}.

In the second bombardment of samarium with alpha particles, sufficient gadolinium activity was made for studies in the permanent magnet spectrographs and double-focusing spectrometer. Electron lines decaying with a 2 day half-life were distinguished from longer lived lines by watching their decay; and Gd^{149} lines (9 day) were identified by comparing the intensities of lines in permanent magnet spectrograph plates exposed at different times. All lines whose intensities stayed the same relative to the intensities of the lines for the 150 kev gamma, which was known to decay with a 9 day half life from lens spectrometer work, were assigned to Gd^{149}.

To study the longer-lived lines, Experiment II was carried out. In this experiment naturally occuring europium, which is composed entirely of Eu^{151} and Eu^{153}, [21] was bombarded with deuterons to produce only Gd^{151} and heavier gadolinium isotopes. Some of the long-lived lines in the Experiment I plates could be assigned to Gd^{151} or Gd^{153} (the two could not be distinguished) if they appeared in the Experiment II plates, but others were left unassigned. The unassigned lines all had approximately the same half life, which is much greater than 9 days. They also definitely belonged to some gadolinium isotope since the energy differences between the gamma energies and the conversion electron energies corresponded to europium binding energies. The possibility that these lines belong to an isomer of one of the gadolinium isotopes should be considered. Lines appearing in later plates which did not appear in earlier ones were assigned to $Eu^{147-149}$. They were so assigned because the energy differences between the gamma energies and the conversion electron energies corresponded to samarium binding energies and because they failed to appear in the first plates. Eu^{147} [22] has a half-life of 24 days, Eu^{149} [21] one of about 120 days, and lines from Eu^{151} and Eu^{153} should not be seen since these isotopes are stable.

Table II lists the gammas assigned to the various isotopes with the lines seen for each. The intensities given are visual ones read from the permanent magnet spectrograph plates. In cases where only one weak line was seen, it was assigned as a K line if seen more than once and neglected if seen only once. Energies are given to the nearest 0.01 kev if five or more different energy determinations were made and to the nearest 0.1 kev if less than five were made. The energy values listed are arithmetical averages of the values obtained from several lines in several plates. Although one of the spectrographs may be better than the others for a particular energy region, no weighting of energy values was done. This is because a spectrograph good for a given energy region shows more lines than one good for other energies, and weighting is therefore automatic. Table III gives the data used in determining the energy for the 115.48 kev long-lived gamma. Using 16 electron lines from three different spectrographs, an average deviation of 0.12 kev was obtained.

Table II

Isotope	Transition Energy (kev)	Lines seen	Visual Relative Intensities* K	L_1	L_2	L_3	M_1	N_1
Gd^{147}	136.1	K	VVW					
	142.2	K	W-M					
	146.8	K	W					
	217.3	K	VVW					
	226.4	K	VVW					
	229.49	K L_1	VVS	W				
		M_1 N_1					VW	VVW
	240.9	K	VW					
	261.01	K L_1	VW	VVW				
	310.1	K	VW					
	348.3	K	VVW					
	370.1	K L_1	W	VVVW				
	374.5	K	VVW					
	390.6	K	VVW					
	396.21	K L_1 M_1	M-S	W			VVW	
	485.2	K	VVW					
	501.9	K	VVW					
Gd^{149}	106.6	K	VVW					
	119.8	K	VW					
	126.06	K L_1	W-M	W				
	132.0	K	W-M					
	149.86	K L_1 L_2	VVS	VVS	VW			
		L_3 M_1 N_1				VVW	W-M	W
	244.3	K L_1	VVVW	VVVW				
	252.7	K	VVVW					
	272.67	K L_{1-2}	W	VVW				
		M_1					VVW	
	298.79	K L_1	W-M	W				
	346.70	K L_1	VS	W				
		M_1 N_1					VW	VVVW
	460.6	K	VVVW					
	496.5	K L_{1-2}	VVW	VVVW				

Table II (continued)

Isotope	Transition Energy (kev)	Lines seen	Visual Relative Intensities* K	L_1	L_2	L_3	M_1	N_1
Gd^{149}	516.7	K	VVW					
(cont'd)	534.2	K	VVW					
	749.5	K L_1	VVVW	VVVW				
	789.8	K	VVVW					
$Gd^{151-153}$	21.55	L_1 L_2		M-S	VW			
		M_1 N_1					W-M	masked
	63.1	K	VVW					
	69.64	K L_1 L_2	W-M	W-M	VVW			
		L_3 M_1				VVVW	VVW	
	97.47	K L_1	M-S	M				
		L_2 L_3			VVW	VVW		
	103.20	K L_{1-2}	S	S				
		M_1 N_1					M	VVW
	154.76	K L_1	M-S	W				
		M_1 N_1					VW	VVVW
	174.87	K L_1	S	M				
		M_1 N_1					W	VVVW
	243.68	K L_1	VW	VVVW				
	308.5	K L_1	W	VVW				
$Gd^{?}$	22.87	L_1 L_2 L_3		M	W	W		
		M_1 N_1					M	VVW
	77.67	K	VVW					
	114.72	K L_1 L_2	VS	M	VVVW			
		L_3 M_1 N_1				masked	VVW	VVW
	115.48	K L_1 L_2	VS	M	VVW			
		M_1 N_1					VVW	VVW
	153.56	K L_{1-2}	M	VVW				
		L_3 M_1 N_1				VW	VVW	VVW
	198.77	K L_1	W	VVW				
	329.2	K	VVW					
$Eu^{147-149}$	37.7	L_1 L_3 N_1		VVW		VVW		VVVW
	53.2	L_1 L_3		VVW		VVW		
	66.3	K	VW					

Table II (continued)

Isotope	Transition Energy (kev)	Lines seen	Visual Relative Intensities* K	L_1	L_2	L_3	M_1	N_1
$Eu^{147-149}$	67.6	K	M					
(cont'd)	69.0	K	VW					
	121.26	K L_1	M-S	VW				
		M_1 N_1					VVW	VVVW
	219.79	K L_1	VVW	VVVW				
	277.1	K L_1	W	VVVW				

* S = Strong
M = Moderare
W = Weak
V = Very

Table III

Determination of Energy for 115.48 kev Transition

Spectrograph	Electron energy (kev)	Shell	Eu binding energy (kev)	Gamma energy (kev)
PM I	66.88	K	48.51	115.39
	66.88	K	48.51	115.39
PM II	66.98	K	48.51	115.49
	107.23	L_1	8.06	115.29
	113.48	M_1	1.81	115.29
	66.96	K	48.51	115.47
	107.38	L_1	8.06	115.44
	107.72	L_2	7.62	115.34
	113.59	M_1	1.81	115.40
	115.01	N_1	0.37	115.38
PM III	67.15	K	48.51	115.66
	107.66	L_1	8.06	115.72
	113.87	M_1	1.81	115.68
	67.13	K	48.51	115.64
	107.58	L_1	8.06	115.64
	113.63	M_1	1.81	115.44
AVERAGE				115.48

B. Excitation Functions for Alpha-Induced Reactions on Sm^{147}

The samarium oxide used in Experiment III was enriched to 85 atomic percent in Sm^{147}, [23] with the other 15 percent chiefly Sm^{148} and Sm^{149}. An excitation function for the Sm^{147} (α,n) Gd^{150} reaction was not obtained because Gd^{150} is very long lived, but ones for the Sm^{147} $(\alpha,2n)$ Gd^{149}, Sm^{147} $(\alpha,3n)$ Gd^{148}, and Sm^{147} $(\alpha,4n)$ Gd^{147} reactions were determined. The $(\alpha,3n)$ function was obtained by alpha-counting the eight sample plates, and the $(\alpha,2n)$ one was determined by counting the samples in the 100-channel gamma pulse height analyzer and integrating the 9 day, 150 kev peak in each plate. A function for the 2 day activity was determined in the same way using the 229 kev peak. The position of this function on the energy scale indicates that the reaction was definitely Sm^{147} $(\alpha,4n)$ Gd^{147} and that the 2 day activity was due to Gd^{147}.

A better half-life to report for Gd^{147} is 29 hours. It was determined by following the decay of the 229 kev photopeak in the 100-channel gamma analyzer. Figure II shows the curve obtained for the decay of this peak. Only a few points were measured because of instrumental problems. This half-life of 29 hours was confirmed by half-lives of 30 hours found in resolving K x-ray (Figure IV), Nucleometer, and Geiger Meuller decay curves into their Gd^{147} and Gd^{149} components.

Figure III gives the excitation functions for alpha-induced reactions on Sm^{147}. Because of uncertainty involved in calculating absolute cross sections, the figure shows the cross sections in arbitrary units. In attempting to calculate absolute cross sections for the $(\alpha,4n)$ and $(\alpha,2n)$ reactions, the assumption that there was one K x-ray per disintegration was made because the total number of disintegrations was not known. Figure IV shows the decay curve used to determine the number of K x-rays in the Gd^{147} and Gd^{149} components of an Experiment III sample. With this assumption of one K x-ray per disintegration, a cross section of 3.44 barns was calculated for the $(\alpha,2n)$ reaction at the point where its excitation peaks, but the calculated Rutherford total cross section at this point is only 1.21 barns. It may therefore be said that there is more than one K x-ray per disintegration of Gd^{149}. Cross sections calculated for the $(\alpha,4n)$ reaction

look relatively as large as the (α,2n) ones. With the (α,3n) reaction, the cross section at the point where the function peaks was calculated to be 0.91 barns using known alpha counting efficiencies and geometries. The Rutherford cross section at this point is 1.60 barns, which makes the value of 0.91 barns look reasonable when the contributions of the (α,2n) and (α,3n) reactions to the total cross section are considered. This means that the approximate half-life of 140 years reported for Gd^{148} [19] is probably close to the real value.

C. Relative Photon and Electron Intensities of Gd^{147} and Gd^{149} Gammas

The 100-channel gamma analyzer was used in Experiment III to determine the photon intensities of the most prominent gammas from Gd^{147} and Gd^{149}, and the double-focusing spectrometer and densitometer were used in Experiment I to determine electron intensities. Figure V shows the gamma spectrum of the Experiment III plate with the greatest amount of Gd^{147} and Figure VI gives the spectrum for the plate with the greatest amount of Gd^{149}. Since energies were accurately known from permanent magnet spectrograph work, complex peaks could be resolved, and where peaks were small and indefinite, upper limits for photon intensities could be set. No photo peaks were seen for any of the $Gd^{151-153}$ transitions or for those gadolinium transitions not assigned to a particular isotope. In later runs on the 100-channel gamma analyzer, the 120- and 210-kev transitions of Eu^{147} were seen. Relative electron intensities were measured with the double-focusing spectrometer and densitometer; and because of the many approximations made in obtaining intensities from the densitometer, more meaning is attached to the values obtained from the double-focusing spectrometer.

Table IV gives the intensity values for some of the gammas of Gd^{149} and Gd^{147}. In the case of Gd^{149}, the electron intensities are given relative to an intensity of 1.00 for the K-line of the 346.70 kev transition; and in the case of Gd^{147}, the same thing is done using the K-line of the 396.21 kev transition. To put the relative photon intensities on the same scale as the electron intensities, multipolarities for the 149.86 kev transition of Gd^{149} and 229.49 kev transition of Gd^{147} were considered. L subshell conversion coefficients calculated by Rose[24] and K shell conversion coefficients calculated by Sliv[25] were

used in assigning multipolarities to these transitions. From K/L_1 ratios, L subshell ratios, and K/M_1 ratios, they both look like M1 transitions (or possibly M2) transitions. Electric multipolarity assignment for either transition is ruled out because of the small amount of conversion in the L_2 subshell, and higher magnetic multipole orders were not considered because of their long lifetimes. In doing coincidence work on these isotopes, Donald Strominger[26] found no delayed transitions (therefore all lifetimes less than a millimicrosecond). Assuming that both of these transitions were M1's, the relative photon intensities were normalized to give these transitions the proper K conversion coefficients. Gammas for which photons but no conversion electrons were seen are placed in parentheses. Their energies are uncertain and may be off by several kilovolts.

Table IV

Relative Intensities of Gd^{147} and Gd^{149} Gammas

Gamma energy (kev)	Line	Electron intensity from double-focusing spectrometer	Electron intensity from densitometer	Photon intensity	Total transition intensity
			Gd^{147}		
229.49	K	1.93	1.57	12.4	15.1
	L_1	0.56	0.29		
	M_1		0.11		
	N_1		0.06		
240.9					
	K		0.04		0.04
261.01					
	K		0.09		0.09
310.1				<0.71	<0.84
	K		0.13		
370.1				2.0	2.2
	K	0.25	0.16		
396.21				4.7	5.8
	K	1.00	1.00		
	L_1	0.14	0.31		
(517)				0.97	0.97
(570)				1.1	1.1
(635)				2.3	2.3
(770)				4.0	4.0
(900)				3.4	3.4
(1080)				1.3	1.3
(1298)				0.62	0.62

Table IV (continued)

Gamma energy (kev)	Line	Electron intensity from double-focusing spectrometer	Electron intensity from densitometer	Photon intensity	Total transition intensity
			Gd^{149}		
106.6				<0.25	<0.25
126.06				<0.20	<0.20
149.86				8.6	13.7
	K		4.30		
	L_1	0.55	0.46		
	M_1	0.19	0.18		
	N_1		0.06		
244.3				<0.26	<0.26
272.67				<0.79	<0.99
	K	0.09	0.08		
	L_1-L_2		0.05		
	M_1		0.06		
298.79				5.1	5.7
	K	0.49	0.44		
	L_1	0.09	0.08		
346.70				3.0	4.3
	K	1.00	1.00		
	L_1	0.23	0.20		
	M_1	0.03	0.06		
460.6				< .25	< .25
496.5				.25	.25
516.7				.68	.68
534.2				.61	.61
(650)				.44	.44
749.5				< 1.1	< 1.1
789.8				< 1.1	< 1.1
(937)				.52	.52

D. Results of Coincidence Measurements

Table V gives the results of coincidence measurements made by Donald Strominger[26] on an Experiment I sample. At the same time, he looked for positrons and was able to set an upper limit of 0.8% for positron activity in the combined gadolinium activities. It will be assumed that Gd^{147} decays entirely by electron capture.

Table V

Isotope	Gate Gamma Energy (kev)	Energy of Gammas in Coincidence (kev)
Gd^{149}	150	350 500 760
Gd^{147}	229	390 760 930
Gd^{149}	630	750
Gd^{149}	750	150 630

IV. DISCUSSION OF RESULTS

A few of the transitions seen in these experiments were ones that had been seen before. The transitions of 69.64, 97.47 and 103.20 kev seen in Experiment II are evidently the ones of 69.4, 97.3 and 103.1 kev reported by Church and Goldhaber[1] for the decay of Gd^{153}. The 310 kev transition tentatively assigned to Gd^{151} by Heydenberg and Temmer[2] may be the 308.5 kev transition seen in Experiment II, and the 20 kev transition for Gd^{151}, seen in the beta decay of Sm^{151} [5] by Wilson and Lewis, is probably the 21.55 kev transition found in Experiment II. Mack, Neuer, and Pool[27] reported gammas of 120 and 210 kev resulting from the decay of Eu^{147}, which are probably the ones of 121.26 and 219.79 kev seen in this work. They also reported transitions of 300 and 570 kev resulting from the decay of Eu^{149}, but these were not seen in these experiments. No experiments done in this work could distinguish between Gd^{151} and Gd^{153} transitions or Eu^{147} and Eu^{149} transitions.

Tentative multipolarities were assigned to a few of the Gd^{149} transitions for which more than K-lines were seen. These multipolarities were assigned assuming the 149.86-kev gamma was an M1 transition, and would have to be reconsidered if the 149.86 kev gamma is shown to be an M2 transition. The 346.70-kev gamma has a K-shell conversion coefficient of 0.185 and a K/L_1 ratio of 5.00, both consistent with an M2 transition ($\alpha_K = 0.190$; $K/L_1 = 5.30$). M1, E1, E2 and higher multipole order transitions could be ruled out because they all have K shell conversion coefficients lower by a factor of 4 or more. The 298.79 kev transition has a K-shell conversion coefficient of 0.048 and a K/L_1 ratio of 5.5, consistent with an M1 ($\alpha_K = 0.077$; $K/L_1 = 5.92$) or E2 ($\alpha_K = 0.048$; $K/L_1 = 8.4$) transition. It was assigned as an M1, however, because of its L-subshell ratios. A fairly strong L_1 line was seen but no L_2 or L_3; and if the transition were an E2, the L_2 line would definitely be seen. M2 was ruled out because of its high α_K, E1 because of its low α_K, and higher multipole orders because of their long lifetimes. Nothing much may be said about the multipole orders of the other transitions, except that of the 272.67 kev gamma. E1 may be ruled out as a multipolarity for this transition, because it has an α_K of 0.017 and the 272.67 kev gamma has a minimum $\alpha_K \gtrsim 0.064$.

Considering results obtained in energy determinations, relative intensity determinations, coincidence measurements, and multipolarity assignments, level schemes could not be uniquely determined for the decays of any of the light gadolinium isotopes studied. The complexity of the schemes is evidently such that without further information about each transition, the gammas may be fit into several different reasonable schemes. A suggested decay scheme for Gd^{149}, which is consistent with all available data, is shown in Figure VII.

No attempt was made to explain the occurence of the gadolinium transitions not belonging to the decay of any of the isotopes from Gd^{147} to Gd^{153}. The possibility that these transitions belong to an isomer of one of these isotopes should be considered, and threshold bombardment work should be done to determine the mass number of the isotope.

V. ACKNOWLEDGMENTS

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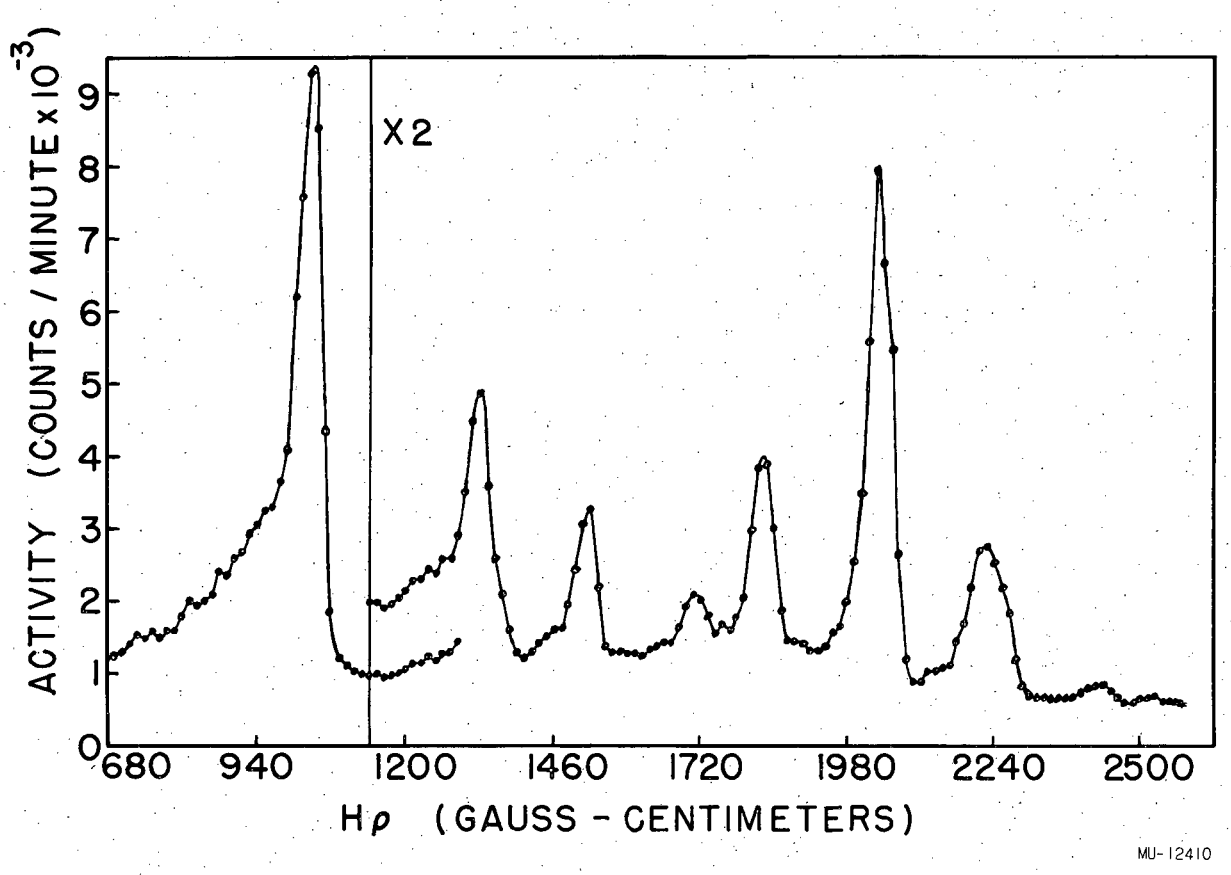

Fig. 1. Lens spectrometer spectrum of Gd^{147} and Gd^{149}.

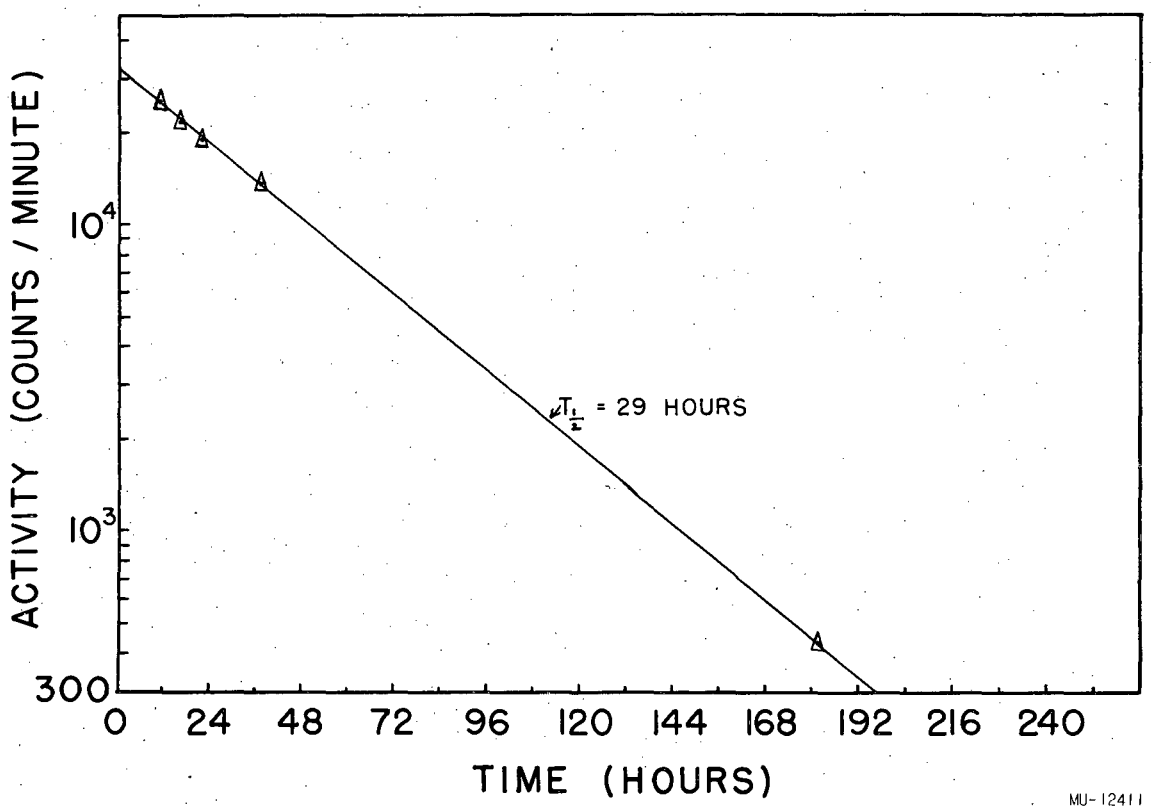

Fig. 2. Decay curve for 229 kev peak of Gd^{147}.

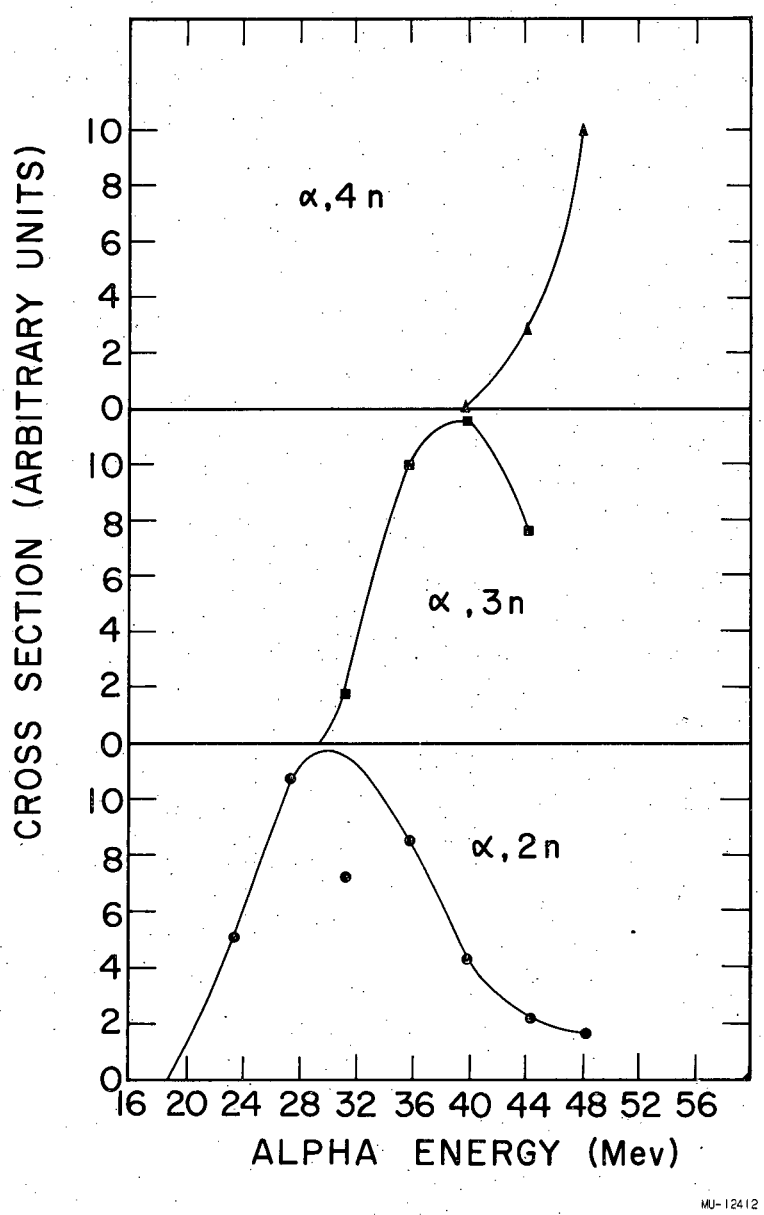

Fig. 3. Excitation functions for alpha-induced reactions on Sm^{147}.

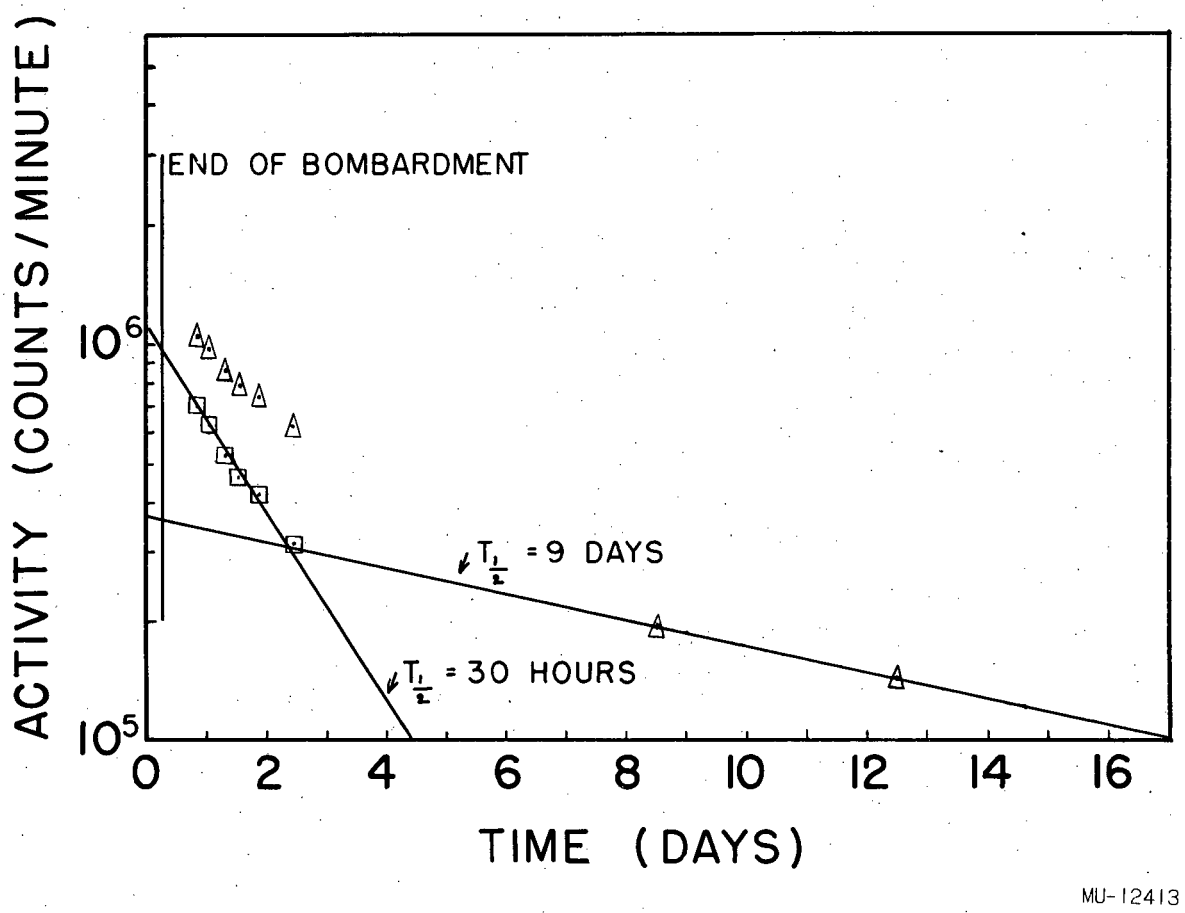

Fig. 4. Resolved decay curve for K x-rays of Gd^{147} and Gd^{149}.

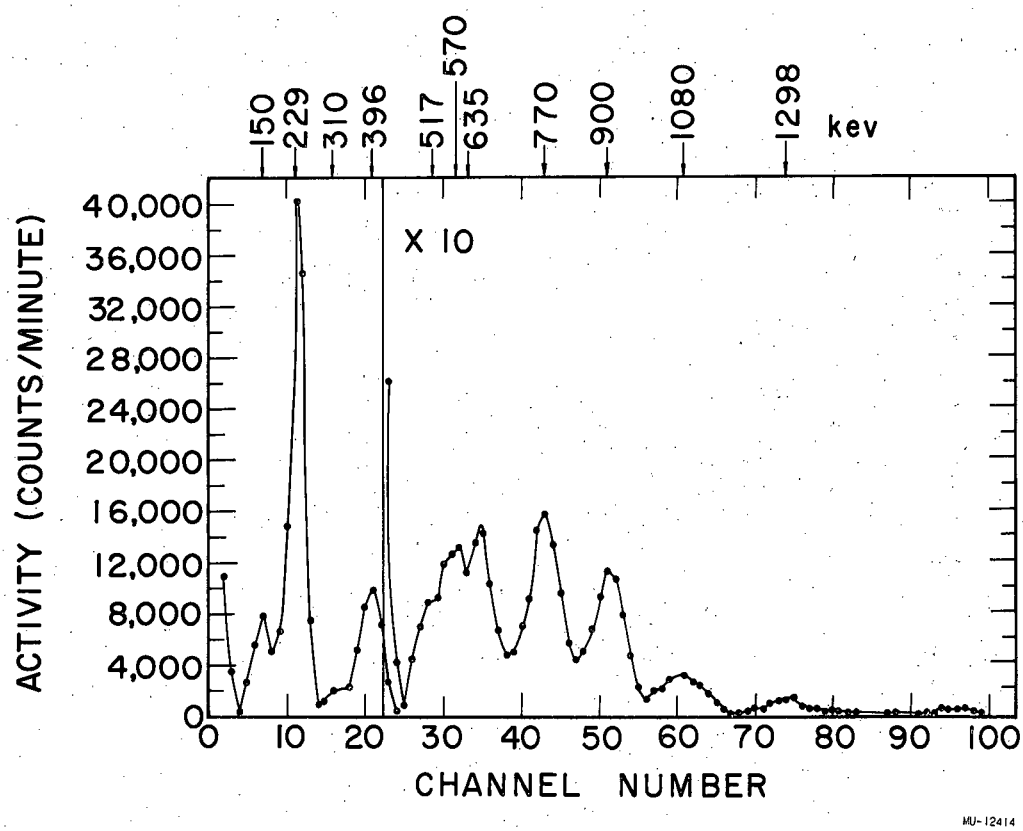

Fig. 5. 100-channel gamma analyzer spectrum of Gd^{147} (background subtracted). The 150 kev peak is the strongest photo-peak of Gd^{149}, present in small abundance in the Gd^{147} sample.

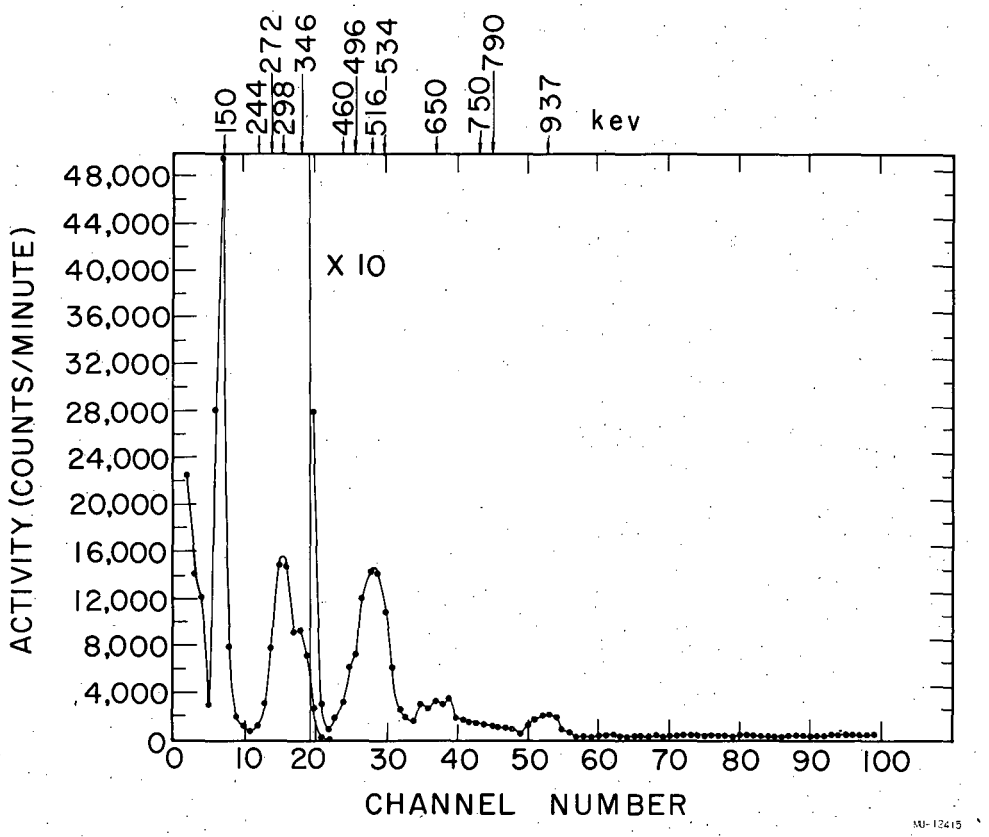

Fig. 6. 100-channel gamma analyzer spectrum of Gd^{149} (background subtracted).

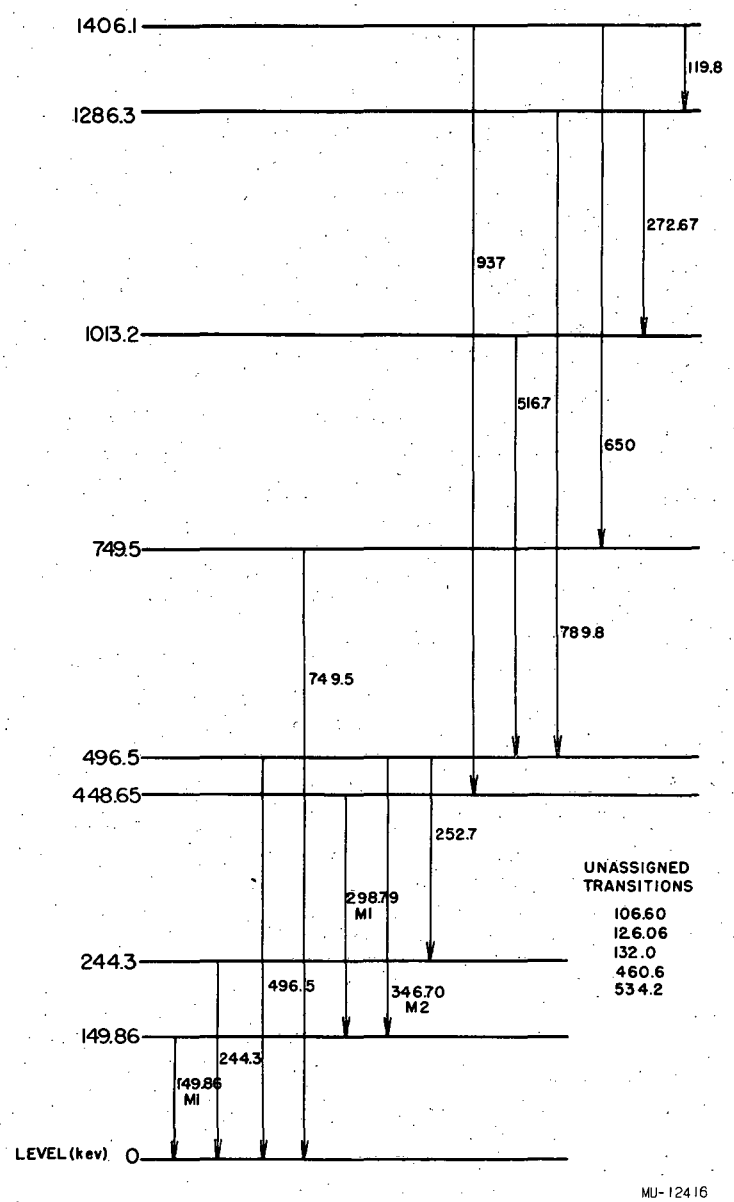

Fig. 7. Suggested decay scheme for Gd^{149}.