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Nuclear Energy Levels of Gd^{156} as Populated by β Emission from Eu^{156} †

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Energy levels of Gd^{156} populated by the beta decay of Eu^{156} have been studied. Energies of 36 transitions were determined absolutely using the Davis solenoidal spectrometer. Twenty-nine transitions were integrated into a decay scheme. In several cases external-conversion technique was used to assign multipolarities. Level energies (in keV), spins, and parities determined are: 88.95, 2+; 288.14, 4+; 1153.9, 2+; 1168.0, 0, 1, 2+; 1242.2, 1−; 1319.3, 2−; 1366.1, 1−; 1965.5, 1, 2+; 2026.2, 1, 2+; 2180.5, 1+; 2186.3, 1+; 2202.5, 0, 1, 2+, and 2203.2.

I. INTRODUCTION

The properties of the energy levels of even-even nuclei with spheroidal equilibrium shapes have been shown to be very similar,[1–3] in that many of the excited levels of these nuclei are of the collective type, consistent with the predictions of the unified model of the nucleus.[4]

The present investigation was undertaken in order to study one of these even-even nuclei, gadolinium 156. The Gd^{156} nuclear configuration is sufficiently removed from a closed shell that one would expect it to be highly deformed and thus offer a complex decay scheme, especially around one MeV, where γ and β vibrational levels are expected to appear. The excited levels of Gd^{156} were observed by studying the decay of 15-day half-life Eu^{156} by β emission. Preliminary results have been previously reported.[5]

Several investigators[6–11] have observed conversion electron lines corresponding to transition energies in Gd^{156} with beta ray spectrometers. Cline and Heath,[12] Henry, Dillman, Gove, and Becker,[13] observed γ rays from Gd^{156} with scintillation spectrometers. Several observers have utilized Coulomb excitation $(p,p'\gamma)$ and $(\alpha,\alpha'\gamma)$ of Gd^{156} to study the lower lying excited levels.[14–18] The excited levels of Gd^{156} have also been studied through the 5.4-day decay of Tb^{156} to Gd^{156} by electron capture.[9,13,18–20]

From the present investigation, some 36 transition energies are presented, of which 29 have been integrated into the decay scheme. Multipolarity assignments have been given based on K to L ratios and utilizing K conversion coefficients measured by external conversion. Spins and parities have been assigned consistent with the multipolarities of the gamma transitions, and Clebsch-Gordan ratios were used to determine the K quantum numbers in cases where relative transition rates had been measured. Some preliminary γ-γ coincidence studies were attempted which, in general, corroborated the decay scheme; but due to the large number of γ rays no quantitative confidence was placed in the data. The continuous β spectrum was measured and a Fermi plot is presented.

II. SOURCE PREPARATION

In order to attain the resolution that the beta-ray spectrometer afforded (0.05%), sources that presented a smooth, flat circular surface with a diameter of 0.45 mm were prepared by various methods, all of which utilized the technique of evaporation. The source material was evaporated through a 0.45-mm orifice onto polished tips of "bottle"-shaped quartz rods with a 2.2-mm-shank diameter drawn to about 0.6 mm diameter. Previous to the source material evaporation, a very thin layer of Al was evaporated onto the tip and one side of the quartz in order to make a conducting path to ground for the excess charge left on the source due to the electron emission. The evaporations were made at a temperature of about 2100°C (approximately 200°C higher than the evaporation temperature of the

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TABLE I. Conversion electron spectrum. Intensities are normalized to K811.6 keV=100. Error is 10% unless noted otherwise. $B\rho$ values for ΣL lines are for identification only.

$B\rho$	Energy (keV)	Assignment	Intensity	$B\rho$	Energy (keV)	Assignment	Intensity
676.0	38.72	K 88.95	19 300	4513.9	935.5	K 985.8	0.4±0.2
994.2	80.57	L_1 88.95	1820	4570.2	951.3	K1011.6	2.1
997.1	81.01	L_2 88.95	11 200	4630.3	968.0	K1018.3	0.7±0.2
1001.7	81.70	L_3 88.95	10 500	4707.7	990.0	K1040.3	9.3
1037.7	87.25	ΣM 88.95	6100	4739.6	999.0	K1049.3	13.9
1046.7	88.65	ΣN 88.95	1380	4795.3	1014.7	K1064.9	17.7
1048.3	88.90	ΣO 88.95	230	4845.2	1028.8	K1079.0	13.9
1393.1	148.96	K 199.19	150	4857.9	1032.4	ΣL1040.3	1.1±0.2
1604.6	190.81	L_1 199.19	15.6	4889.7	1041.4	ΣL1049.3	1.4±0.2
1606.8	191.25	L_2 199.19	15.3	4944.8	1057.0	ΣL1064.9	2.7±0.4
1610.1	191.94	L_3 199.19	15.3	4994.1	1071.0	ΣL1079.0	2.0±0.2
1851.7	243.5	K 293.7	3.6	5107.1	1103.1	K1153.3	6.7
3046.7	535.6	K 585.8	1.4±0.8	5109.2	1103.7	K1153.9	14.5
3099.0	549.3	K 599.5	8.7	5158.8	1117.8	K1168.0	4.8
3259.1	591.6	ΣL 599.5	0.9±0.3	5257.1	1145.8	ΣL1153.3, 1153.9	3.1
3275.7	596.0	K 646.2	21.4	5377.6	1180.2	K1230.4	7.3
3433.9	638.3	ΣL 646.2	2.9±0.3	5418.2	1191.8	K1242.1	6.0
3513.4	659.7	K 709.9	12.1	5525.4	1222.5	ΣL1230.4	0.6±0.2
3563.0	673.1	K 723.3	17.0	5541.1	1227.0	K1277.2	2.6
3669.6	702.0	ΣL 709.9	2.0	5565.9	1234.1	ΣL1242.1	0.9
3718.8	715.4	ΣL 723.3	2.2±0.4	5850.7	1315.9	K1366.1	1.4±0.2
3835.2	747.2	K 797.4	0.9±0.1	7607.8	1826.3	K1876.5	2.8±0.3
3887.0	761.4	K 811.6	100.0	7815.2	1887.0	K1937.2	3.0
4040.6	803.7	ΣL 811.6	14.3	7911.4	1915.2	K1965.4	5.2
4056.5	808.1	K 858.3	1.4±0.8	8118.6	1975.9	K2026.1	4.5
4062.6	809.8	K 860.0	2.6±0.8	8360.6	2047.0	K2097.2	4.1
4084.0	815.7	K 865.9	1.1±0.3	8644.0	2130.3	K2180.5	2.2
4087.9	816.8	K 867.0	2.7±0.6	8663.7	2136.1	K2186.3	4.0
4422.9	910.0	K 960.3	7.4				

source material in order to assure complete evaporation) and pressure of about 10^{-5} mm of Hg. The raw material for the source was spectrographically pure europium +3 oxide enriched in the 153 isotope by mass spectrographic separation at Oak Ridge, Tennessee (5.0±0.1% $Eu_2^{151}O_3$, 95±0.1% $Eu_2^{153}O_3$).

Although many sources were prepared, two sources were selected for use in the internal conversion studies, one with a thickness of 1 mg/cm² and the other with the thickness of 40 μg/cm². The thickness of the 1 mg/cm² source was determined by using constant evaporating conditions (i.e., fixed geometry, tank pressure, and evaporating temperature) and evaporating a known amount from the crucible. The amount of Eu_2O_3 collected was then determined chemically[21] by forming the water-soluble $EuCl_3$, adjusting the pH to 8.4 with phenol red, adding an acetic-ammonium acetate buffer solution, and allowing the color of alizarin red S-$EuCl_3$ complex to develop. The optical density of the complex solution was then measured in a 5-cm path-length cuvette with a Beckman D. U. Spectrophotometer. By subtracting the optical density due to a reagent-blank sample, and running various standard $EuCl_3$ solutions, the amount Eu_2O_3 collected was then determined. It was found that about 2% was deposited onto the source tip. The 40-μg/cm² source was obtained by evaporating a sample of radioactive Eu_2O_3 onto several quartz rods simultaneously. The rods were placed at angles of 0°, 30°, 45°, and 60° to the vertical center line of the crucible. By measuring the radiation from the known amount (48 μg) before evaporation and measuring the radiation from each source afterwards, the thickness was determined. The 40-μg/cm² source was the thinnest source from this set.

Gamma lines were measured by utilizing the technique of external conversion. The external conversion lines were studied by using an 0.8-mg/cm² uranium converter with a diameter of 0.8 mm on an aluminum foil backing of 0.12 mm thickness with an absorber of platinum which was 0.18 mm thick. The source weighed about 40 μg and was embedded in quartz, with a mean

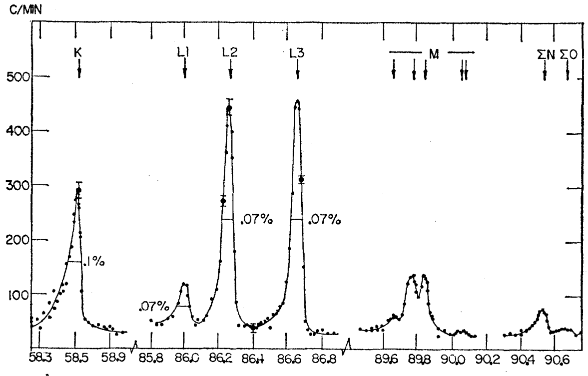

FIG. 1. 88.95-keV conversion electron spectrum. Counter window absorption and source thickness effects are apparent for the K line (38.7 keV). The uncertainties for the M, N, and O lines are roughly the size of the plotted points (~±2 counts/min).

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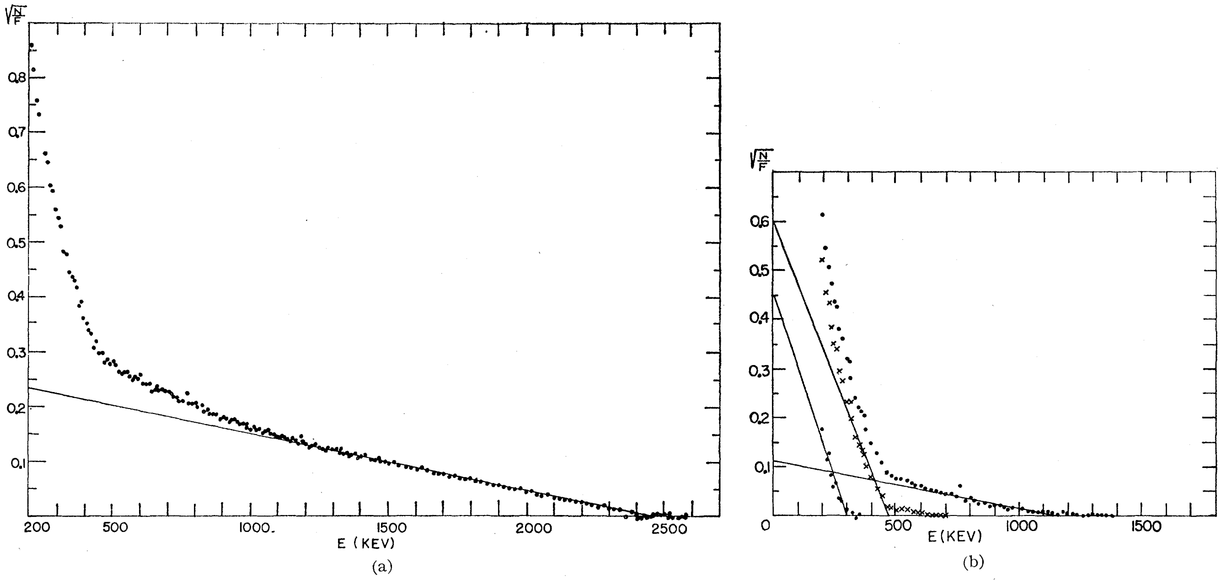

FIG. 2. (a.) Fermi plot of the 2450-keV β component. Each plotted point is an average of six experimental points. The plot from ~1200 to 2450 keV is linear, although $\log_{10}$ (ft) ~10. (b.) Fermi plot of the 1140-, 470-, and 300-keV β components. The β spectrum was not scanned below 200 keV.

distance of about 0.6 mm from the converter. The exact source-converter geometry was very difficult to measure due to the irregular shape of the source. However, relative measurements of γ intensities were possible.

The sources were exposed to a thermal-neutron flux of about 4×10^{14} n/cm^2 sec in the Arco MTR reactor for 16 days. Quartz was used as a source backing because of its small cross section for thermal neutrons and because the activities produced by thermal neutrons on quartz all have very short half-lives compared to the activity of Eu^{156}. Eu^{156}, with a 15-day half-life, is produced by a $3n$-γ reaction on Eu^{153}. The production of Eu^{156} in this manner has a nearly cubic dependence on the neutron-flux density and exposure time. The resulting specific activity of the Eu^{156} was not too high, but this method of source production had the advantage that chemical separation was not necessary and, with repeated irradiations, the specific activity was higher than the preceding irradiation due to the build-up of the longer lived Eu^{154} and Eu^{155}.

III. EXPERIMENTAL PROCEDURE

The electron spectrum was surveyed twice from approximately 30 to 2500 keV at about 1% resolution in the lens spectrometer at the Lawrence Radiation Laboratory at Livermore, California.[22] The transition energies were studied by utilizing the high resolution (0.06-0.1%) of the Davis precision spectrometer[23] to measure the internal conversion electrons of the excited states of Gd^{156}. In all the transition energies studied, the conversion electrons from the K shell were observed. (Table I.) Whenever the electron intensity allowed, the L lines were observed also. In the case of the 88.95-keV line, the K through O lines were observed. (Figure 1.) All electron lines reported were rescanned at a later time and were observed to decay with a half-life of about 15 days. The only lines found that were not from Gd^{156} were from the longer lived isotopes of Eu which were produced from the n-γ and $2n$-γ reactions of Eu^{153}.

The continuous β spectrum was obtained from two sets of scans on the Davis spectrometer from which a Fermi plot was calculated (Fig. 2). It is possible that there may be small errors in the end-point energies and intensities of the spectrum below 1 MeV since the source used for the β spectrum had a thick backing. Each set of β spectrum runs consisted of an initial scan when the source was fresh and a final scan after the internal and external conversion runs were completed. This procedure allowed maximum use of the sources. The contribution to the β spectrum from the longer lived isotopes of Eu was then subtracted from the total spectrum, thereby allowing a determination of the Eu^{156} β spectrum.

IV. TREATMENT OF DATA

A. Transition Energies

The $B\rho$ values of the lines, as seen in the Davis instrument, are obtained absolutely. The instrument is an iron-free solenoid and its field is measured and kept constant by nuclear magnetic resonance techniques, thereby allowing calculable $B\rho$ values.[23] The calculations are based on physical constants as reported by

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[22] We are indebted to Dr. H. West and Dr. L. Mann of that laboratory for making this equipment as well as gamma-gamma coincidence apparatus available to us.

[23] J. A. Jungerman, M. E. Gardner, C. G. Patten, and N. F. Peek, Nucl. Instr. Methods **15**, 1 (1962).

TABLE II. K/L and L subshell ratios. Theoretical values of L. A. Sliv and I. M. Band[a] are given for comparison. For the 709.9-keV transition an $E0$ assignment gives[b] $K/L=7.3$.

E_γ(keV)	Ratio	Experimental	Theoretical $E1$	$E2$	$M1$
88.95	$K/L_{\rm I}$	10.6 ± 0.8	9.7	11.0	7.3
	$K/L_{\rm II}$	1.72 ± 0.14	43	1.82	93
	$K/L_{\rm III}$	1.84 ± 0.15	34	1.88	52
	$L_{\rm I}/L_{\rm II}/L_{\rm III}$	$1/(6.2\pm0.6)/(5.8\pm0.6)$	1/0.2/0.3	1/6.0/5.9	1/0.08/0.01
199.19	$K/L_{\rm I}$	9.6 ± 2.8	9.1	10.0	7.7
	$K/L_{\rm II}$	9.8 ± 2.8	72	8.1	102
	$K/L_{\rm III}$	9.8 ± 2.8	61	10.1	612
	$L_{\rm I}/L_{\rm II}/L_{\rm III}$	$1/(0.98\pm0.28)/(0.98\pm0.28)$	1/0.13/0.15	1/1.23/0.98	1/0.075/0.012
599.5	$K/\Sigma L$	9.6 ± 3.1	7.3	5.8	7.0
646.2	$K/\Sigma L$	7.4 ± 0.7	7.3	5.9	7.0
709.9	$K/\Sigma L$	6.1 ± 1.3	7.3	6.0	7.0
723.3	$K/\Sigma L$	8.0 ± 1.4	7.3	6.1	7.0
811.6	$K/\Sigma L$	7.0 ± 0.4	7.3	6.3	7.0
1040.3	$K/\Sigma L$	8.6 ± 1.2	7.3	6.6	6.9
1049.3	$K/\Sigma L$	9.8 ± 1.7	7.3	6.6	6.9
1064.9	$K/\Sigma L$	6.6 ± 0.9	7.3	6.6	6.9
1079.0	$K/\Sigma L$	7.0 ± 0.8	7.3	6.6	6.9
1230.4	$K/\Sigma L$	12.0 ± 4.0	7.3	6.6	6.9
1242.1	$K/\Sigma L$	6.7 ± 1.5	7.3	6.7	6.9

[a] L. A. Sliv and I. M. Band, *Tables of Internal Conversion Coefficients* (Academy of Sciences USSR Press, Moscow, 1956).
[b] See Ref. 28.

Cohen to Breivogal and Holtz.[24] The reproducibility of line positions is well within 1 part in 10^4 over a long period. The limiting factor in determining the line energy is the electron intensity of the line. The estimated uncertainty in energy is about 2 parts in 10^4. In general, the transition energies reported here agree within experimental error with values determined by Ewan *et al.*,[10] although they are systematically lower by 1 to 2 parts in 10^4.

B. Source Thickness

The majority of lines were seen with the 1-mg/cm^2 source, which, because of its excessive thickness, broadened them and shifted their positions downward in energy. The more intense lines were observed with the 40-μg/cm^2 source and a correction curve (Fig. 3), was prepared from these data which was used to correct the energies obtained from the 1-mg/cm^2 source.

C. Conversion Electron Intensities

Electron intensities were computed by utilizing area measurements normalized with the proper $B\rho$ values. Intensities presented in Table I are given relative to the intensity of the 811.6-keV K electron line. (Intensity of the 811.6-keV K line$=100$.) The uncertainties are within $\pm10\%$ unless otherwise stated. The detector used in the spectrometer was a Geiger counter with a 1 mg/cm^2 aluminized Mylar window with the electron beam striking the window at about 23° from the normal to its face. Therefore, the apparent window thickness was about 1.1 mg/cm^2. An intensity correction was necessary below about 100 keV. The work of Geiger *et al.*[25] was used as a guide to calculate the window transmission coefficients. The window absorption problem becomes quite apparent in the case of 88.95-keV transition (Fig. 1). The K line (38 keV) is reduced in intensity by 35%.

D. Multipolarities and Intensities of Gamma Rays

The multipolarities of the transitions were determined by L subshell ratios and K/L ratios (whenever statistical errors allowed) (Table II), external conversion

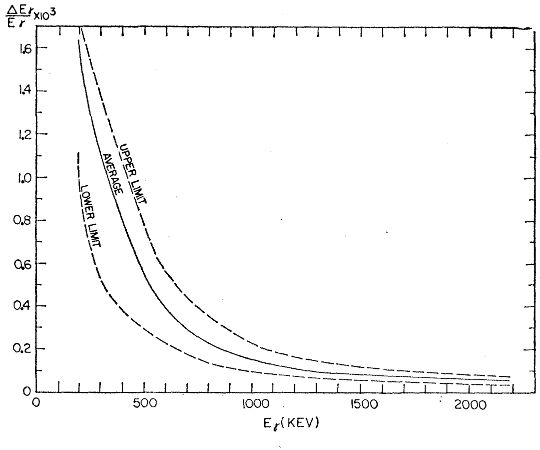

FIG. 3. Source-thickness correction curve. Differences of internal-conversion electron line energies observed from scans with the 1 mg/cm^2 and 40 μg/cm^2 sources were taken. A plot of $\Delta E_\gamma/E_\gamma$ (relative energy shift due to the excessive thickness of the 1 mg/cm^2 source) is shown. The dashed lines represent an upper and lower limit to the relative energy shift. The correction shown is the extrapolated value for zero thickness.

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[24] F. W. Breivogel and M. D. Holtz, University of California Radiation Laboratory Report No. UCRL 10494, 1962 (unpublished).

[25] J. S. Geiger, R. L. Graham, and G. T. Ewan, Nucl. Phys. **16**, 1 (1960).

TABLE III. Gamma-ray intensities. Intensities are given in % per disintegration. All conversion coefficients are given $\times 10^4$.

Gamma-ray energy (keV)	I_ϵ[a]	I_γ[b]	α_k	α_k Theoretical[c] $E1$	$E2$	$M1$	Assigned multipolarity	I_γ[d]
88.95	13.1						$E2$	9.3
199.19	0.10						$E2$	0.6
293.7	0.0025							
585.8	0.0009±0.0005							
599.5	0.0059	1.7±0.5	35±11	28	71	140	$E1$	2.1
646.2	0.0144						$E1$	6.4
709.9	0.0082	−1±1						
723.3	0.0115	7.7±1.0	15± 2	18	47	86	$E1$	6.5
797.4	0.0005						$E2$[e]	0.2
811.6	0.068						$M1$	10.5
858.3	0.0009±0.0005						$E2$[e]	0.3
860.0	0.0018±0.0005							
865.9	0.0007±0.0003						$E2$[f]	0.3
867.0	0.0019±0.0004						$E1$[f]	1.4
960.3	0.0051	4.2±1.5	12±5	11	25	44	$E1$	4.6
985.8	0.0005±0.0003							
1011.6	0.0015							
1018.3	0.0005±0.0002							
1040.3	0.0063	−1±1						
1049.3	0.0095	−3±3					$E2$[e]	4.3
1064.9	0.0120	4.7±1.4	26±9	8.8	21	34	$E2$	5.9
1079.0	0.0095	5.9±1.5	16±4	8.6	21	34	$E2$	4.6
1153.3	0.0046	8.6±2.0	5.3± 1.3	7.5	18	28	$E1$	6.2
1153.9	0.0098						$E2$	5.6
1168.0	0.0032	−2±2		7.1	17	27	$E2$[e]	2.0
1230.4	0.0050	10.2±1.7	4.9± 0.8	6.8	16	24	$E1$	7.4
1242.1	0.0041						$E1$	6.2
1277.2	0.0018						$E1$[f]	2.8
1366.1	0.0010±0.0002						$E1$[f]	1.7
1876.5	0.0019	2.8±0.5	6.7± 1.1	3.3	7.0	9.3	$E2$[e]	2.7
1937.2	0.0021						$E2$[e]	3.1
1965.4	0.0035						$E2$[e]	5.5
2026.1	0.0031	3.0±2.5	10± 8	3.0	6.1	7.6	$E2$[e]	5.0
2097.2	0.0028	4.2±0.5	6.6± 0.8	2.8	5.6	7.0	$M1$	4.0
2180.5	0.0015	1.9±0.7	7.9± 3.2	2.6	5.3	6.5	$M1$	2.3
2186.3	0.0027	3.6±0.6	7.6± 1.4	2.6	5.3	6.5	$M1$	4.3

[a] K conversion electron intensity (error in 10% unless otherwise noted).
[b] From external conversion data.
[c] L. A. Sliv and I. M. Band *Tables of Internal Conversion Coefficients* (Academy of Science USSR Press, Moscow, 1956).
[d] Calculated from multipolarity assignment and I_ϵ.
[e] Assumed assignment for intensity calculation.
[f] Inferred from decay scheme.

studies (Table III), and in some instances Clebsch-Gordan ratios (Table IV). When none of the above techniques were satisfactory, the multipolarities were inferred from the decay scheme.

Gamma-ray intensities were calculated from electron intensities after the multipolarity of the transition was determined. The transition intensities were then calculated assuming the 2450-keV β spectrum component to be 29.5% of the total. Gamma-ray intensities were determined empirically by external-conversion technique, but the errors are in general larger than those from internal-conversion data. Gamma-ray intensities obtained from these data are shown in column 3 of Table III, whereas intensities calculated from assigned multipolarities and conversion electron intensities are given in column 9.

The external-conversion source geometry is described in Sec. II. The following procedure was used to obtain gamma-ray intensities from external-conversion lines: An empirical efficiency curve for observing external-conversion versus gamma-ray energy was obtained using four prominent gamma rays (646.2, 811.6, 1242.1, and 1965.4 keV), whose multipolarities were determined by other means. The 811.6-keV external-conversion line is shown in Fig. 4 and the efficiency curve is Fig. 5.

Using the efficiency curve, the gamma intensity of an unknown line relative to the 811.6-keV gamma ray I_x can be determined from the relation

$$E_x = \epsilon_x I_x .$$

E_x is the area of the external-conversion line relative to the area of the 811.6-keV line, and ϵ_x is the relative efficiency at various gamma ray energies of the beta-ray spectrometer using the fixed external-conversion geometry.

For the calibration points, the relative gamma-ray intensity Γ_c is calculated from

$$\Gamma_c = I_c \alpha_{811.6} / \alpha_c .$$

I_c is the internal-conversion intensity of the calibration line relative to the 811.6-keV line, α_c is its K internal conversion coefficient, and $\alpha_{811.6}$ is the K internal con-

TABLE IV. Reduced transition probabilities. Theoretical branching ratios are compared with observation.

Transition pair (keV)		Reduced transition probability ratio experimental	theoretical $K_i=0$	$K_i=1$	$K_i=2$
2097.2($E2$) 2186.3($E2$)	$2+\rightarrow 2+$ $2+\rightarrow 0+$	1.18	1.43	0.36	1.43
2097.2($M1$) 2186.3($M1$)	$1+\rightarrow 2+$ $1+\rightarrow 0+$	1.09	2.00	0.50	
1937.2($E2$) 2026.1($E2$)	$2+\rightarrow 2+$ $2+\rightarrow 0+$	0.68	1.43	0.36	1.43
1937.2($M1$) 2026.2($M1$)	$1+\rightarrow 2+$ $1+\rightarrow 0+$	0.62	2.00	0.50	
1876.5($E2$) 1965.4($E2$)	$2+\rightarrow 2+$ $2+\rightarrow 0+$	0.62	1.43	0.36	1.43
1876.5($M1$) 1965.4($M1$)	$1+\rightarrow 2+$ $1+\rightarrow 0+$	0.56	2.00	0.50	
1277.2($E1$) 1366.1($E1$)	$1-\rightarrow 2+$ $1-\rightarrow 0+$	2.07	2.00	0.50	
1153.3($E1$) 1242.1($E1$)	$1-\rightarrow 2+$ $1-\rightarrow 0+$	1.25	2.00	0.50	
1079.0($E2$) 1168.0($E2$)	$2+\rightarrow 2+$ $2+\rightarrow 0+$	3.44	1.43	0.36	1.43
1079.0($M1$) 1168.0($M1$)	$1+\rightarrow 2+$ $1+\rightarrow 0+$	2.93	2.00	0.50	
1064.9($E2$) 1153.9($E2$)	$2+\rightarrow 2+$ $2+\rightarrow 0+$	1.56±0.15	1.43	0.36	1.43
865.9($E2$) 1064.9($E2$)	$2+\rightarrow 4+$ $2+\rightarrow 2+$	0.13±0.04	1.80	3.20	0.05
646.2($E1$) 723.3($E1$)	$1+\rightarrow 2-$ $1+\rightarrow 1-$	1.38	1.00	1.00	
646.2($E1$) 723.3($E1$)	$2+\rightarrow 2-$ $2+\rightarrow 1-$	1.38	5.00	0.56	0.56
1153.3($E1$) 1230.4($E1$)	$1-\rightarrow 2+$ $2-\rightarrow 2+$	1.01		0.33	

version coefficient of the 811.6-keV $M1$ transition (6.5×10^{-3}).

The 811.6- and 646.2-keV gamma rays were assumed to be pure $M1$ and $E1$ transitions, respectively, as determined from K/L ratios. The 1242.1-keV gamma ray is a transition from a negative parity level to the 0+ ground-state level and is assumed $E1$. Although the possibility of anomalous conversion coefficients for $E1$ transitions exists, the effect was found mainly in the low-energy region (~100 keV) where the transitions were highly retarded.[26] For the efficiency calculations in the present work (~1 MeV) this effect was ignored since the transitions were from collective states and not expected to be hindered appreciably. The parity of the 1965.5-keV level is positive, but the multipolarity of the gamma ray could be either $M1$ or $E2$. The former choice gives conversion coefficients larger than for $M1$ for several other gamma rays in the 2-MeV region (see

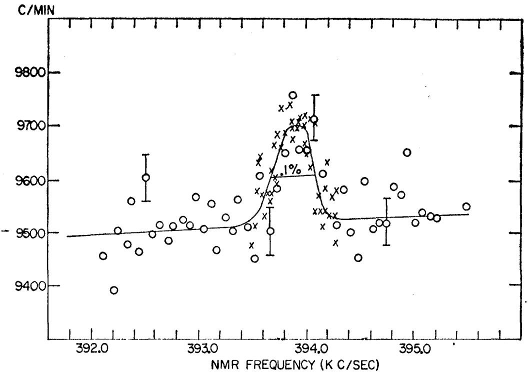

FIG. 4. 811.6-keV external-conversion line. The counting time for each experimental point was 5 min with an uncertainty for each point of ±44 counts per min. The circles represent the first pass over the line and the crosses represent a second pass. The line was measured at a resolution of 0.1%. A uranium converter of 0.8 mg/cm² was used.

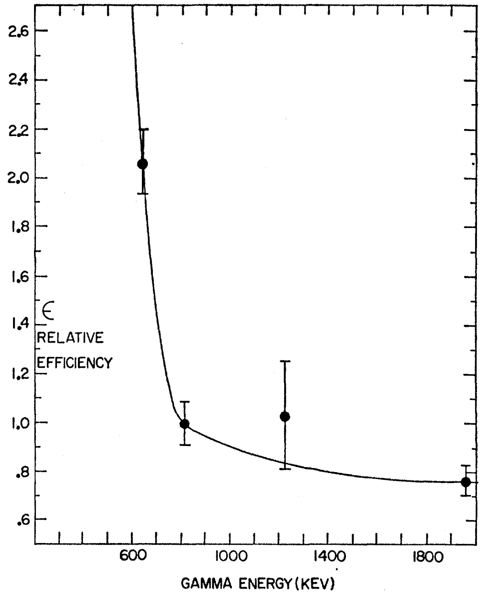

FIG. 5. External-conversion efficiency curve. The relative spectrometer efficiency for measuring photoelectric electrons from a uranium converter is plotted against the gamma-ray energy. Four lines were taken as standards (646.2-keV $E1$, 811.6-keV $M1$, 1242.1-keV $E1$, and 1965.4-keV $E2$).

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[26] S. G. Nilsson and J. O. Rasmussen, Nucl. Phys. 5, 617 (1958).

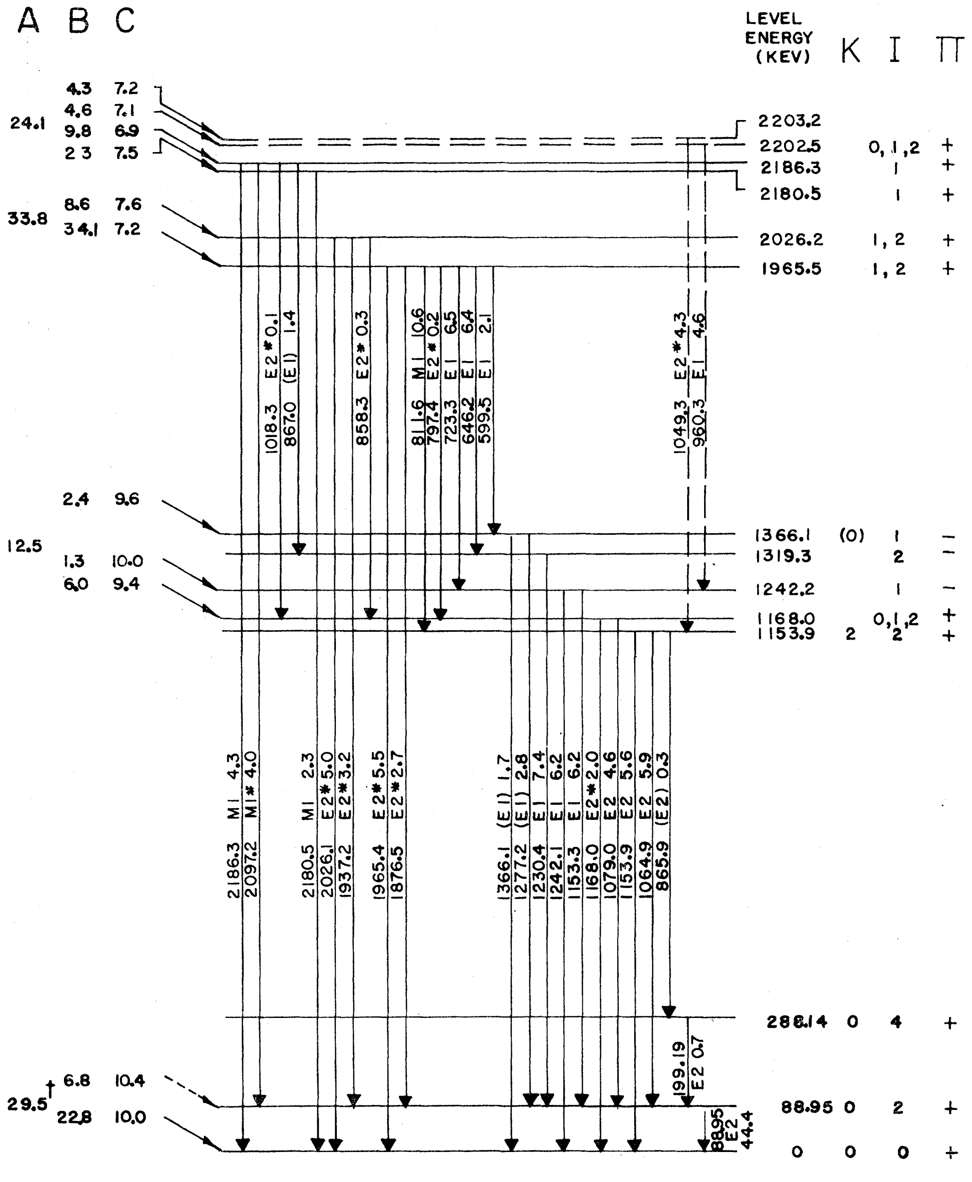

FIG. 6. Decay scheme. Intensities are given as percent per Eu^{156} disintegration assuming 29.5% β decay to the ground-state rotational band. Energies are given in keV. Column A: β population (%) as deduced from Fermi plot. Column B: β population (%) as calculated from the gamma-ray balance. Column C: Log$_{10}(ft)$ values †: Log$_{10}$ $(ft)=9.9$ assuming 29.5% β population 0+ state. *: Assumed assignment for intensity calculations. ( ): Inferred from decay scheme.

Sec. V), so $E2$ multipolarity has been assumed for the 1965.5-keV gamma ray.

To compare external conversion areas relative to the 811.6-keV line shape, an IBM-1620 computer program was written. This program adjusts the amplitude and position of the unknown line to minimize the residuals resulting from comparison of data points of the unknown with the 811.6-keV external-conversion prototype shape. In all cases line positions were within a few parts in 10^4 of their predicted positions (using internal-conversion data to calculate the gamma-ray energy).

The error made in determination of the gamma intensities includes statistical error in the external-conversion line and background (weak lines have large relative errors due to this cause). An additional possible systematic error of 24% has been assumed in determining the efficiency from Fig. 5. This systematic error was reduced to 10% in the 2-MeV region since there the efficiency curve is slowly varying with energy. The curve has the general shape to be expected from the decrease in photoelectric cross section with energy combined with increased spectrometer efficiency for transmitting the photoelectrons as their intensity maximum moves forward relativistically.

In evaluating the intensity of the 1153.3-keV line, the 1153.9-keV transition was assumed $E2$. The corresponding position and amplitude of the expected contribution in external conversion of the 1153.9-keV gamma ray was then subtracted from the measured external conversion line (which contained both lines unresolved, resolution 0.13%).

TABLE V. Energy-level determination. An average obtained from the several cascading gamma rays that proceed from a level were used to calculate the level energy. It will be noted that individual values for a given energy level agree within ±1 part in 10^4.

Sum γ's (keV)						Crossover γ (keV)	Level (keV)
865.9							
199.19	1064.9						
88.95	88.95						
1154.04	1153.85					1153.9	1153.9
1079.0							
88.95							
1167.95						1168.0	1168.0
1153.3							
88.95							
1242.25						1242.1	1242.2
1277.2							
88.95							
1366.15						1366.1	1366.1
	646.2						
599.5	1230.4	723.3	811.6	1876.5	797.4		
1366.1	88.95	1242.1	1153.9	88.95	1168.0		
1965.6	1965.55	1965.4	1965.5	1965.45	1965.4	1965.4	1965.5
858.3	1937.2						
1168.0	88.95						
2026.3	2026.15					2026.1	2026.2
867.0							
1230.4	2097.2	1018.3					
88.95	88.95	1168.0					
2186.35	2186.15	2186.3				2186.3	2186.3

V. DECAY SCHEME

The basic-decay scheme (Fig. 6) was determined by energetics, and further developed by multipolarity assignments resulting from K to L ratios (Table II), external-conversion studies (Table III), and branching ratios to levels of the same rotational band as calculated by Clebsch-Gordan ratios. Table V illustrates the linearity of the β-ray spectrometer and demonstrates the ability to use energy considerations in determining the levels in the decay scheme. The sums of the cascade gamma rays were averaged with the crossover gamma ray to determine the level energy. (In the case of the 1965.5-keV level, seven sums were averaged.)

The 88.95- and 288.14-keV levels have previously been shown to be the first and second excited levels of the ground-state rotational band by Coulomb excitation and coincidence studies.[14–18] The present study has confirmed the pure $E2$ multipolarity of the transitions 88.95 and 199.19 keV by analysis of ratios of K and L subshell intensities (Table II).

The 1153.9-keV level assignment is $n_\gamma = 1$ $(K,I,\pi, = 22+)$, and is assumed to be the lowest state of the γ vibrational band. This level is fed by the 1049.3-keV transition from the 2203.2-keV level[10] and the 811.6-keV ($M1$) transition from the 1965.5-keV level. The level is depopulated by the 1153.9 $E2$, 1064.9 $E2$, and 865.9-keV transitions to the 0+, 2+, and 4+ levels of the ground-state rotational band. The 811.6-keV transition is found to be $M1$ by K/L ratios. External conversion studies indicate $E2$ with possible $M1$ mixing for the multipolarity of the 1064.9-keV transition. Clebsch-Gordan ratios shown in Table IV indicate a $K=2$ assignment to this level as most probable in agreement with other workers.[10,20] However, there appears to be an enhanced transition probability to the 4+ level compared to that predicted for a pure $K=2$ assignment.

The 1168.0-keV level assignment is $I=0$, 1 or 2+. This level is fed by transitions (797.4 $E2$, 858.3, 1018.3 keV) from the 1965.5-, 2026.2-, 2186.3-keV levels, and is depopulated by transitions (1168.0-, 1079.0-keV $E2$) to the 0+ and 2+ levels, respectively, of the ground-state rotational band. The most probable multipolarity assignment for the 1079.0-keV transition is $E2$. External-conversion data indicate a value of α_k favoring an $E2$ over an $E1$ transition and the K/L ratio also favors $E2$. If the 1079.0- and 1168.0-keV transitions have the same

TABLE VI. Calculated intensities for depopulation of the 1319.3- and 2180.5-keV levels.

Transition pair considered (keV)		Line (keV)	Expected intensities (% per disintegration) $K_i=0$	$K_i=1$	Observed intensity
1230.4($E1$)	$1- \rightarrow 2+$	1319.3	4.55	18.2	≤ 1.2
1319.3($E1$)	$1- \rightarrow 0+$				
1031.4($E1$)	$3- \rightarrow 4+$	1031.4	5.79	3.26	≤ 0.2
1230.4($E1$)	$3- \rightarrow 2+$				
2091.6($M1$)	$1+ \rightarrow 2+$	2091.6	4.10	1.02	≤ 0.5
2180.5($M1$)	$1+ \rightarrow 0+$				

multipolarity, Clebsch-Gordan ratios favor an $M1$ or $E1$ assignment. Therefore, the data indicate that the multipolarity of the two transitions is different. External-conversion data are consistent with an $E0$, $M1$ or $E2$ multipolarity assignment for the 1168.0-keV transition, but an $E1$ assignment appears unlikely.

The 1242.2-keV level is given the assignment $I\pi=1-$. This level is fed by transitions (960.3-keV $E1$, 723.3-keV $E1$) from the 2202.5-[10] and 1965.5-keV levels and is depopulated by transitions (1153.3 $E1$, 1242.1-keV $E1$) to the 0+ and 2+ levels of the ground-state rotational band. External-conversion data are consistent with $E1$ assignments to the 723.3-, 1153.3-, and 1242.1-keV gamma rays, indicating that the level is 1−.

The 1319.3-keV level assignment is 2−. This level is fed by transitions (646.2-keV $E1$, and 867.0 keV) from the 1965.5- and 2186.3-keV levels and is depopulated by a single transition (1230.4-keV $E1$) to the 2+ level of the ground-state rotational band. Searches were made for a possible transition to the 0+ ground state and the 4+ state (1031.4 keV), since the $E1$ transition from the 1965.5-keV 1, 2+ level permits spin and parity of 1−, 2−, or 3− for the 1319.3-keV level. Intensities were calculated from reduced transition probability ratios and are shown in Table VI. Since neither the 1319.3- or the 1031.4-keV transitions were observed, 1− and 3− assignments appear improbable. A 2− assignment requires an $M2$ transition to the 0+ level and decay by $M2$ and $E3$ to the 4+ level. Since these transition probabilities are greatly depressed compared to $E1$, the 2− assignment best fits the observations.

The 1366.1-keV level is populated from the 1965.5-keV (1,2+) level by the 599.5-keV $E1$ transition. The multipolarity of the 599.5-keV gamma ray is determined by external conversion and the assignment is supported by its K/L ratio. The parity of this level is therefore negative. The level is depopulated by the 1366.1- and 1277.2-keV transitions. Since the former transition is to the ground (0+) level, $E1$ multipolarity is inferred for the 1366.1-keV gamma ray and the spin of the level is therefore unity. If one also assumes that the 1277.2-keV multipolarity is $E1$, then the calculated branching ratio to the 0+ and 2+ states indicates an assignment of $K=0$. (See Table IV.)

The 1965.5-keV level is fed by β decay and depopulated by 7 gamma rays (1965.4-keV $E2$, 1876.5-keV $E2$, 811.6-keV $M1$, 797.4 keV, 723.3-keV $E1$, 646.2-keV $E1$, and 599.5-keV $E1$). The parity of the 1965.5-keV level is found to be positive since the level is depopulated by the 723.3-keV ($E1$) and 646.2-keV ($E1$) transitions to negative parity states. This assignment is further confirmed by the 811.6-keV ($M1$) transition to the 1153.9-keV (2+) level. External-conversion studies show the 723.3-keV transition to be $E1$, an assignment supported by its K/L ratio. Also the assignment of a spin of 1 or 2 to this level is consistent with the observed multipolarities of the gamma rays originating from it. A weak transition of 797.4- to the 1168.0-keV level has been observed. Its multipolarity is inferred to be $E2$ or $M1$ or $E2+M1$. A spin-2 assignment has been assumed for this level, being most consistent with the external-conversion data. Since the 1965.5-keV transition is used in the external-conversion calibration curve (Fig. 5), a 1+ assignment to the level would elevate the experimental conversion coefficients of the 1876.5-, 2026.1-, 2097.2-, 2180.5-, and 2186.3-keV gamma rays by a factor of 1.30. The values obtained in most cases would then be higher than the theoretical value for $M1$ (see Table III).

On the other hand there are several theoretical arguments that favor a 1+ assignment to the 1965.5-keV level. The theoretical branching ratio to the 0+ and 2+ levels of the ground-state rotational band are in better agreement with empirical values if the assignment (K, I, $\pi=1$, 1, +, respectively) is used (see Table IV) for 1965.5-keV level. If the 1−, 2− states at 1242.2 and 1319.3 keV are members of a rotational band built on an intrinsic level, the predicted branching ratio is again in better agreement with experiment if the 1965.5-keV level is 1+ (see Table IV). Finally, it may be argued that since beta decay to the 88.95- and 1153.9-keV 2+ state is quite weak, it should be expected that decay to a 2+ state at 1965.5 keV (with less available beta transition energy) would also be weak. But in fact, 34.1% of the beta decay feeds the 1965.5-keV level. Cline and Heath[12] predict the 1+ assignment by gamma-gamma angular correlation measurements.

The 2026.2-keV level is fed by β decay and depopulated through three gamma transitions of 2026.1, 1937.2, and 858.3 keV. The level is assigned an $I=1$, 2 and a positive parity primarily due to the probable $E2$ or $M1$ nature of the 2026.1-keV transition. The multipolarity is determined by external-conversion measurement with a large probable error. Although, an $E1$ assignment is possible, the experimental conversion coefficient favors $M1$ or $E2$. The data for determining the multipolarity of the 1937.2-keV transition were inconclusive. Theoretical branching ratios to the 0+ and 2+ state of the ground-state rotational band favor a 1+ assignment to the 2026.2-keV level (Table IV), but a 2+ assignment is not excluded because the emperical transition ratios are sensitive to band mixing, which is very likely in the 2-MeV excitation region.

The 2180.5-keV level is assigned an $I=1$ and positive parity on the basis of the $M1$ nature of the 2180.5-keV transition. The level is fed by β decay and depopulated to the ground-state level through the 2180.5-keV transition. This gamma ray appears to be $M1$ by external-conversion data. Although a transition to the 88.95-keV 2+ state is expected, a search for the internal-conversion line showed that the transition intensity is less than 0.5% per disintegration for $E2$ (Table VII), whereas one would expect 1.02% for K initial$=1$ (Table VI). Ewan *et al.*[10] show that there is no coincidence between the 88.95- and 2180.5-keV gamma rays, so the transition is presumably to the ground state. Searches were also conducted for gamma rays associated with transitions from the 2180.5 → 1319.3- and 2180.5→ 1242.2-keV levels. The results indicate that both of these gamma rays occur less than 0.3% per disintegration, respectively (Table VII). The possibility that the 2180.5-keV transition is $E0$ is excluded since it was observed in external conversion.

The 2186.3-keV level is assigned an $I=1$ and positive parity from external-conversion data. The level is depopulated by four transitions (2186.3-keV $M1$, 2097.2-keV $E2$ or $M1$ or $E2+M1$, 1018.3 keV, 867.0 keV). Since the observed branching ratio to the 2+, 0+ ground-state band does not agree with calculated rates, (Table IV), band mixing is indicated for the 2097.2-keV transition.

The work of Ewan *et al.*[10] indicates that a level exists at 2203.4-keV and is depopulated by gamma rays of 1049.5 and 960.8 keV to levels at 1154.0 and 1242.4 keV. The present work gives gamma-ray energies of 1049.3 and 960.3 keV and the correspondingly fed levels are 1153.9 and 1242.2 keV. Therefore, two levels are predicted at 2203.2 and 2202.5 keV. It is unlikely that these levels are the same since the level energies obtained by summing different gamma rays agree within 2 parts in 10^4 (see Table V).

Four groups of β spectra were observed by analysis of a Fermi plot (Fig. 2). The 2450±15-keV β group feeds the ground-state rotational band; the 1140±50-keV group, the 1-MeV region; the 470±50-keV group, the 2-MeV region and the 300±70-keV group, the 2.2-MeV region. The gamma balance indicates that the 2.2-MeV region requires 21.0% β population and 24.1% was measured; the 2-MeV region requires 42.7% β's while 33.8% was measured and the 1-MeV region requires 9.7% β feed while 12.5% was measured. The lack of agreement of the measured values with the intensities as required by the gamma balance indicates that due to the thick source and backing the low-energy portion of the β spectrum was enhanced. Ewan *et al.*[10] show by β-γ coincidence measurement that there is no β population to the 2+ level of the ground-state rotational band. From the present work, the gamma balance requires 6.8% β feed into that level. This could be due in part to an incomplete decay scheme since there are seven gamma rays known which could not be integrated into it.

TABLE VII. Unsuccessful searches. Conversion electron intensities observed at predicted positions for assumed transitions are shown. Since null results were obtained, the values given are upper limits to the conversion electron intensities.

Transition	E_γ(keV)	Electron Intensity (% per dis)	Transition Intensity (% per dis)
2203.2 → 88.95	2114.3	≤0.0004	≤0.8($E2$)
2203.2 → 0	2203.2	≤0.0004	≤0.8($E2$)
2202.5 → 88.95	2113.6	≤0.0004	≤0.8($E2$)
2202.5 → 0	2202.5	≤0.0004	≤0.8($E2$)
2186.3 → 1153.9	1032.4	≤0.0003	≤0.1($E2$)
2186.3 → 1049	1137	≤0.0003	≤0.2($E2$)
2186.3 → 1040	1146	≤0.0003	≤0.2($E2$)
2186.3 → 709	1477	≤0.0003	≤0.2($E2$)
2180.5 → 2026.2	154.3	≤0.0004	≤0.002($E2$)
2180.5 → 1319.2	861.0	≤0.0004	≤0.3($E1$)
2180.5 → 1242.2	938.3	≤0.0004	≤0.3($E1$)
2180.5 → 88.95	2091.6	≤0.0003	≤0.5($E2$)
2026.2 → 288.14	1738.1	≤0.001	≤1.5($E2$)
1965.5 → 1040	926	≤0.0003	≤0.1($E2$)
1965.5 → 709	1257	≤0.0003	≤0.2($E2$)
1965.5 → 288.14	1677.4	≤0.0003	≤0.3($E2$)
1366.1 → 1242.2	123.9	≤0.0004	≤0.001($M1$)
1366.1 → 1153.9	212.2	≤0.001	≤0.03($E1$)
1366.1 → 1049	317.1	≤0.001	≤0.02($E1$)
1366.1 → 1040	326.1	≤0.001	≤0.02($E1$)
1319.3 → 1168.0	151.5	≤0.0004	≤0.002($M1$)
1319.3 → 288.14	1031.4	≤0.0003	≤0.2($E3$)
1319.3 → 0	1319.3	≤0.0002	≤1.2($M2$)
1242.2 → 1153.9	88.3	≤0.0004	≤0.002($E1$)
1242.2 → 1049	193	≤0.001	≤0.03($E1$)
1242.2 → 709	533	≤0.001	≤0.4($E1$)
1242.2 → 288.18	954	≤0.0004	≤0.08($E3$)
1168.0 → 709	459	≤0.001	≤0.05($E2$)
1168.0 → 288.14	879.8	≤0.0002	≤0.07($E2$)
1153.9 → 1040	114	≤0.0004	≤0.001($E2$)
1040 → 88.95	951.1	≤0.0001	≤0.05($E2$)
709.9 → 88.95	621.0	≤0.0001	≤0.02($E2$)

VI. DISCUSSION

Thirty-six transitions associated with the 15-day decay of Eu^{156} have been observed; the decay scheme accommodates 29. Three (585.8, 860.0, and 1011.6 keV) cannot be accounted for and four (1040.3, 985.8, 709.9, and 293.7 keV), have been given possible assignments, but were not included in the decay scheme.

External-conversion studies on the 709.9-keV transition show, as in the case of the 1040.3-keV transition, very little gamma-ray intensity. Sheline[27] predicts the ground state of the β vibrational band (0, 0+) to be around 800 keV, so that the possibility exists that the 709.9-keV transition is $E0$ and would establish the $n_\beta=1, 0, 0+$ level. Several searches were made in order to establish some population into that level (2186.3 → 709.9, 1965.5 → 709.9, 1242.2 → 709.9, 1168.0 → 709.9 keV) with null results (Table VII). Since an $E0$ transi-

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[27] R. K. Sheline, Rev. Mod. Phys. **32**, 1 (1960).

tion would proceed only by conversion electrons, and the feeding to the 0+ level would probably be by a transition of $E1$, $E2$, or $M1$ multipolarity, one would expect that the corresponding conversion electrons would be very difficult to see. A search was made for the $709.9 \rightarrow 88.95$ transition (621.0 keV) which showed its intensity to be $\leq 0.03\%$ (Table VII). Church and Weneser[28] predict that the transition probability for an $E2$ is 3 orders of magnitude less than that of an $E0$ transition. It is possible that the $E2$ enhancement due to collective motion is not large enough to produce a measurable conversion electron line.

The 1040.3- and 985.8-keV lines appear to be cascading transitions from the 2026.2-keV level to the 0+ level of the ground-state rotational band by energetics considerations ($1040.3+985.8=2026.1$ keV). From the available data, however, it is impossible to determine which of the two transitions follows the other. If one assumes an $E1$ multipolarity for the 1040.3-keV gamma ray, its intensity would be 6.8% per Eu^{156} disintegration. External conversion data are not consistent with this assignment. In fact there were three external-conversion runs made in the 1040-keV region and the average intensity found was less than that predicted with an $M1$ assignment (1.7%). It can be concluded, therefore, that the parity of the level (whether 1040.3 or 985.8 keV) is positive.

Yoshizawa *et al.*[29] give evidence from Coulomb excitation studies for a 0+ level at 1040 keV. Such evidence is consistent with the work reported here, if the 985.8- and 1040.3-keV transitions are not in cascade. Since conversion electrons corresponding to the transition $1040.3 \rightarrow 88.95$ keV were not observed (see Table VII), the 0+ assignment is further supported. Depopulation of the proposed 1040-keV 0+ level by an $E0$ transition is not sufficient to account for the feeding by the 985.8-keV gamma ray if these transitions are in cascade.

The 293.7-keV gamma ray could be the 6+ to 4+ transition in the ground-state rotational band. The only evidence that was found for this transition was that based on energetics. This transition would set the 6+ level at 581.8 keV. The 6+ level was found to have an energy of 584 keV by Hansen *et al.*,[20] 581 keV by Ofer,[2] and 585 keV by Mihelich *et al.*[9] (all from Tb^{156} decay). A feed was not found for this level, but on the other hand it is a very weak transition (0.03%) and one would expect that such a high spin state (6+) would be quite weakly fed, especially when the parent nucleus (Eu^{156}) has a ground-state spin of zero.[10]

The 6+ level of the ground-state rotational band is predicted to be at 578 keV by utilizing the rigid rotator energy-level formula and correcting for the coupling of the rotational mode of motion with other modes (vibrational or particle)

$$E_I=(\hbar^2/2\mathcal{J})I(I+1)-BI^2(I+1)^2.$$

This formula gives the moment of inertia as 1.5×10^{-47} g cm^2 and the coupling constant $B=29.9$ eV, by using the energy levels determined for the 2+ and 4+ states of the ground-state rotational band. The same data, along with the 1153.9-keV (2+) level, give the nonaxiality parameter, $\gamma=10.5°$ with the nonadiabaticity parameter, $\mu=0.26$ for the asymmetric rotator model of Davydov and Filippov.[30,31] This model, with the above parameters predicts the 6+ level of the ground-state rotational band to be at 578 keV as does the rigid rotator calculation.

The 1242.2-keV (1−) and 1319.3-keV (2−) levels may form part of a rotational band built on an intrinsic level with $K=1$ (Table IV). The branching ratio fits the experimental value best if the 1965.5-keV level is given a 1+ assignment. On the other hand, branching from these states to the 88.95-keV (2+) level is poorly predicted. The level spacing, 77.1 keV, is reasonable in that increased moments of inertia are expected at higher nuclear excitations.

The energy levels in the 2-MeV region all seem to have low spin and positive parity. $M1$ transitions are observed from the 2186.3- and 2180.5-keV levels which indicate that these levels are due to single particle excitations.

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