If we assume that the neutron transfer takes place at D, the distance of closest approach of the incoming trajectory, and that D is the same for the smoothly joined outgoing trajectory, the two orbits differ by 12 units of angular momentum at $\theta=60$ deg (c.m.). These twelve units of angular momentum cannot be accounted for by the spin changes in the nuclei following the reaction. Therefore, it may be concluded that smooth joining of orbits at D is not a good description of the trajectories.

The histogram in Fig. 3 must be regarded as a sum of differential transfer cross sections leaving the residual Mg^{26} in various states of excitation. This experiment should be repeated with greater energy and angular resolution to determine the angular distributions of the transfer reaction going to individual states of Mg^{26}.

ACKNOWLEDGMENTS

The authors are indebted to F. R. Duncan for the preparation of the targets, to J. G. Harris who constructed the apparatus, and to Mrs. P. L. Rittenhouse and Miss N. E. Alley who assisted with the counting. Our thanks go also to M. H. Shelton who operated the cyclotron.

PHYSICAL REVIEW VOLUME 108, NUMBER 2 OCTOBER 15, 1957

Decay of Europium-154†

JOSÉ O. JULIANO AND F. S. STEPHENS, JR.
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
(Received June 21, 1957)

The gamma rays and electrons of fission-product europium (Eu^{153}, Eu^{154}, and Eu^{155}) have been studied, and the results obtained for Eu^{154} are presented. Gamma rays belonging to this isotope have been identified at 0.1229 Mev (35%), 0.2480 Mev, 0.593_3 Mev (4%), 0.694_1 Mev ($\leq 3.5\%$), 0.705_8 Mev ($\leq 3.5\%$), 0.724_9 Mev (21%), 0.758_9 Mev ($\leq 3.5\%$), 0.875_3 Mev (13%), 0.998_2 Mev (14%), 1.007 Mev (17%), 1.277 Mev (42%), and ~1.6 Mev (~3%). Beta end points of Eu^{154} were measured at 1.85, 0.87, 0.59, and 0.25 Mev. Multipolarities for most of the above gamma-ray transitions have been suggested on the basis of the measured K-shell conversion coefficients. The decay scheme of Eu^{154} has been deduced, and, in most respects, the resulting levels of Gd^{154} conform well with the Bohr-Mottelson unified nuclear model and with other even-even nuclei in the strong-coupling regions.

INTRODUCTION

EUROPIUM-154 was first produced in 1938 by Scheichenberger,[1] using a neutron-capture reaction on natural europium. It decays principally by electron emission, with a half-life given by Karraker *et al.*[2] as 16±4 years. A number of studies[3–11] have been made of the gamma-ray and electron spectra of this isotope; however, the results are rather confusing. This is probably because Eu^{154} has been made together with 13-year Eu^{152} (natural europium is about an equal mixture of Eu^{151} and Eu^{153}), and owing to similarity of the decay schemes and half-lives, it has been difficult to assign transitions with certainty to either isotope. As will be seen, this difficulty was not encountered in the present study.

From the studies made of Eu^{154}, the following information seems clearly established. A 123-kev gamma ray has been observed both from the decay of Eu^{154},[3,4] and from Coulomb excitation of Gd^{154}.[5] Andersson[9] measured the energy of this gamma ray to be 123.54±0.09 kev, whereas Boehm and Hatch[10] reported this energy to be 123.07 kev. Sunyar[11] observed that the level giving rise to this transition has a half-life of 1.2×10^{-9} second, which he used to classify the gamma ray as $E2$. The transition probabilities calculated from Coulomb excitation[5] and from Sunyar's[11] lifetime measurements agree within experimental accuracy. Huus *et al.*[5] measured the K/L ratio for this transition to be 1.0. Many higher energy gamma rays and beta end points have been reported, but, as has been mentioned, the agreement among these data has been poor. By observing the microwave paramagnetic resonance hyperfine structure, Kedzie *et al.*[12] have recently determined the spin of Eu^{154} to be 3 and the magnetic moment to be 2 nm.

The europium used in this study was prepared by

† This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] Scheichenberger, Anz. Akad. Wiss. Wien, Math.-naturw. Kl. **75**, 108 (1938).
[2] Karraker, Hayden, and Inghram, Phys. Rev. **87**, 901 (1952).
[3] E. L. Church and M. Goldhaber, Phys. Rev. **95**, 626(A) (1954).
[4] Cork, Keller, Rutledge, and Stoddard, Phys. Rev. **77**, 848 (1950).
[5] Huus, Bjerregaard, and Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 17 (1956).
[6] M. R. Lee and R. Katz, Phys. Rev. **93**, 155 (1954).
[7] Dubbey, Mandeville, and Rothman, Phys. Rev. **103**, 1430 (1956).
[8] Cork, Brice, Helmer, and Sarason, Bull. Am. Phys. Soc. Ser. II, **2**, 16 (1957).
[9] B. Andersson, Proc. Phys. Soc. (London) **A69**, 415 (1956).
[10] F. Boehm and E. N. Hatch, *Nuclear Data Cards* (National Research Council, Washington, D. C.), No. 57-1-95, 1957.
[11] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).
[12] Kedzie, Abraham, and Jeffries, Bull. Am. Phys. Soc. Ser. II, **1**, 391 (1956).

irradiating plutonium for about two years in the Materials Testing Reactor at Arco, Idaho. In this manner, Eu^{154} was produced principally from neutron-capture reactions on the fission products and, because of the absence of Eu^{151}, no Eu^{152} was made. In order to separate europium from the plutonium and from the many fission products, the following chemical procedure was used. The sample, contained in an aluminum ring, was dissolved in a $NaOH-NaNO_3$ solution. This procedure left the actinides and lanthanides (and many other fission products) as precipitates, but dissolved the aluminum ring. The precipitate was then dissolved in hydrochloric acid solution and the actinides and lanthanides reprecipitated as fluorides, separating them from most of the other fission products. The fluoride precipitate was dissolved in boric acid, and the lanthanides and actinides reprecipitated with the addition of hydroxide. This precipitate was treated with hydrochloric acid solution and evaporated almost to dryness. A 10.5*M* solution of LiCl was used to dissolve the residue, and the solution was passed through a column of Dowex A-1 anion resin maintained at 80°C. The lanthanides came through this column almost immediately, whereas the actinides were held up for some time. The lithium was removed from the lanthanides by precipitating the latter as hydroxides and then redissolving the precipitate in hydrochloric acid. To separate the europium from the other lanthanide elements, the material was placed on a column containing Dowex-50 cation resin and maintained at 80°C. The lanthanides were then eluted in an ammonium alpha-hydroxyisobutyrate solution, which brought them off the column individually, in order of decreasing atomic number. To insure complete separation, the europium fraction was passed through a second "isobutyrate column." From the purified europium solution samples were prepared for analysis of the electron spectrum by electrodeposition onto a platinum wire of 0.010 inch diameter. The samples for the gamma-ray studies were evaporated to dryness on 0.006-inch-thick aluminum plates.

TABLE I. Electron lines from Eu^{154} decay.

Electron energy (kev)	Intensity[a] (permanent magnet)		Intensity (double focusing)	Conv. shell	E_γ (kev)	Transition energy[b] (kev)
72.67	vvvs	c	100	K	122.9	
114.52	vs	c		L_I	122.9	
115.10	vvs	c	109	L_{II}	123.0	122.9
115.65	vvs	c		L_{III}	122.9	
121.1	ms	c	18.9	M	123.0	
122.6	wm	c	···	N	123.0	
197.7	wm	c	3.1	K	247.9	247.9
239.6	···	c	1.2	$L_{I,II}$	248.0	
543.1	d	ms	···	K	593.3	593.3
643.6	d	vvs	0.55	K	694.1	694.1
685.6	d	vw	···	L_I	694.0	
655.6	d	vvw	···	K	705.8	705.8
697.4	d	vvw	···	L_I	705.8	
703.8	d	vvw	···	M	705.7	
674.7	d	vs	0.31	K	724.9	724.9
716.4	d	vvw	···	L_I	724.8	
722.6	d	vvw	···	M	724.5	
708.7	d	m	0.08	K	758.9	758.9
825.1	d	ms	0.40	K	875.3	875.3
867.0	d	···	···	L_I	875.4	
948.0	d	ms	0.15	K	998.2	998.2
990.2	d	···	···	L_I	998.6	
956.7	d	s	0.39	K	1006.9	1006.9
998.8	d	···	···	L_I	1007.2	
1226.5	d	w	0.37	K	1276.7	1276.7
1268.4	d	vvw	···	L_I	1276.8	

[a] v = very, s = strong, m = moderate, w = weak.
[b] Errors estimated to be ±0.1%.
[c] Film too black to read.
[d] Film too light to read.

Europium samples from two separate plutonium irradiations were used in this work. Both samples gave the same results, with the exception that the low-energy gamma rays of Eu^{155} were found to be less intense in the first sample, which had been out of the reactor for three to four years. This is sufficient time for an appreciable decay of two-year Eu^{155} to occur. The second sample was mass analyzed and the following constituents reported: Eu^{155}, 6.5%; Eu^{154}, 15.2%; Eu^{153}, 78.9%; Eu^{152}, <0.1%. The Eu^{152} was below the limit of detection of the mass analysis, and there was no evidence for its presence in the gamma-ray or electron data.

EXPERIMENTAL

The conversion-electron and beta-ray spectra of Eu^{154} were studied on two types of instruments. The first of these was four 180° permanent-magnet electron spectrographs described previously by Smith and Hollander.[13] These instruments were used principally to measure the conversion-electron energies with high precision. The conversion-electron lines were recorded photographically on glass-backed Eastman no-screen x-ray plates having an emulsion thickness of 25 microns. The resolution (full width of a peak at one-half its maximum height) of these spectrographs in the present experiments was about 0.1%. The lowest-energy transition from the conversion electrons was measured on this instrument to be 122.9 kev, compared to 123.07 kev from the bent-crystal spectrometer measurements.[10]

Measurements of the electron spectrum of Eu^{154} were also made, using a double-focusing semicircular magnetic beta-ray spectrometer having a radius of 25 cm.[14,15] The focused electrons were detected by a thin-window Geiger counter in this instrument with a resolution of about 0.5%. The relative intensities of the conversion electrons were determined with considerably more accuracy with this instrument than on the permanent magnets, and it was also possible to investigate the high-energy beta end points.

The conversion-electron data taken on these instruments are summarized in Table I. The energy measure-

[13] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).
[14] G. D. O'Kelley, University of California Radiation Laboratory Report UCRL-1243, 1951 (unpublished).
[15] T. O. Passell, University of California Radiation Laboratory Report UCRL-2528, 1954 (unpublished).

TABLE II. Gamma-ray and coincidence abundances.

E_γ (Mev)	Rel. abund.	Rel. abund. (coincidence with 0.123 Mev)	Rel. abund. (coincidence with 0.73 Mev)	Abs. abund. (coincidence with 1.0 Mev)	Abs. abund. (coincidence with 1.28 Mev)
0.040	...[a]	...	...	...	0.20
0.123	(1.00)	...	...	...	0.40
0.60	0.2	0.1	...	0.12[b]	*x*[c]
0.75	0.70	0.29	...	0.34	*x*
0.88	0.39	0.35	(0.37)	*x*	*x*
1.00	0.90	0.50	0.39	*x*	*x*
1.28	1.20	(1.20)	*x*	*x*	*x*
~1.6	0.09	...	...	...	...

[a] ... indicates either no data or an ambiguous result.
[b] Absolute abundances given in photons per "gate" photon.
[c] *x* indicates no coincidence.

ments are from the permanent-magnet spectrographs, and the limit of error on these energies is expected to be 0.1%. The qualitative relative-intensity data from the permanent magnets are given in columns 2 and 3, whereas the numerical values from the double-focusing spectrometer are listed in column 4. The errors associated with the relative-intensity data taken on the double-focusing spectrometer are estimated to be about 20%. The assignment of the lines in Table I is straightforward, and, as will be seen, is in good agreement with the gamma-ray and coincidence data (Table II).

In addition to the electron lines, it was possible to determine beta end points at 1850, 870, 590, and 250 kev, although at the lower energies the resolution of the Fermi-Kurie plot was not very good. The reason for this is not clear; however, it might be at least partially explained if the above beta groups had forbidden rather than allowed shapes. It will be shown that the log*ft* values for these transitions are all around 10 or larger. Because of these uncertainties, and others which will be discussed later, it was not possible to obtain reliable relative intensities for any of the beta groups.

To study the gamma-ray spectrum of Eu^{154}, a NaI(Tl) crystal coupled to a 50-channel pulse-height analyzer was used. A resolution (full width of a peak at half-maximum, divided by the energy of the peak) of about 8% was obtained for the 661-kev gamma ray of Cs^{137}. For coincidence work the 50-channel analyzer could be gated with the output of a single-channel analyzer, which analyzed the spectrum of a second NaI(Tl) crystal. A resolving time (2τ) of about two microseconds was used in these experiments. This equipment has been described in detail elsewhere.[16] Counting-efficiency[17] and escape-peak[18] corrections for the NaI crystal have been applied to all the gamma-ray intensities considered.

A portion of the gamma-ray spectrum of Eu^{154} is shown in Fig. 1(a). The resolution of this region into five gamma rays is also indicated, and was made, using the peak shapes measured for the following single photopeaks: Cs^{137}, 0.661 Mev; Mn^{54}, 0.84 Mev; Bi^{207}, 1.063 Mev; Na^{22}, 1.277 Mev. The resolution of the gamma ray at 0.60 Mev is not very reliable, and its relative intensity is particularly uncertain owing to the low abundance of this peak and the large amount of Compton radiation beneath it. There is a slight indication of a peak around 1.1 Mev; however, its intensity, both in the gamma-ray spectrum and in the coincidence work, was too low for careful study. Other gamma rays in the sample at 0.12, 0.25, and ~1.6 Mev were observed and assigned to Eu^{154}. The low-energy gamma rays of Eu^{155} were also present. Table II lists the best energies and relative intensities of the Eu^{154} gamma rays. An intensity of the 0.25-Mev gamma ray was not obtained, owing to the fact that a backscattering peak from the higher energy gamma rays is expected at about this energy, and it was not certain how much of this peak was caused by true nuclear 0.25-Mev photons.

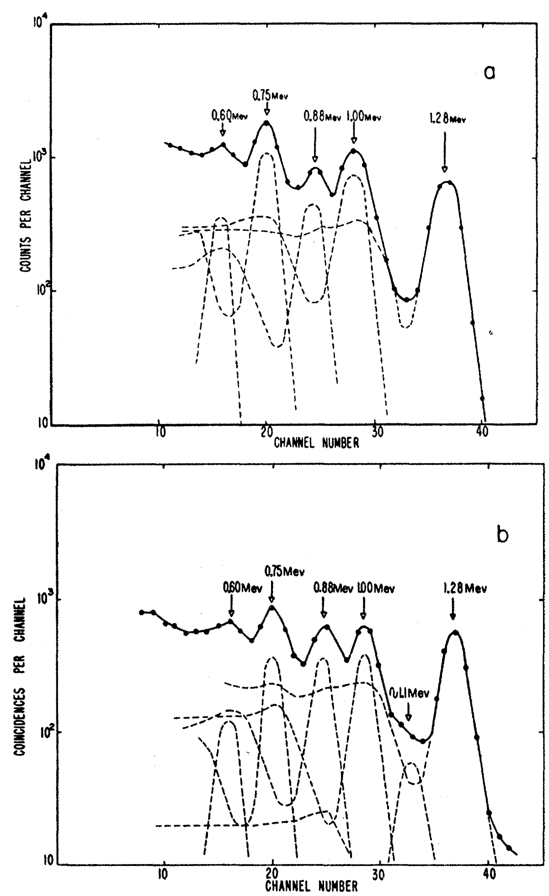

FIG. 1. (a). Gamma-ray spectrum of Eu^{154} in the region 0.5 to 1.4 Mev. (b). Spectrum in coincidence with the 0.12-Mev photons of Eu^{154}.

[16] F. S. Stephens, Jr., University of California Radiation Laboratory Report UCRL-2970, 1955 (unpublished).
[17] M. I. Kalkstein and J. M. Hollander, University of California Radiation Laboratory Report UCRL-2764, 1954 (unpublished).
[18] P. Axel, Brookhaven National Laboratory Report BNL-271, 1953 (unpublished).

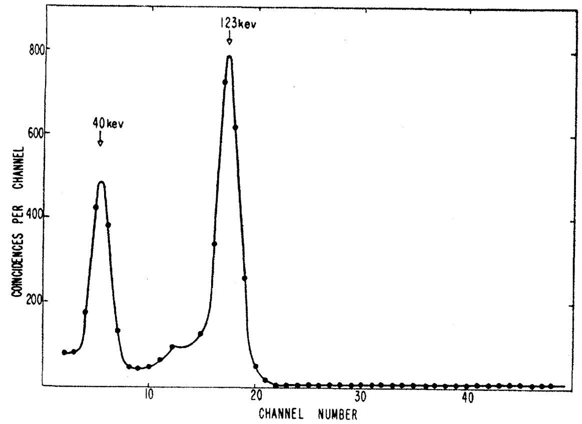

FIG. 2. Gamma-ray spectrum in coincidence with the 1.28-Mev photons of Eu^{154}.

The peak at $\sim$1.6 Mev was probably not a single peak, and the intensity listed is a maximum intensity for radiation in this energy region. The relative intensities listed are the average of four determinations, and from the reproducibility of these results it is estimated that they should be accurate within 10 to 15%.

The gamma-ray spectrum in coincidence with the 0.12-Mev photons is shown in Fig. 1(b). Its resolution is also indicated, and the relative abundances of the peaks are given in Table II. The intensity of the 1.28-Mev peak has been normalized to the value from the gamma-ray spectrum. The intensities listed are the averages of two determinations, and again are expected to be good to 10 to 15%. It should be added that in these measurements the coincidence rate due to the Compton-scattered radiation beneath the 0.12-Mev peak was determined by setting the gate just above this peak and running for an equal length of time. This small contribution was then subtracted from the total coincidence curve.

Coincidences among the higher energy gamma rays were complicated by the fact that beneath each photopeak (except the one at 1.28 Mev) there is a large amount of Compton-scattered radiation from the gamma rays of still higher energy. For this reason, some of the relative intensities measured were not meaningful and, in a few cases, uncertainties arose as to whether a coincidence did or did not exist. The results of some of these measurements have been included in Table II. Inconclusive measurements have been indicated by three dots $(\cdots)$, whereas an x indicates that there was definitely no coincidence. Only relative intensities were obtained from the spectrum in coincidence with the 0.73-Mev gamma ray, and in this case the intensity of the 0.88-Mev peak was normalized to the average intensity of this peak from the preceding two columns.

From a knowledge of the "gate" counting rate and the solid angle subtended by the "signal" NaI crystal, it was possible to obtain absolute intensities for the radiations in coincidence with the 1.00- and 1.28-Mev gamma rays. In the case of the 1.28-Mev gate, a subsequent run was made with the gating energy just above the 1.28-Mev peak, and both the coincidences and the "gates" from this run were subtracted from those of the true 1.28-Mev coincidence measurement. The resulting spectrum is shown in Fig. 2, and it is seen that only the 0.12-Mev gamma ray and a peak at 0.04 Mev are present. The latter peak is almost undoubtedly gadolinium K x-rays. The intensities of these two peaks per 1.28-Mev gate are given in Table II. In order to obtain absolute intensities of the gamma rays in coincidence with the 1.00-Mev photons, it was necessary to subtract from the gate-counting rate those counts that were due to Compton-scattered radiation from the 1.28-Mev gamma ray. This was accomplished by assuming the same ratio of Compton-scattered radiation at 1.00 Mev to photopeak height at 1.28 Mev for Eu^{154} as was measured by using a Na^{22} source. Both sources were on 0.006-inch aluminum plates and the geometrical conditions were as nearly identical as possible. Since the 1.28-Mev gamma ray of Eu^{154} was found not to be in coincidence with any radiation above 0.12 Mev, it was safe to assume that the Compton radiation beneath the 1.0-Mev peak did not contribute to the high-energy coincidence-counting rate.

Beta-gamma coincidences were measured also; however, owing to the many beta components present, these measurements were not very helpful. It was possible to show, however, that the very highest energy beta particles were in coincidence with the 0.12-Mev gamma ray in an intensity of about 0.4 per beta particle.

Decay Scheme

The level scheme of Gd^{154} is readily deduced from the precise gamma-ray energies and the coincidence data. It is shown in Fig. 3. The energy sums all agree to within 0.1%. The gamma-ray and coincidence data will presently be shown to be in good agreement quantitatively with this decay scheme. Only two gamma transitions seen on the permanent magnets have not been placed in Fig. 3. These are the 0.694_1-Mev and the 0.705_8-Mev gamma rays. It is interesting that their sum is 1.399_9 Mev, which is well within the limit of error of the 1.400-Mev level; however, there does not seem to be sufficient evidence to place them in the decay scheme at present. It will be seen that there is no evidence that an appreciable number of 0.694-Mev photons are present in the gamma-ray spectrum, which, considering the large electron intensity in Table I, is somewhat surprising.

It is possible to calculate a K-conversion coefficient (α_K) for the 0.12-Mev transition from the spectrum in coincidence with the 1.28-Mev gamma ray, which is shown in Fig. 2. If a K-fluorescence yield[19] of 0.93 is

[19] P. R. Gray, Phys. Rev. 101, 1306 (1956).

used for gadolinium and if all the K x-rays in Fig. 2 are assumed to arise from conversion of the 0.12-Mev transition, then α_K may be calculated to be 0.54. Also, since one would expect each 1.28-Mev gamma ray to be followed by one 0.12-Mev transition, a total conversion coefficient (α_T) of 1.5 can be deduced for the 0.12-Mev gamma ray. Hence, from the scintillation-counter data alone the ratio α_K/α_T is determined to be 0.36. An independent value for this ratio may be calculated from the electron data of Table I, if N-shell and higher level conversion are assumed to be negligible. To within a very few percent, this assumption is almost undoubtedly correct, and leads to a ratio, α_K/α_T, of 0.44 from the electron data. The agreement between the two methods is seen to be reasonably good. Since a K/L ratio of 0.9 is readily calculated from the electron intensities, an absolute L-conversion coefficient of 0.60 is obtained by combining the electron and gamma-ray data. Theoretical estimates of the K (Sliv[20]) and L (Rose[21]) conversion coefficients for this energy and atomic number for $E1$, $E2$, and $M1$ transitions are given in Table III. The transition is clearly $E2$, in agreement with Sunyar's[11] conclusion from the lifetime, and with the qualitative L-subshell ratios from the permanent-magnet spectrograph.

A comparison of the scintillation-counter intensities (Table II) with the decay scheme of Fig. 3 is now in order. It can be seen from the decay scheme that, of the gamma rays resolved in Fig. 1, three are expected to decay essentially completely through the 0.12-Mev level. These are at energies of 1.28, 0.88, and 0.60 Mev. Because the intensity of the 1.28-Mev gamma ray is the most precisely measured of these three, it was used to normalize the gamma-ray and coincidence relative-intensity data shown in Table II. When this was done, it was noted that the two intensities measured for the 0.88-Mev gamma ray agreed to within about 10%. Because the intensities of the 0.60-Mev transitions are considerably less accurately known, they are not considered to be in disagreement with each other. The data, then, are consistent, with each of these three gamma rays being completely in coincidence with the 0.12-Mev transition. We next consider the 1.00-Mev peak. The electron spectrum shows two gamma rays with energies of 1.007 and 0.998 Mev, and this peak is expected to include both of them. Of these, the 1.007-Mev gamma ray is expected to be in coincidence with

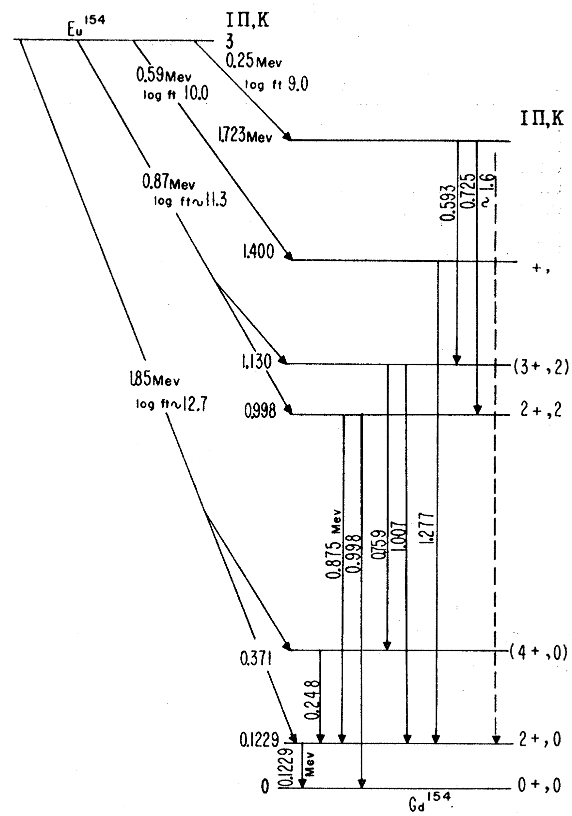

FIG. 3. Decay scheme of Eu^{154}.

the 0.12-Mev transition, whereas the 0.998-Mev gamma ray is not. Thus, the 0.50 measured as the relative intensity of the 1.0-Mev peak in the spectrum coincident with 0.12-Mev photons must be due to the 1.007-Mev gamma ray; and the residual intensity of 0.40 should be attributed to the 0.998-Mev gamma ray. This may be checked by considering the spectrum in coincidence with the 0.73-Mev photons. This spectrum should include the 0.875- and 0.998-Mev gamma rays in their true relative intensity, and should include no 1.007-Mev photons. Accordingly, the intensity of the 0.88-Mev gamma ray in this spectrum (column 3, Table II) was normalized to the average intensity of this transition in the other two measurements, and an intensity of 0.39 was obtained for the 0.998-Mev gamma ray. This is in good agreement with the value of 0.40 arrived at independently above. Considering now the 0.725-Mev transition, we note that of the coincidences with the 1.00-Mev peak, only the 0.998-Mev photons are preceded by a 0.725-Mev gamma ray, while only the 1.007-Mev photons are preceded by a 0.60-Mev gamma ray. As the relative intensities of the two components of the 1.0-Mev peak are now known, the absolute-intensity data in Table II may be corrected to the following: 78% of the 0.73-Mev photons per 0.998-Mev gate; and 21% of the 0.60-Mev photons per 1.007-Mev gate. The total intensity of the 0.725-Mev

TABLE III. Conversion coefficient of the 0.123-ev transition.

	$E1$	$E2$	$M1$	Experimental
K	0.14	0.65	1.1	0.54
L	0.02	0.5	0.2	0.60
Total	0.17	1.5	1.4	1.5

[20] L. Sliv (privately circulated tables).
[21] M. E. Rose (privately circulated tables).

TABLE IV. Gamma-ray and electron absolute abundances and multipolarity assignments.

E_γ	γ ray abs. abun.	K electron abs. abun.	α_K(Exp.)	$\alpha_K(E1)$[a]	$\alpha_K(E2)$	$\alpha_K(M1)$	$\alpha_K(M2)$	Probable multipolarity
0.123	0.35	(0.19)	(0.54)		See Table III			$E2$
0.248	...	0.0068	...	...	...	...	...	$E2$[b]
0.593	0.04	...	...	...	...	...	...	...
0.694	$<0.03_5$	1.0×10^{-3}	$>2.9\times10^{-2}$					$M2$ or higher
0.706	$<0.03_5$	...	...	1.9×10^{-3}	4.9×10^{-3}	$9\ \times10^{-3}$	2.4×10^{-2}	...
0.725	0.21	5.9×10^{-4}	2.8×10^{-3}					$E1$, $E2$
0.759	$<0.03_5$	1.6×10^{-4}	$>5\ \times10^{-3}$					$M1$, $E2$, or higher
0.875	0.13	7.6×10^{-4}	5.8×10^{-3}	1.4×10^{-3}	3.3×10^{-3}	5.8×10^{-3}	1.5×10^{-2}	$M1$
0.998	0.14	2.9×10^{-4}	2.1×10^{-3}	1.1×10^{-3}	2.4×10^{-3}	4.2×10^{-3}	1.0×10^{-2}	$E2$
1.007	0.17	7.4×10^{-4}	4.4×10^{-3}					$M1$
1.277	0.42	7.0×10^{-4}	1.7×10^{-3}	$7\ \times10^{-4}$	1.5×10^{-3}	2.4×10^{-3}	5.7×10^{-3}	$M1$, $E2$, $M1-E2$
~1.6	0.03	...	...	...	...	...	...	...

[a] Theoretical K-conversion coefficients of Sliv, reference 20.
[b] From K/L conversion-electron ratio.

gamma ray is then expected to be 78% of the combined intensity of the 0.88- and 0.998-Mev transitions, or, relative to the numbers in Table II, 0.60. An independent maximum intensity for the 0.725-Mev transition may be obtained from the intensity of the 0.73-Mev peak in coincidence with the 0.12-Mev photons. This peak will contain at least the 0.725- and the 0.759-Mev gamma rays, but by considering the 0.759-Mev intensity to be negligible, we may calculate a maximum intensity for the 0.725-Mev gamma ray. It is necessary to increase the relative intensity of 0.29 from Table II by the ratio of total radiation from the 0.998-Mev level to 0.88-Mev radiation, since only the fraction of the 0.73-Mev photons which are followed by the 0.88-Mev gamma rays are subsequently followed by a 0.12-Mev transition. This ratio has been determined to be 2.1, giving a total maximum intensity of 0.60 for the 0.725-Mev gamma ray. A second upper limit on the intensity of the 0.73-Mev gamma ray is the total intensity of radiation in this energy region observed in the gamma-ray spectrum. From Table II, this upper limit is 0.70. Thus, a measured value and two upper limits on the intensity of the 0.725-Mev gamma ray have been determined to be 0.60, 0.60, and 0.70, respectively. Within the limits of error of the measurements, these numbers probably do not differ. This is taken to indicate that the gamma rays of 0.705, 0.694, and 0.759 Mev are all weak compared to the 0.725-Mev transition, the abundance of which, relative to the numbers in Table II, is about 0.6. In addition to the two values for the relative intensity of the 0.60-Mev gamma ray listed in Table II, a third and probably more accurate value may be calculated by using the result that the 1.007-Mev transition is preceded by a 0.60-Mev photon 21% of the time. Considering that the 0.759-Mev transition is of negligible intensity compared to the one at 1.007 Mev, an abundance of 0.11 is obtained for the 0.60-Mev transition. This is in reasonable agreement with the 0.1 and 0.2 listed in Table II for this transition.

The relative intensities in Table II and those derived in the preceding discussion may be converted into absolute intensities in the following manner. The beta-gamma coincidence measurements showed that the very highest energy beta particles were in coincidence with about 0.4 of the 0.12-Mev photons. Using the conversion coefficient of 1.5 determined for the 0.12-Mev transition, this result indicates that the highest energy beta particles measured are all in coincidence with the 0.12-Mev transition. Direct beta population of the ground state is thus shown to be small compared with population to the 0.12-Mev level, which, itself, will presently be shown to be only around 5%. From the decay scheme in Fig. 3, it is seen that only two gamma transitions terminate at the ground state. These are at energies of 0.998 and 0.123 Mev, and together must carry all the beta decay, since there is no appreciable direct beta population of the ground state. Using the sum of these transition intensities to determine the beta-decay rate, the absolute gamma-ray intensities listed in Table IV were calculated. The limits on the 0.694-, 0.705-, and 0.756-Mev gamma rays were obtained by concluding from the discussion of the preceding paragraph that none of these is over 15% as large as the 0.725-Mev gamma ray. From the measured K-conversion coefficient of 0.54 for the 0.12-Mev transition, the absolute electron intensities can also be calculated, and these are listed in column 3 of Table IV. The resulting K-conversion coefficients, together with the theoretical values of Sliv and the probable multipolarity of the gamma rays, are also included in Table IV. The limits of error on the conversion coefficients are expected to be about 20 to 30%. Because a 50% error would be sufficient to change the multipolarity assignment in many cases, the assignments made in Table IV should be considered somewhat tentative. However, for the most part the agreement with the theoretical values is good, and there is no evidence to indicate that any assignment is incorrect.

From the gamma-ray intensities in Table IV and the decay scheme shown in Fig. 3, it is possible to reconstruct the beta spectrum. The population to the

1.724-Mev level is simply the sum of the intensities of the 0.60-, 0.725-, and 1.6-Mev gamma rays, or about 28%. Similarly, the population to the 1.400-Mev level is just equal to the intensity of the 1.277-Mev transition, or 42%. For the 1.130- and 0.998-Mev levels, it is necessary to add together the intensities of the gamma rays de-exciting each of these levels and subtract from this sum the intensity of the photons populating the level. The difference must be accounted for as direct beta population, and turns out to be 13 and 6%, respectively, for these levels. In this calculation the 0.759-Mev gamma ray has not been included, because its measured intensity is only an upper limit. It should be pointed out that the low-intensity beta groups, both those mentioned above and those which will be mentioned below, result from differences between rather large gamma-ray intensities, and hence have large limits of error associated with them. If the intensities of all the gamma rays populating any of the three lowest levels are summed, a total of about 88% of the beta transitions is accounted for. This implies that around 12% of the beta population goes directly to the three lowest levels. It has already been shown that the ground state receives essentially no direct population, so that the 12% must be divided between the 0.123- and 0.371-Mev levels. There are not sufficient data to determine unambiguously how this 12% is distributed; however, the following argument may be made. The 0.248-Mev gamma ray is very likely electric quadrupole, in agreement with the rotational model of Bohr and Mottelson.[22] If this is so, one may calculate from the intensity of the K electrons of this transition and the theoretical K-conversion coefficients of Sliv[20] that the gamma ray should have an abundance of 8 or 9%. Somewhere between 1 and 3% of this probably comes from gamma-ray rather than direct beta population of the 0.371-Mev level. This leaves 5 to 8% for direct beta population, which in turn leaves 4 to 7% for direct population to the 0.123-Mev level. The highest energy portion of the beta spectrum was re-examined to see whether the Fermi-Kurie plot was consistent with the above conclusions, and it was found that the population to the 0.371-Mev level could be anywhere from zero to almost equal the amount going to the 0.123-Mev level. Thus, there is no inconsistency, with the highest energy beta groups populating the 0.123- and 0.371-Mev levels almost equally. Table V summarizes the beta groups and lists the logft value for each group. The total beta-decay energy of 1.99 Mev was obtained from the 0.59- and 0.25-Mev beta groups and the levels which they populate at 1.400 and 1.723 Mev, respectively.

The spin and parity assignments shown in Fig. 3 are rather easily deduced. The parity of all the states except the one at 1.723 Mev must be even (+), since

[22] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).

TABLE V. Beta groups of Eu^{154} (indirect).

Energy (Mev)	Abundance (%)	logft
0.25	28±5	9.0
0.59	42±5	10.0
(0.86)	13±5	11.0
(0.99)	6±5	11.6
(1.62)	6±5	12.5
(1.87)	6±5	12.9

the transitions are all either $M1$ or $E2$. Since it was not possible to decide between $E1$ and $E2$ for the 0.725-Mev gamma ray, the 1.723-Mev level could have either even or odd parity. The spin of the 0.123-Mev level is certainly two, since the 0.123-Mev transition has been shown to be $E2$. The spin and parity of the 0.371-Mev level are only tentative, but are assigned on the basis of the Bohr-Mottelson rotational theory[22] and the absence of the crossover transition to the ground state. The $E2$ character of the 0.998-Mev gamma ray fixes the spin of the 0.998-Mev level at two. The suggested spin of the 1.130-Mev level will be considered in the following section.

Discussion

Gd^{154}, with 90 neutrons, lies just within the region of the rare earth elements where the Bohr-Mottelson[22] collective nuclear model is applicable. It has been shown that a rather sudden change from the transition region into the strong-coupling region occurs between neutron numbers 88 and 90.[22,23] This shift is readily observed in the first excited-state energies of Gd^{152} and Gd^{154}, which are 344 kev[23] and 123 kev,[24] respectively. Because Gd^{154} is at the very edge of the strong-coupling region, it would not be surprising to find deviations from the rotational formulas of Bohr and Mottelson,[22] and such deviations are easily noticeable. For example, using the formula

$$E=(\hbar^2/2\mathcal{I})I(I+1),$$

which gives the energy, E, of a rotational state as a function of the spin of the state, I, we may use the energy of the 2+ state to fix the value of the moment of inertia, $\mathcal{I}$, and then calculate the energy of the 4+ state to be 412 kev. This is about 11% larger than the experimental value. For nuclei in a comparable position in the strong-coupling region of the heavy elements, these corrections run as high as 23%.[25] The above value of 11%, therefore, is not particularly disturbing.

The levels at 0.998 and 1.130 Mev are quite interesting. The spin of the 0.998-Mev level is very likely 2+, as has been discussed. If the moment of inertia were the same as for the ground-state rotational band, the 3+ member of the rotational band based on this

[23] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[24] O. Nathan and M. A. Waggoner, Nuclear Phys. **2**, 548 (1956/57).
[25] F. Asaro and I. Perlman, Phys. Rev. **104**, 91 (1956).

level would be expected to be about 124 kev higher in energy. The 1.130-Mev level is 131 kev higher in energy, and, furthermore, the decay of this level to the 2+ and 4+ members of the ground-state band is consistent with its having a spin of 3+. For these reasons the two levels at 0.998 and 1.130 Mev are tentatively considered to be members of a rotational band with spins 2+ and 3+, respectively. This situation appears to be very similar to the levels in Pu^{238} populated by the beta decay of Np^{238}.[26,27] In this case two levels about 1 Mev above the ground state were observed, and were assigned spins 2+ and 3+. From the radiations from these levels in Pu^{238} (which are all $E2$) it was possible to deduce that K, the projection of the spin on the nuclear symmetry axis, was two for these levels. This, in turn, led to the suggestion that this rotational band might represent the gamma vibrational band predicted by Bohr and Mottelson to have these properties. The present case differs from Pu^{238} in that all the radiations from these levels do not seem to be $E2$. This could perhaps be due to the fact that Gd^{154} is on the very edge of the strong-coupling region, whereas Pu^{238} is well within this region in the heavy elements. Another possibility which should not be entirely discounted is that the multipolarity assignments are not correct. As was mentioned, the limits of error are sufficiently large that the assignments are considered to be only probable and not certain. However, the similarity of the two bands, and the observation of apparently analogous levels in other heavy element and rare-earth even-even nuclei suggest that such bands may occur systematically throughout both strong-coupling regions.

One rather puzzling aspect of the Eu^{154} decay scheme shown in Fig. 3 is that of the large $\log ft$ values calculated for the beta transitions. The transitions to the ground-state rotational band of Gd^{154} have $\log ft$ values between 12 and 13; this is perhaps understandable in that, while ΔI is only one, ΔK is quite likely three for these transitions. Hence, insofar as K is a good quantum number, these transitions would be second or higher forbidden. For the beta transitions leading to the 0.998- and 1.130-Mev levels, however, no such reason is evident. Here ΔI is probably one and zero respectively, and ΔK is probably one for both transitions. Depending on the parity of Eu^{154}, these should be allowed, or first forbidden, transitions, and yet the $\log ft$ values are around 11. Since the spins of the other levels in Gd^{154} are not known, expected $\log ft$ values cannot be estimated; however, with a spin of Eu^{154} as low as 3, it is a little surprising that the smallest $\log ft$ value observed is 9.

[26] Rasmussen, Slätis, and Passell, Phys. Rev. **99**, 42 (1955).

[27] Rasmussen, Stephens, Strominger, and Aström, Phys. Rev. **99**, 47 (1955).

ACKNOWLEDGMENTS

We wish to acknowledge many helpful discussions with Professor I. Perlman and Professor J. O. Rasmussen and with Dr. Frank Asaro and Dr. D. Strominger. We are grateful to Dr. M. C. Michel for the mass analysis. The fission-product sample was made available by Dr. S. G. Thompson, and the chemical separations were carried out by R. Silva, H. Simens, T. Parsons, and J. Grover, to whom we are very much indebted.