PHYSICAL REVIEW C VOLUME 10, NUMBER 5 NOVEMBER 1974

Levels in ^{158}Gd populated in the decay of 46-min ^{158}Eu

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(Received 10 June 1974)

The series of investigations of level properties in even gadolinium nuclei has been extended to ^{158}Gd. γ rays emitted in the radioactive decay of ^{158}Eu were studied with large volume Ge(Li) detectors in both singles and coincidence modes to reveal a total of 132 transitions, 94 of which were incorporated in a level scheme involving 31 excited states. Several of the level assignments clarified conflicting data in the literature and 12 of the levels had not been observed previously. The coincidence measurements have provided reliable branching ratios for members of the γ-vibrational band and members of $K = 0^-$ and 1^- octupole bands. Analyses of the data for the octupole bands are compared with theory. In ^{154}Gd and ^{156}Gd the $K = 0^-$ octupole band lies lower than the $K = 1^-$ band, in agreement with theoretical expectations that the $K = 0^-$ component of the $\lambda = 3$ vibration is the most collective. However, in ^{158}Gd this trend is reversed and the $K = 1^-$ component is lowest.

[RADIOACTIVITY ^{158}Eu [from ^{160}Gd(d, α)]; measured E_γ, I_γ, γ-γ coin; deduced $\log ft$. ^{158}Gd deduced levels, J, π. Enriched target, Ge(Li) detectors.]

I. INTRODUCTION

The present work is part of a systematic investigation of the level properties of nuclei just at the beginning of the deformed region. Previous studies by this and other groups (for example, see Refs. 1–9) have shown the difficulties in explaining the properties of the vibrational states in ^{152}Sm, ^{154}Gd, and ^{156}Gd.

We have now extended these studies to the levels of ^{158}Gd populated by the radioactive decay of 46-min ^{158}Eu which has a very large available decay energy (Q value ≈ 3500 keV). This investigation not only has provided insight into some of the specific levels of interest, but in addition has yielded the properties of many other levels, some of which may have a strong interactive influence on the vibrational states.

This is the first comprehensive investigation of ^{158}Eu by present day high resolution techniques. Previous studies included scintillation spectrometry measurements on ^{158}Eu by Schima and Katoh[10] and Daniels and Hoffman[11] who also used a small-volume Ge(Li) detector to obtain γ-ray singles. Higher spin levels were studied by (n,γ) experiments,[12–16] by internal conversion following neutron capture,[17] and by ^{158}Tb decay.[18,19] Reaction work on this nucleus includes the (d,d') inelastic scattering studies of Bloch *et al.*[20] and the (d,p) work of Shelton and Sheline[21] and Kern *et al.*[22] More recently, Riedinger[23] made improved singles measurements on ^{158}Eu with a Ge(Li) detector of modest size and resolution and White and Siddiqi[24] reported on some of the positive parity states of ^{158}Gd populated in (n,γ) experiments.

Here we report the results of our high resolution γ-ray analysis of ^{158}Eu decay. From both singles and extensive γ-γ coincidence experiments, 132 γ-ray transitions were assigned to ^{158}Eu decay. We placed 94 of these transitions in a ^{158}Gd level scheme consisting of 31 excited states, 12 of which are proposed for the first time. Six additional levels are tentatively proposed on the basis of energy sums and these incorporate 13 more γ-ray transitions. This work has been described extensively in Ref. 25 and portions which relate to band mixing theory were published recently.[8] In the interest of brevity, many of the experimental details as well as the lengthy arguments necessary for some of the conclusions are omitted from this report.

II. SOURCE PREPARATION

Sources of ^{158}Eu were prepared by bombardment of Gd_2O_3 (enriched to 95.95% in ^{160}Gd by the Oak Ridge Isotopes Division) in a 13.5 MeV beam of deuterons at the Oak Ridge isochronous cyclotron. The principal radioactive impurities included ^{157}Eu produced by the $(d, \alpha n)$ reaction, ^{160}Tb produced by the $(d, 2n)$ reaction, and ^{159}Gd produced by the $(d,d'n)$ reaction. Ten minutes after counting began, the principal impurity ^{157}Eu comprised about 1% of the source activity. The primary transitions from this impurity lie below 420 keV.

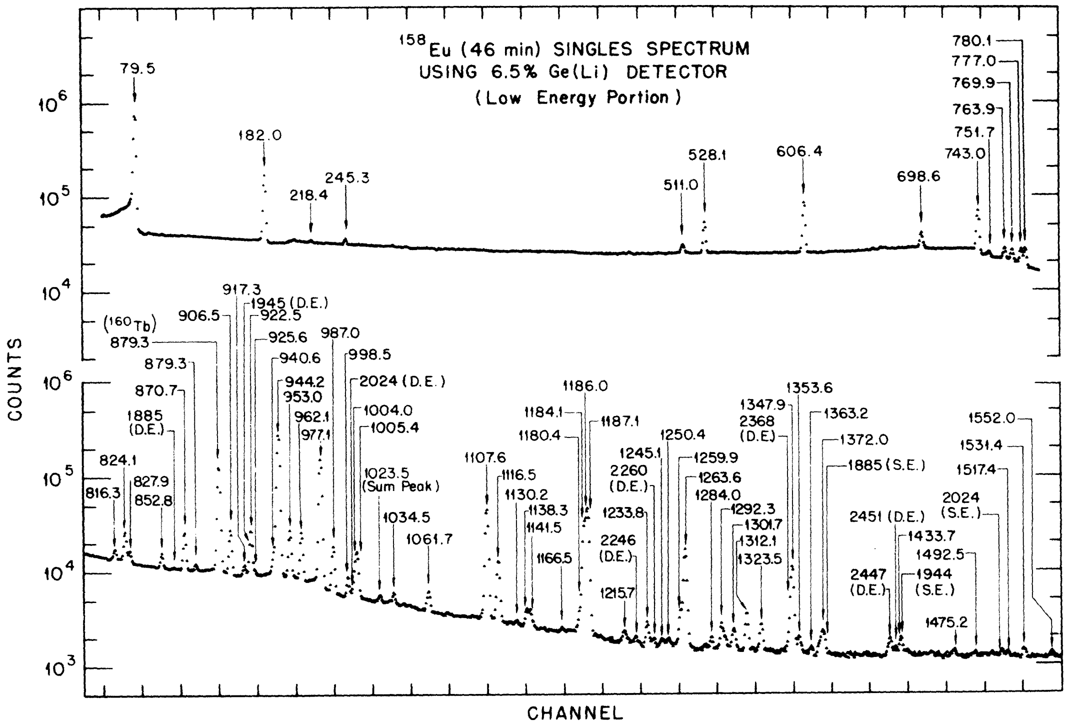

FIG. 1. Low energy section of ^{158}Eu singles spectrum taken with a large-volume Ge(Li) detector.

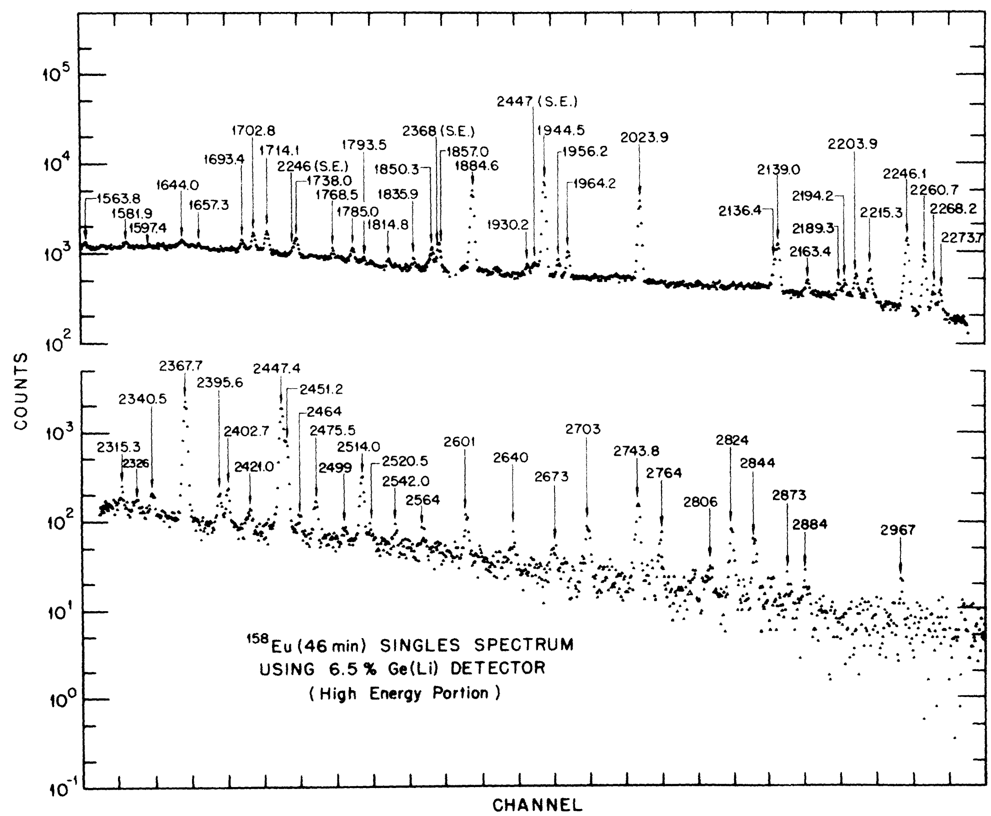

FIG. 2. High energy section of ^{158}Eu singles spectrum taken with a large-volume Ge(Li) detector.

After bombardment for about 90 min, the 50 mg oxide targets were dissolved in concentrated HCl and europium was separated from the other rare earths by standard chemical techniques (see Ref. 25). Basically, this procedure involved a reduction of europium ions to the +2 oxidation state while other rare-earth ions, which remained in the +3 oxidation state, were precipitated as hydroxides. Europium was then brought to the +3 oxidation state and precipitated for use as source material.

III. SINGLES EXPERIMENTS

The γ-ray singles spectrum for ^{158}Eu decay is shown in Figs. 1 and 2 with the long-lived impurity spectrum removed. The background was subtracted by computer program using a normalization factor determined from the average ratio of peak heights of several impurity peaks present in the original ^{158}Eu spectrum to the identical peaks found in the background spectrum. The primary impurity peaks resulted from 18-h ^{159}Gd and 15-h ^{157}Eu so that a representative background spectrum was obtained 12 h after counting began. With the exception of the 879.3 keV γ ray, all peaks labeled in Figs. 1 and 2 decay with a half-life similar to that of the main ^{158}Eu peaks. The 879.3 keV peak may result from improper background subtraction since this energy corresponds to that of the most intense γ ray in the decay of 72-day ^{160}Tb (see Ref. 26). The peak at 1023.6 keV ($I_\gamma = 0.30$ units) arises from the true sum of the 79.49 and 944.15 keV cascade γ rays. The single and double escape peaks are labeled as SE and DE, respectively.

The experimental apparatus for the singles measurements consisted of a 39 cm^3 Ge(Li) detector and an Ortec 450 amplifier which was dc coupled to a Nuclear Data ND-2200 analyzer and included baseline restoration. The resolution of the 1107.6 keV peak in Fig. 1 is ~2.5 keV, a value slightly greater than the inherent resolution of the system. This effect results from small fluctuations in the dc level of the amplifier with counting rate change. During data accumulation, the source-detector distance was varied from 10 to 5 cm while the count rates ranged between 7000 and 2000 counts/sec. At these source-detector distances, the shape of the relative efficiency curve remains essentially constant. Two cyclotron bombardments were required to obtain this spectrum and the combined counting times were approximately 5 h.

Listed in Table I are the energies and relative intensities of all ^{158}Eu γ rays labeled in Figs. 1 and 2. The prominent ^{158}Eu peaks were accurately measured by the standards-in-place method and then used as standards to measure the remaining ^{158}Eu γ rays. Error assignments for the energies vary from 90 eV for the most intense γ rays to 3.0 keV for weak transitions above 2000 keV while errors for the relative intensities range from 5% for the intense peaks to 50% for the weak peaks. The 5% error for the relative intensity (10% for the region below 200 keV) represents essentially the upper limit on the error in the detector efficiency and the 50% error results mainly from errors in the background determination.

In the energy measurements, γ-ray peak positions were determined by a computer program which used a three-parameter linear least-squares fitting procedure to fit a Gaussian curve to the background corrected photopeak. The background was determined by fitting a straight line to the data points on both sides of the photopeak. To determine the energy calibration, a third degree polynomial was fitted by the least-squares method to the γ-ray standards peak positions which were first corrected for system nonlinearity. The linearity correction as measured by an Ortec 448 precision pulser, was $\leq(\pm 0.55)$ channels over 95% of the analog-to-digital converter (ADC) range. The error in peak position (≤ 0.01 channels) was combined with the error in the linearity correction (0.05 to 0.1 channels) to estimate the error in peak energy.

The relative intensities were obtained from the peak areas corrected for the detector efficiency. Two methods were used to measure peak areas. One was the channel by channel summation of the counts in the peak and another measured the area of the fitted Gaussian curve. Except for the very weak peaks where the Gaussian fit was obviously poor, these two methods agreed within assigned errors. The complex peaks such as those at 1004 and 1187 keV, both of which include decay transitions from γ-vibrational levels, were resolved in the coincidence data.

IV. COINCIDENCE EXPERIMENTS

Coincidence experiments were performed with two large-volume Ge(Li) detectors coupled to a Nuclear Data 3300 analyzer which was operated in the 4096×4096 two-parameter mode. The two germanium diodes were located at 180° to one another with the source sandwiched between them to gain maximum coincidence efficiency. A copper filter was placed between the source and each detector to reduce the number of low energy events recorded. Gating pulses were generated with a time-to-amplitude converter (TAC) for which constant fraction timing units provided the start and stop pulses. The resolution (2τ) of the pulse distribution from the TAC was 25 nsec. A pileup re-

TABLE I. Energies and relative intensities of γ rays observed in the decay of ^{158}Eu.

Energy (keV)	Relative intensity	Energy (keV)	Relative intensity
79.49 ± 0.10	44.4 ± 4.4	1250.4 ± 0.4 [c]	0.11 ± 0.04
181.97 ± 0.11	7.8 ± 0.8	1256 ± 0.8	<0.10
218.4 ± 0.4 [c]	0.15 ± 0.05	1259.9 ± 0.3	1.3 ± 0.2 [b]
245.33 ± 0.17	0.32 ± 0.04	1263.6 ± 0.4	0.7 ± 0.3 [b]
528.05 ± 0.10	5.1 ± 0.3	1263.61 ± 0.20	7.3 ± 0.6 [b]
606.39 ± 0.09	13.2 ± 0.7	1284.0 ± 0.2	0.21 ± 0.03
698.63 ± 0.12	3.52 ± 0.19	1292.3 ± 0.2	0.89 ± 0.11
743.02 ± 0.09	12.0 ± 0.6	1301.68 ± 0.14	0.61 ± 0.06
751.70 ± 0.16	0.94 ± 0.15	1312.08 ± 0.12	0.89 ± 0.07
763.94 ± 0.12	2.10 ± 0.15	1323.46 ± 0.14	0.76 ± 0.06
769.87 ± 0.12	2.16 ± 0.16	1347.95 ± 0.13	5.5 ± 0.3
776.98 ± 0.15	2.6 ± 0.3	1353.64 ± 0.14	0.39 ± 0.05
780.13 ± 0.19	3.0 ± 0.3	1363.2 ± 0.4 [e]	0.12 ± 0.03
816.33 ± 0.16	1.22 ± 0.08	1372.0 ± 0.2 [f]	0.44 ± 0.10 [f] 0.25 ± 0.10 [f]
824.11 ± 0.10	4.3 ± 0.3	1433.7 ± 0.3	0.21 ± 0.08
827.93 ± 0.16	1.29 ± 0.13	1438.0 ± 0.3	0.12 ± 0.04
852.81 ± 0.12	1.32 ± 0.09	1475.2 ± 0.4	0.16 ± 0.04
870.67 ± 0.11 [a]	0.81 ± 0.09 [b]	1492.5 ± 0.7 [c]	0.08 ± 0.04
870.70 ± 0.20 [a]	4.2 ± 0.4 [b]	1517.4 ± 0.5	0.10 ± 0.03
879.31 ± 0.15 [c,d]	0.56 ± 0.09	1531.4 ± 0.5	0.20 ± 0.04
897.61 ± 0.09	41.2 ± 2.1	1552.0 ± 0.7 [c]	0.11 ± 0.03
906.50 ± 0.10	6.1 ± 0.4	1563.8 ± 0.6 [e]	0.09 ± 0.03
917.28 ± 0.16	0.93 ± 0.13	1596.9 ± 0.7	0.08 ± 0.02
922.4 ± 0.3 [a]	1.02 ± 0.12 [b]	1644.0 ± 0.4	0.12 ± 0.04
922.51 ± 0.11	5.4 ± 0.6	1657.3 ± 0.8 [e]	0.06 ± 0.03
925.6 ± 0.3 [a]	0.40 ± 0.11 [b]	1693.4 ± 0.3	0.21 ± 0.05
940.6 ± 0.3	1.1 ± 0.3	1702.8 ± 0.2	0.45 ± 0.60
944.15 ± 0.10	100	1714.1 ± 0.2	0.61 ± 0.07
953.03 ± 0.10	6.6 ± 0.4	1738.0 ± 0.3	0.42 ± 0.08
962.09 ± 0.09	6.3 ± 0.4	1768.5 ± 0.5	0.13 ± 0.03
977.14 ± 0.09	54.3 ± 2.7	1785.0 ± 0.3	0.24 ± 0.04
986.96 ± 0.10	4.5 ± 0.3	1793.5 ± 1.5	0.05 ± 0.02
998.47 ± 0.15	1.27 ± 0.14	1814.8 ± 0.4	0.12 ± 0.03
1004.0 ± 0.3 [a]	1.6 ± 0.3 [b]	1835.9 ± 0.6	0.12 ± 0.03
1005.4 ± 0.3 [a]	4.1 ± 0.5 [b]	1850.3 ± 0.4	0.50 ± 0.10
1034.5 ± 0.2	0.48 ± 0.10	1857.0 ± 0.5 [c]	0.32 ± 0.07
1061.68 ± 0.16	1.08 ± 0.09	1884.62 ± 0.20	4.1 ± 0.2
1107.63 ± 0.09	17.1 ± 0.08	1930.2 ± 0.6	0.15 ± 0.03
1116.49 ± 0.10	4.2 ± 0.3	1944.47 ± 0.20	5.4 ± 0.3
1130.2 ± 0.4 [c]	0.06 ± 0.03	1956.2 ± 0.3 [c]	0.30 ± 0.04
1138.3 ± 0.3	0.71 ± 0.09	1964.2 ± 0.3	0.44 ± 0.05
1141.5 ± 0.3	0.61 ± 0.09	2023.9 ± 0.3	3.08 ± 0.18
1166.5 ± 0.5 [c]	0.05 ± 0.03	2136.4 ± 0.9 [e]	0.42 ± 0.14
1180.4 ± 0.3 [a]	1.1 ± 0.2 [b]	2139.0 ± 0.4 [c]	0.88 ± 0.22
1184.1 ± 0.3 [a]	10.1 ± 1.2 [b]	2163.4 ± 0.4 [c]	0.14 ± 0.02
1186.0 ± 0.3 [a]	9.8 ± 1.8 [b]	2189.3 ± 0.8	0.09 ± 0.02
1187.1 ± 0.2 [a]	14.7 ± 1.0 [b]	2194.2 ± 0.7 [c]	0.11 ± 0.03
1215.7 ± 0.4	0.28 ± 0.06	2203.8 ± 0.4 [c]	0.28 ± 0.04
1233.7 ± 0.2	0.52 ± 0.11	2215.3 ± 0.3 [e]	0.37 ± 0.05
1245.1 ± 0.4 [c]	0.10 ± 0.04	2246.1 ± 0.3	1.53 ± 0.11

TABLE I (*Continued*)

Energy (keV)	Relative intensity	Energy (keV)	Relative intensity
2260.7 ± 0.3 [e]	0.82 ± 0.08	2520.5 ± 1.2 [e]	0.023 ± 0.012
2268.2 ± 0.5 [c]	0.21 ± 0.03	2542.0 ± 1.6	0.035 ± 0.011
2273.7 ± 0.5 [c]	0.17 ± 0.03	2564 ± 2 [e]	0.030 ± 0.010
2315.3 ± 1.0	0.07 ± 0.03	2601 ± 1.2 [e]	0.097 ± 0.018
2326.0 ± 1.5	0.06 ± 0.02	2640 ± 2 [e]	0.037 ± 0.015
2340.5 ± 1.0 [e]	0.10 ± 0.03	2673 ± 2	0.040 ± 0.016
2367.7 ± 0.3	2.62 ± 0.14	2703 ± 2 [c]	0.11 ± 0.02
2395.6 ± 0.5	0.17 ± 0.03	2743.8 ± 1.5 [e]	0.21 ± 0.02
2402.7 ± 0.4	0.16 ± 0.03	2764 ± 2	0.062 ± 0.012
2421.0 ± 1.1 [c]	0.05 ± 0.02	2806 ± 3 [c]	0.017 ± 0.008
2447.4 ± 0.4	2.54 ± 0.20	2824 ± 2 [e]	0.11 ± 0.02
2451.2 ± 0.6	0.75 ± 0.02	2844 ± 2 [e]	0.069 ± 0.014
2464 ± 2.0 [c]	0.04 ± 0.02	2873 ± 2 [c]	0.016 ± 0.008
2475.5 ± 0.5	0.13 ± 0.02	2884 ± 2 [c]	0.018 ± 0.009
2499.0 ± 1.0	0.208 ± 0.012	2967 ± 3 [c]	0.016 ± 0.008
2514.0 ± 0.5 [c]	0.36 ± 0.03		

[a] Deduced from energy levels.

[b] Deduced from coincidence data.

[c] This transition has not been placed in the level scheme of Fig. 5.

[d] This peak may be due to improper subtraction of the long-lived background since the 879.3 keV γ ray is the most intense peak in the decay of ^{160}Tb.

[e] Although this transition is not placed in the level scheme of Fig. 5, it is presumed to be associated with a ^{158}Gd level tentatively assigned on the basis of energy sums and a ground state transition. These additional levels are listed in Table III.

[f] The coincidence experiments show there are two γ rays of this energy with 0.44 units of intensity feeding the 1023.64 keV level and the remainder belonging to the $0_\beta^+ \to 2_g^+$ transition.

jection system consisting of an integral discriminator, a pileup rejector, delay amplifier, and linear gate was operated between the first and second stages of each TC-200 amplifier.

The maximum accumulation rate for the coincidence data was 2000 events per second. Each coincidence event was stored on magnetic tape as an element (X_i, Y_i) of a 4096×4096 array. A total of six magnetic tapes containing about 2×10^6 events each were accumulated and processed. A computer program was used to sort the data into spectra, each of which was coincident with a particular region of interest called a coincidence window or "gate" in the spectrum of one of the detectors. Coincidence windows were set on all full-energy photopeaks of interest, and in addition on the background just above or below the full-energy peaks to compensate for counts which represent events that are coincident with the Compton background. In analyzing the data, corrections were made for chance coincidences and for backscattered γ rays which were recorded as coincidence events. Proper correction of the coincidence spectra for these events is difficult and the region of maximum backscatter between 150 and 250 keV was therefore distorted.

During the coincidence measurements, singles spectra were sampled for 10% of the clock time and stored in two 2048-channel blocks of the "hard wired" memory. At preselected time intervals singles spectra were automatically transferred to magnetic tape. The singles count rate ranged to a maximum of 70,000 counts/sec.

A summary of the results of the two-parameter coincidence experiments is presented in Table II. The coincidence gates were selected in an energy range from 70 to 2100 keV. The gates used to establish the level scheme are listed in the top row, and the γ rays that are observed in the spectra coincident with these gates are listed in the first column. The relative magnitudes of peak areas observed in a spectrum coincident with a particular gate are indicated by the entries VS, S, W, VW, and P, which represent very strong, strong, weak, very weak, and probable, respectively. These entries represent the strength of the observed γ ray relative to the other γ rays in the coincidence spectrum. The last entry represents a coincidence relationship which within the error limits of the coincidence data is probable, yet not conclusive.

We will neither describe the extensive data nor show the many coincidence spectra which led to all of the conclusions in Table II. A detailed account of all coincidence measurements and the rationale involved in the assignments in Tables I and II as well as in the construction of the level scheme of Fig. 5 can be found in Ref. 25. Here we will only illustrate the utility of these coincidence data by discussing how complex peaks were resolved to provide the branching ratios from the γ-vibrational levels. Figures 3 and 4 show the primary coincidence spectra necessary for this.

In Fig. 3(a) the 1107.63 keV γ ray is found to be a singlet, all of whose intensity belongs between the $I\pi K = 2+2$ and $2+0$ levels. This fact is substantiated by the data in Fig. 4(d). The relative intensities of the 925.6 and 1187.1 keV transitions (listed in Table I) were then determined by comparing their intensities relative to the 1107.63 keV γ ray of Fig. 3(a) and normalizing by the relative singles intensity of the 1107.63 keV transition. The relative intensities of the 1186.0 and 1180.4 keV transitions were determined from the coincidence spectra shown in Figs. 3(b) and 3(c), respectively. After correcting the 1263.61 keV γ ray [0.7 ± 0.3 units belongs to Fig. 3(a)] as determined from a quantitative analysis of the data in Fig. 4(d), the relative singles intensity of the 1263.61 keV γ ray was used to determine the relative intensity of the 1184.1 keV transition shown in Fig. 4(a). By this technique, the relative intensities of all four members of the complex peak at 1187 keV were determined. When their intensities are summed, the results agree within error with the relative intensity of the complex as measured in the singles data. Having established the intensity of the 1186.0 keV transition, we can now determine the intensity of the 1004.0 keV γ ray from the spectrum coincident with the 528.05 keV γ ray shown in Fig. 3(b).

V. ^{158}Gd LEVEL SCHEME

The coincidence relationships summarized in Table II and the energies and intensities listed in Table I were used to construct the ^{158}Gd level scheme shown in Fig. 5. Of the 132 γ-ray transitions we were able to assign to ^{158}Eu decay, 94 of these were incorporated into the level scheme of Fig. 5 which consists of 31 excited states. The energy in keV of each transition is given at the top of the arrow representing it and the relative intensity is listed in parentheses. The level energies are weighted averages of the cascade sums and ground state transitions and the assigned errors represent weighted average errors.

Transitions which were shown by the coincidence data to populate an excited level are indicated by a dot at the tip of the arrow while those which were observed in a coincidence relationship as

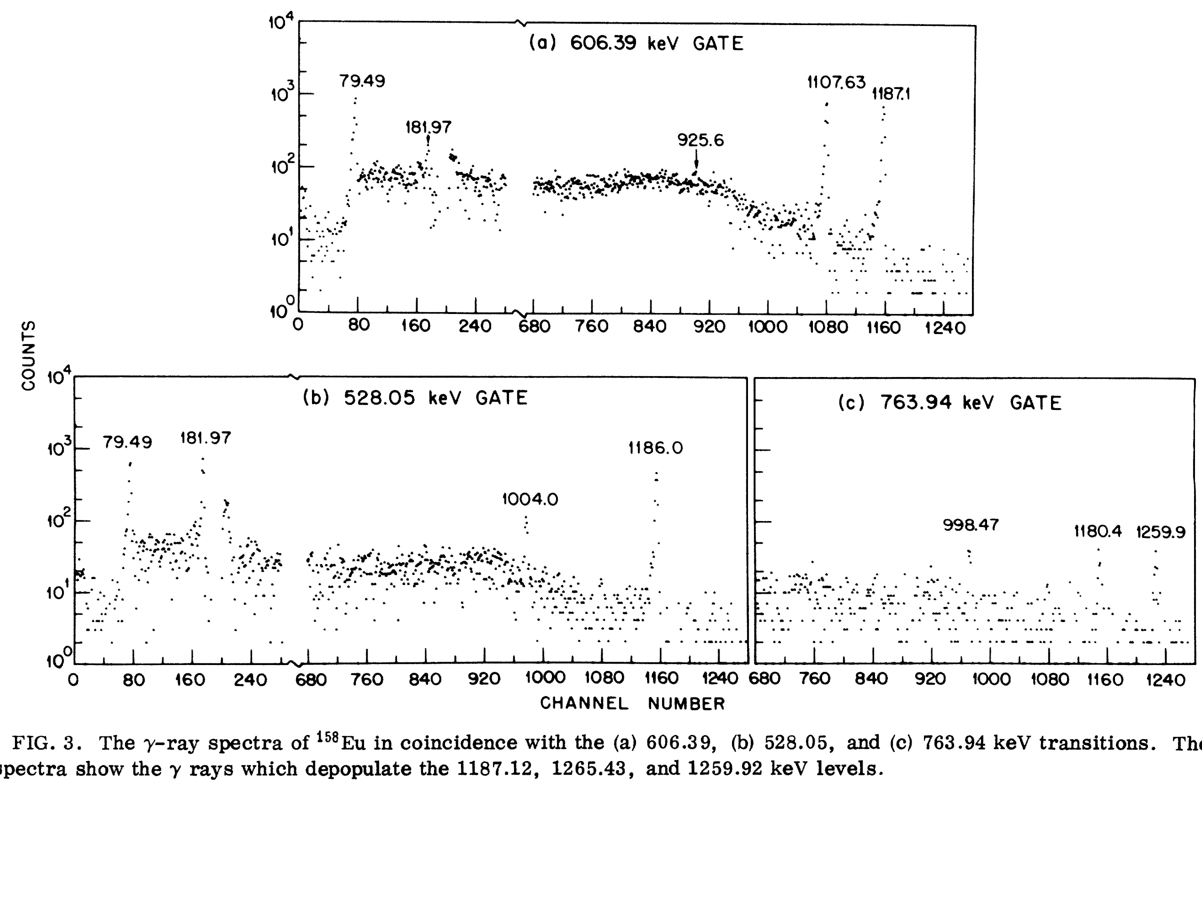

FIG. 3. The γ-ray spectra of ^{158}Eu in coincidence with the (a) 606.39, (b) 528.05, and (c) 763.94 keV transitions. The spectra show the γ rays which depopulate the 1187.12, 1265.43, and 1259.92 keV levels.

TABLE II. Summary of the results of the MPA coincidence experiment for ^{158}Eu. All entries in the table are given relative to the individual spectrum, and the code for the entries is given as follows: VS = very strong, S = strong, W = weak, VW = very weak, P = probable, Blank = not observed.

E_γ (keV) \ Gate (keV)	79.49[a]	181.97	528.05	606.39	698.63	743.02	751.70	763.94	769.87	776.98	780.13	816.33	824.11	827.93	852.81	870.7[b]	879.3[c]	897.61	906.50	917.28	922.5[b]	944.15[b]	953.03	962.09	977.14
79.49		VS	VS	VS	VS	VS	S	S	P	VS	VS	S	VS	VS	S	S*		VS	VS	S	VS*	VS*	S	S	
181.97			VS	P	S	P	P	P		P	VS				S						VS*				
245.3								W						P											
528.05		S																							
606.39		W																							
698.63		S																							
743.02		W																							
751.70		P									W													S	
763.94		P																							
769.87																						S			
776.98		P																							
780.13		S					W								S						S				
816.33																		S							S
824.11																						S			
827.93																									
852.81		S									W													S	
870.67																						W			
870.70																		S							S
897.61												S				S				S			S		
906.50																						S			
917.28																		W							W
922.4		S																							
922.51		S									S													VS	
925.6		P		VW		VW				W															
940.6																						S			
944.15									S				VS			W*			VS			S*			
953.03																		S							S
962.09							S								S						S				
977.14												S				S				S			S		
986.96																		S							S
998.47		S						S																	
1004.0		S	S		S																				
1005.4																									
1034.5		P																							
1061.68																									
1107.63				VS		S				S															
1116.49														VS											
1138.3		P																							
1141.5		S																			W*				
1180.4								S																	
1184.1																									
1186.0			VS		VS																				
1187.1				VS		S				S															
1215.7		P																							
1233.7		P																							
1259.9								S																	
1263.6		P			W																				
1263.61																									
1284.0		P									W													VW	
1292.3																		W							W
1301.68																						W			
1312.08		P																							
1323.46																					W*				
1347.95																		S							S
1353.64		P									W													W	
1363.2																									
1372.0																						W			
1433.7																						VW			
1475.2																									
1531.4		W																							
1596.9																						VW			
1644.0																		P							W
1693.4																		VW							W
1702.8		S																							
1738.0																						W			
1785.0																		VW							W
1835.9																						VW			

[a] The data from this coincidence gate were inconclusive because of the high random contribution at this energy and the complexity of the spectrum.

[b] This spectrum was coincident with a complex γ ray; the starred entries in the table for this gate indicate γ rays

TABLE II *(Continued)*

E_γ (keV) \ Gate (keV)	986.96	998.47	1005.4[b]	1034.5	1061.68	1107.63	1116.49	1138.3[b]	1141.5	1186.0[b]	1187.1[b]	1215.7	1233.7	1259.9	1263.61[b]	1292.3	1301.68	1312.08	1323.46	1347.95	1353.64	1372.0	1884.6	1944.47	2023.9
79.19	S	S	VS*	P	P	VS	VS	S	W	VS*	VS*	W	W		VW*	S	W	S	S	VS	W	S	VS	VS	
181.97			VS*	P				S	S			W	W					P			W				
245.3																								W	W
528.05			S*							S	S*														
606.39						VS				S*	S														
698.63			S*							S	S*														
743.02						VS				S*	S														
751.70																									
763.94		S								S*				S	W*										
769.87																									
776.98						S				W*	S														
780.13																					VW				
816.33																									
824.11																									
827.93							S																		
852.81																									
870.67																									
870.70																									
897.61	S															S				VS	W*				
906.50																									
917.28																									
922.4								W*	W										S						
922.51																									
925.6				P				P										P							
940.6																									
944.15																W*	S					S			
953.03																									
962.09																					VW				
977.14	S															S				VS	W*				
986.96																									
998.47												P													
1004.0													VW												
1005.4										S*	S*			W*	S										
1034.5						W					W														
1061.68										S*	W*			W*	S										
1107.63				W				W							W*			S							
1116.49																									
1138.3						W					W														
1141.5																									
1180.4												W													
1184.1		W*	S		W																				
1186.0													W												
1187.1				W				W							W*			S							
1215.7		W								VW				W											
1233.7			P							VW	W*														
1259.9												VW													
1263.6						W				W*	VW														
1263.61		W*	S		W																				
1284.0																									
1292.3																									
1301.68																									
1312.08						W					W														
1323.46																									
1347.95																									
1353.64																									
1363.2																									
1372.0						VW					VW														
1433.7																									
1475.2																									
1531.4																									
1596.9																									
1644.0																									
1693.4																									
1702.8																									
1738.0																									
1785.0																									
1835.9																									

which are partially or totally in coincidence with the unlisted member(s) of the complex peak.

[c] This is the most intense γ ray in the ^{160}Tb decay spectrum. A γ ray at 299 keV was observed to be in coincidence with it.

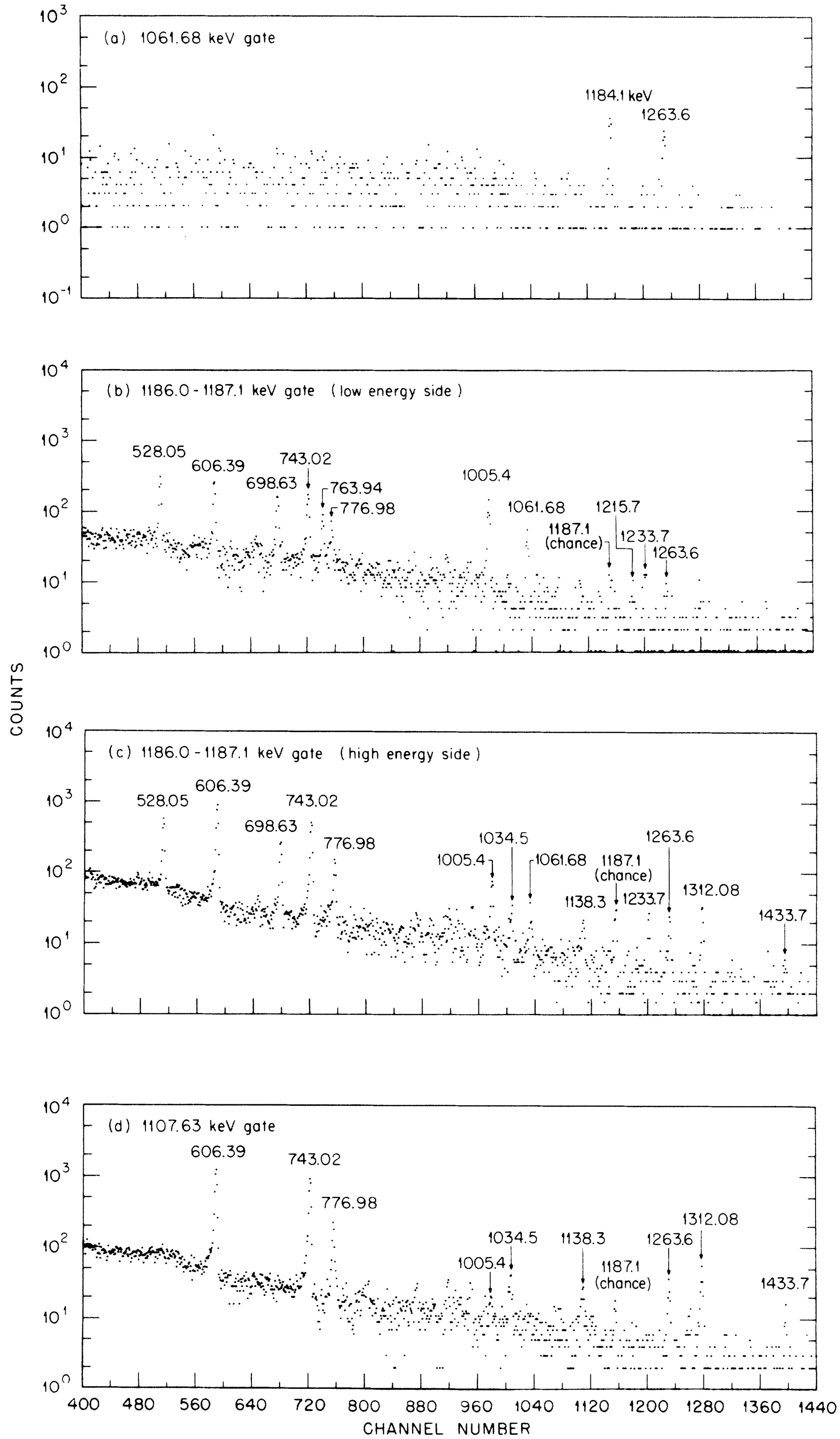

FIG. 4. The γ-ray spectra of ^{158}Eu in coincidence with the (a) 1061.68, (b) 1186.0–1187.1 (low energy side), (c) 1186.0–1187.1 (high energy side), and (d) 1107.63 keV transitions. These spectra show the γ rays which depopulate the 1263.61 keV level and those which populate the 1187.12, 1263.61, and 1265.43 keV levels.

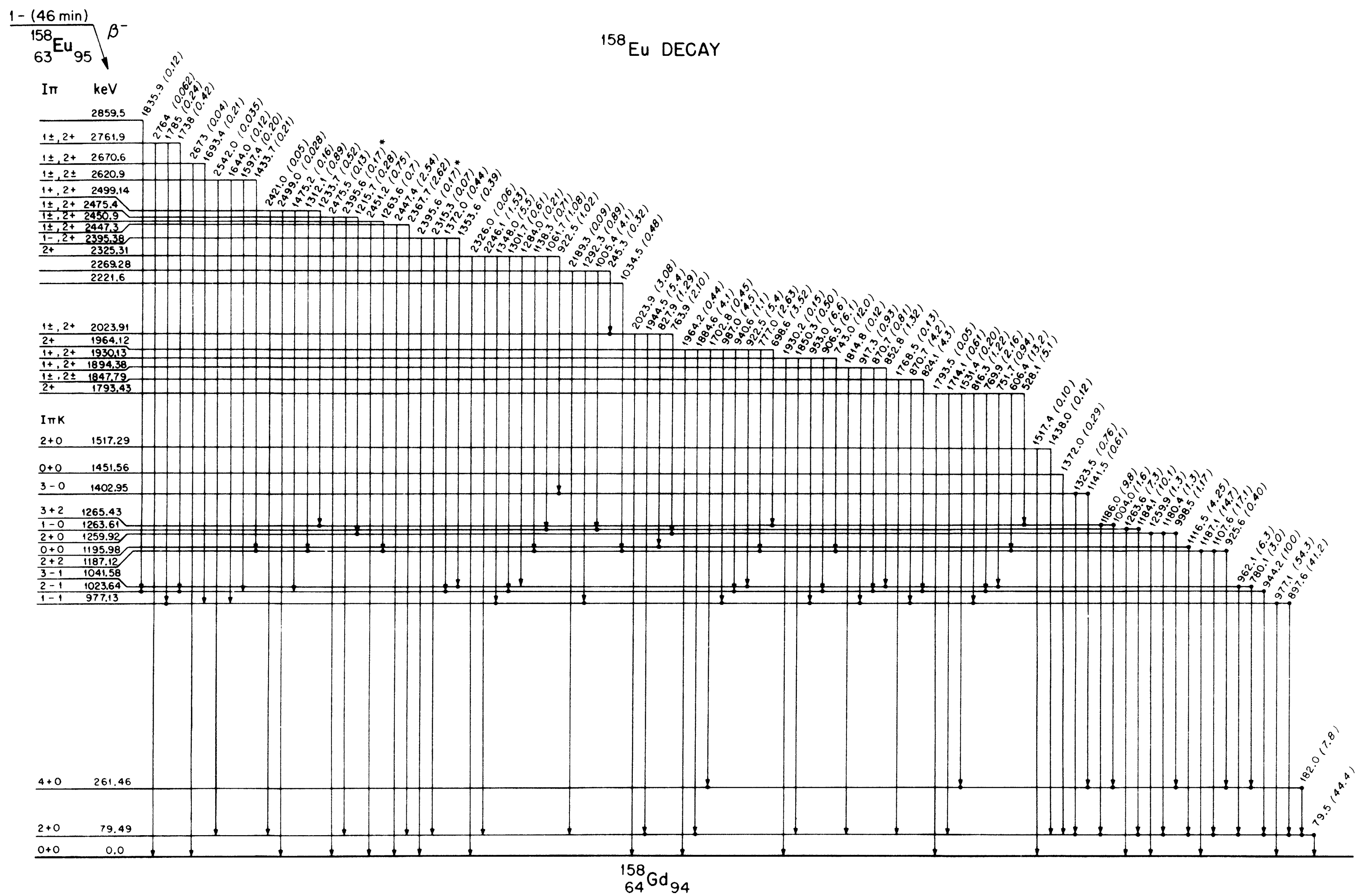

FIG. 5. Level scheme of ^{158}Gd populated in the decay of ^{158}Eu. Transitions which were shown by the coincidence data to populate an excited level are indicated by a dot at the tip of the arrow while those which were observed in a coincidence relationship as transitions which deexcite a level are indicated by a dot at the top of the arrow. The spin (I) and parity (π) of each level is listed in the left column; the quantum number K is listed only for those levels below 1517 keV since it is not known to be different than I for levels of higher energies. Note, the asterisk on the 2395.6 keV transition indicates that energetically it fits in two places. Several additional energy levels suggested by energy fits of high energy transitions are given in Table III, but are not shown in the level scheme because of their tentative nature.

transitions which deexcited a level are indicated by a dot at the top of the arrow. The quantum number K is listed only for those levels below 1518 keV since it is not known to be different than I for levels of higher energies.

The β^- branching to each level was calculated from the γ-ray intensities of Table I and the available internal conversion electron intensities.[12,15] For the conversion electron intensity of the 79.49 and 181.97 keV $E2$ transitions we used the γ-ray intensities listed in Table I and the theoretical $E2$ conversion coefficients given by Hager and Seltzer.[27] The percent β^- population calculated for each excited level is listed in column 3 of Table III. In Refs. 10 and 11 a limit of 5% was set for the total β-ray feeding to the ground and first excited states, but our γ-ray data indicate that this is too low. We calculated our percentage β-ray branchings on the basis of zero β feeding to the ground state. This approach inserts some error into all the $\log ft$ values, but it is probably too small to affect any of the spin assignment arguments presented below. (In these arguments a spin-parity of 1^- was assumed for ^{158}Eu on the basis of other Nilsson orbital assignments in this region.) The $\log ft$ values for the levels were determined with the aid of a computer code[28] and are listed in column 4. Note that the errors on the entries in column 3 represent only the statistical error of the γ-ray intensity balance. The spin assignments of column 2 are the best assignments inferred from all available data. The total β-ray intensity resulting from the 23 unplaced γ-ray transitions is 0.93% of which 0.84% feeds states below 2 MeV. Only the β-ray feeding to the 1195.98 and 1259.92 keV states can be significantly altered by these unplaced γ-ray transitions.

A. 2^+ and 4^+ members of the ground state rotational band

For the previously established 2^+ and 4^+ members of the ground band we assign energies of 79.49 ± 0.10 keV and 261.46 ± 0.14 keV, respectively. A $\log ft$ of 7.9 to the 2^+ level is consistent with a normal first-forbidden, nonunique β^- transition.

B. 0^+ and 2^+ members of the $K^\pi = 0^+$ β band

The 0^+ and 2^+ members of the β-vibrational band in ^{158}Gd have been reported by Bloch, Elbek, and Tjom[20] and by Greenwood and Reich[16] at energies of 1451.56 and 1517.29 keV, respectively. In our singles measurements a weak peak of 1372.0 keV is partially masked by the single escape peak of the 1885 keV transition. The coincidence data show that 60% of the 1372.0 keV γ ray is in coincidence with the 944.15 keV transition and that it feeds the 1023.64 keV level. The remaining intensity (0.25 units) of this γ ray may depopulate the 0^+ level at 1451.5 keV and feed the first excited state. γ rays of 1438.0 and 1517.4 keV are seen in the singles spectrum and fit as transitions from the 1517.29 keV level to the 2_g^+ and ground states. Only an upper limit was obtained for the $2_\beta^+ \to 4_g^+$ transition which was masked by another strong peak. Unfortunately, these data are insufficient for a meaningful study of these important branching ratios.

C. 0^+ and 2^+ members of a second $K^\pi = 0^+$ band

The levels at 1195.98 and 1259.92 keV are placed on the basis of the coincidence data. They have been reported previously from neutron-capture work[16] as the 0^+ and 2^+ members of another $K^\pi = 0^+$ band. Respective $\log ft$ values of 8.6 and 8.9 in Table III are consistent with these assignments.

D. 2^+ and 3^+ members of the γ-vibrational band

The $I^\pi = 2^+$ through 5^+ members of the γ-vibrational band have been reported from the (d,p) reaction data[21,22] and (n,γ) work,[15] while the 2^+ and 4^+ levels are seen in the (d,d') experiments.[20] The energies of the 2^+ and 3^+ members of the γ band seen in our work agree within experimental error with the previous works. In Sec. IV we discussed the use of coincidence data to unravel the very complex singles data and provide the branching ratios from these levels. The branching ratios from the 1187.12 ± 0.11 keV level are compatible with a 2^+ spin-parity assignment (see Ref. 8). Similar arguments limit the assignment of the 1265.43 ± 0.10 keV level to 3^+.

E. $K^\pi = 1^-$ octupole band

A group of three levels with spin-parities of 1^-, 2^-, and 3^- near 1 MeV have been assigned as members of a $K^\pi = 1^-$ band in the previous ^{158}Eu decay studies,[10,11] in (n,γ) studies,[12,14,16] and in work on the ^{158}Tb decay.[18] The many coincidence experiments with the numerous transitions associated with these levels provide us an excellent picture of their properties. We assign respective energies of 977.13 ± 0.07, 1023.64 ± 0.14, and 1041.58 ± 0.11 keV. Both the γ-ray branching patterns and the $\log ft$ values for β decay to them support the proposed spins and parities.

F. $K^\pi = 0^-$ octupole band

In previous works,[16,20] two other negative parity levels with spins of 1 and 3 and energies of 1263 and 1403 keV, respectively, were reported as members of an expected $K^\pi = 0^-$ band. Again our coincidence experiments completely corroborate this and in addition yield accurate energy values of 1263.61 ± 0.20 and 1402.95 ± 0.15 keV.

TABLE III. Energies and logft values for the levels of ^{158}Gd populated by ^{158}Eu decay.

Level energy (keV)	$I\pi K$ [a,b]	β^- feeding [c] (%)	Logft
0	0+0		
79.49 ± 0.10	2+0	22.3 ± 8.0	7.9
261.46 ± 0.15	4+0	0.67 ± 0.60 [d]	
977.13 ± 0.07	1−1	18.3 ± 0.9	7.4
1023.64 ± 0.14	2−1	21.4 ± 1.3	7.3
1041.58 ± 0.11	3−1	0.27 ± 0.21 [d]	
1187.12 ± 0.11	2+2	0.36 ± 0.42 [d]	
1195.98 ± 0.14	0+0	0.77 ± 0.07	8.6
1259.92 ± 0.17	2+0	0.36 ± 0.09	8.9
1263.61 ± 0.20	1−0	3.15 ± 0.37	8.0
1265.43 ± 0.10	3+2	0.58 ± 0.73 [d]	
1402.95 ± 0.15	3−0	0.09 ± 0.07 [d]	
1451.45 ± 0.10 [e]	0+0	0.06 ± 0.03 [d]	
1517.29 ± 0.10 [e]	2+0	0.06 ± 0.03 [d]	
1793.46 ± 0.08	2+	6.0 ± 0.2	7.2
1847.79 ± 0.10	1±, 2±	2.22 ± 0.13	7.6
1894.38 ± 0.11	2+	0.82 ± 0.05	8.0
1930.13 ± 0.08	1+, 2+	6.5 ± 0.2	7.0
1964.12 ± 0.07	2+	5.7 ± 0.2	7.0
2023.91 ± 0.11	1±, 2+	3.00 ± 0.10	7.3
2221.6 ± 0.2	0+, 1±, 2±, 3+ [f]	0.12 ± 0.03	8.4
2269.28 ± 0.13	0+, 1±, 2±, 3+ [f]	1.39 ± 0.13	7.3
2325.31 ± 0.09	2+	2.76 ± 0.10	6.9
2395.38 ± 0.14	1−, 2+	0.34 ± 0.03	7.7
2447.3 ± 0.2	1±, 2+	1.33 ± 0.06	7.0
2450.9 ± 0.3	1±, 2+	0.37 ± 0.08	7.6
2475.4 ± 0.3	1±, 2+	0.150 ± 0.018	7.9
2499.14 ± 0.12	1+, 2+	0.41 ± 0.04	7.5
2620.9 ± 0.2	1±, 2±	0.14 ± 0.02	7.7
2670.6 ± 0.3	1±, 2+	0.064 ± 0.014	8.0
2761.9 ± 0.2	1±, 2+	0.19 ± 0.02	7.3
2859.5 ± 0.6	1±, 2+, 3+ [f]	0.031 ± 0.008	7.9
2215.5 ± 0.3 [g]		0.20 [h]	
2340.3 ± 0.3 [g]		0.26 [h]	
2600.3 ± 1.2 [g]		0.03 [h]	
2642 ± 2 [g]		0.02 [h]	
2823.5 ± 0.6 [g]		0.10 [h]	
2844.2 ± 0.8 [g]		0.03 [h]	

[a] For the levels above 1517.29 keV, only the possible I and π choices have been listed because there is no evidence available that indicates K is different from I for these cases.

[b] The spins shown here are the best values deduced from all available data, including the logft values of column 4.

[c] In these experiments we did not obtain information on the amount of β-ray branching to the ground state of ^{158}Gd. Therefore, to calculate the β-ray feeding to the excited states, we used our γ-ray intensity balances and assumed zero β branching to the ground state. Obviously this approach adds a small uncertainty to the logft values shown in column 4, but it does not change any of the basic conclusions of this paper.

[d] When the error in the percent β^- feeding is comparable to the value, the logft value is not shown.

[e] Here we use the energy from Greenwood and Reich (Ref. 16) since they were able to extract the value with greater accuracy than was possible in our data.

[f] When the spin possibilities are not restricted to less than three values, they are not shown on the level scheme of Fig. 5.

[g] No attempt was made to assign the spin to this level since it is tentatively assigned on the basis of γ-ray energy sums and a ground state transition.

[h] Since this level is tentatively assigned, only a qualitative indication of the β-ray feeding is given.

G. Previously reported levels with energies >1518 keV

Of the 18 energy levels above 1518 keV observed in this work, those at 1793.46, 1894.38, 1930.13, 2023.91, 2325.31, and 2395.38 keV were previously indicated in either ^{158}Eu decay studies[10,11] or neutron-capture work.[12,14,16] However, in some cases the earlier values differ by as much as 5–10 keV from the values of our work. None of the levels reported here are populated by ^{158}Tb decay since only 1200 keV of energy is available via this decay mode.

1. *(1793.46 ± 0.07) keV level, 2^+*

This strongly populated level, reported in prior studies[10,12,14,16] is well confirmed by many of our coincidence spectra. Decays to 1^- and 4^+ levels eliminate spin-parity assignments of $0^\pm$, $1^\pm$, 2^- and 3^+ while the $\log ft$ of 7.2 for population by β decay indicates a spin change of 0 or 1. The spin-parity is probably 2^+ in agreement with the positive parity reported by Bollinger and Thomas.[14]

2. *(1894.38 ± 0.11) keV level, 2^+*

This level probably corresponds to that reported at 1898 keV by Groshev *et al.*[12] and at 1894.53 keV by Greenwood and Reich.[16] Our coincidence data indicate that it has γ-ray branches to the three members of the $K^\pi = 1^-$ band. The observed decay pattern, the positive parity established by Bollinger and Thomas,[14] and a $\log ft$ value of 8.0 restrict I^π to 2^+ for this level.

3. *(1930.13 ± 0.08) keV level, $1^+, 2^+$*

A level decaying to the 977.13, 1023.64, and 1187.12 keV levels was reported at 1924 keV by Daniels and Hoffman[11] while Schima and Katoh[10] placed a level at 1940 keV decaying to the 1187.12 keV state. In addition a level has also been reported at 1930 keV from (n, γ) studies.[12,14,16] The present coincidence work confirms a 1930.13 ± 0.08 keV level. The $\log ft$ of 7.0, which indicates $\Delta I = 0$ or 1, the observed γ-ray decay to 2^+, 2^-, and 1^- levels, and a positive parity assignment from (n, γ) work[14] restrict I^π to 1^+ or 2^+.

4. *(2023.91 ± 0.11) keV level, $1^\pm, 2^+$*

In this energy region Daniels and Hoffman[11] reported a level at 2020 keV, Schima and Katoh[10] reported one at 2030 keV, and (n, γ) data[12,14] indicated a state at 2034 keV. Our coincidence data establish a 2023.91 ± 0.11 keV level, but it is of a different character from that seen in the (n, γ) work[12,14] since it deexcites by different transitions. A $\log ft$ of 7.3 to this level yields $\Delta I = 0$ or 1 and γ-ray decay to two 0^+ levels restrict I^π to $1^\pm$ and 2^+.

5. *(2325.31 ± 0.09) keV level, 2^+*

A 2330 keV level was reported by Daniels and Hoffman.[11] We definitely establish a level at 2325.31 ± 0.09 keV on the basis of six transitions placed by our coincidence data. From the $\log ft$ of 6.9 which restricts ΔI to 0 or 1, from γ-ray decay to the two 3^- levels, and from a positive parity reported[14] for this level, I^π is assigned 2^+. A nearby state has recently been reported[24] at 2326.6 keV, but we have no conclusive evidence for such a level.

6. *(2395.38 ± 0.14) keV level, $1^-, 2^+$*

A level reported[10,12] at 2400 keV may correspond to the one we assign at 2395.38 ± 0.14 keV both on the basis of our coincidence data and the energy sums. This $\log ft$ of 7.7 and the fact that it decays to 0^+ and 3^- levels eliminate all but 1^- and 2^+ for I^π.

No evidence for a level reported at 2240 keV by Daniels and Hoffman[11] is observed in this work, and although the levels reported by Schima and Katoh[10] at 2440 and 2760 keV are close in energy to the 2447.3 and 2761.9 keV levels which we see, they are established from different coincidence relationships and will be considered in the next section.

H. Energy levels reported for the first time

Twelve levels in ^{158}Gd are observed for the first time in the present work. Two of these levels at 2221.3 and 2449.2 keV were included by White and Siddiqi[24] but they showed no depopulating transitions. In most cases we have more than one coincidence relationship available on which to establish a new level. However, one well verified coincidence relationship, or the agreement within the error limits of the energy sum of transitions in a proposed cascade with the energy of a probable ground state transition was considered the minimum evidence necessary to establish a level. The last criterion was used only for high energy transitions which feed the ground or first excited state.

As for many of the levels discussed above, the spin-parity possibilities for the energy levels above 1500 keV were determined by the patterns of γ-ray deexcitation and by the $\log ft$ values associated with the β-ray population of each level (see Table III). Since there are no additional data on which to draw conclusions or with which to make comparisons, we will not give here any of the discussion on the individual levels, but will simply list their energies and spin possibilities. They are as follows: (1847.79 ± 0.10), $1^\pm$, $2^\pm$; (1964.12 ± 0.07), 2^+; (2221.6 ± 0.2), 0^+, $1^\pm, 2^\pm, 3^\pm$; (2269.28 ± 0.13), 0^+, $1^\pm, 2^\pm, 3^+$; (2447.3 ± 0.2), $1^\pm$, 2^+;

(2450.9 ± 0.3), $1^{\pm}$, 2^{+}; (2475.4 ± 0.3), $1^{\pm}$, 2^{+}; (2499.14 ± 0.12), 1^{+}, 2^{+}; (2620.9 ± 0.2), $1^{\pm}$, $2^{\pm}$; (2670.6 ± 0.3), $1^{\pm}$, 2^{+}; (2761.9 ± 0.2), $1^{\pm}$, 2^{+}; and (2859.5 ± 0.6), $1^{\pm}$, $2^{\pm}$, 3^{+}. All of these levels except the strongly populated 2447.3 keV state are substantiated by coincidence information.

Several additional levels are suggested on the basis of energy fits at 2215.5 ± 0.3, 2340.3 ± 0.3, 2600.3 ± 1.2, 2642 ± 2, 2823.5 ± 0.6, and 2844.2 ± 0.8 keV. These levels are listed in Table III but are not shown in the level scheme of Fig. 5 because of their tentative nature.

VI. DISCUSSION

We[8] recently published the details of our second order perturbation treatment of the effects of mixing between the β- and γ-vibrational bands and the ground band in ^{158}Gd. A detailed account of our considerations and references to other possible treatments of this problem are contained in Ref. 8. Unlike the earlier results for ^{152}Sm, ^{154}Gd, and ^{156}Gd, we found that in ^{158}Gd this treatment still did not provide agreement between experiment and theory for the branching ratios from the γ-vibrational band.

Other investigators also have considered the problem of the branching ratios for the γ-vibrational band. A point of disagreement is the $(3_\gamma \rightarrow 4_g)/(3_\gamma \rightarrow 2_g)$ $B(E2)$ ratio, where Baader[29] reports 0.59 ± 0.09 from (n,γ) work, White and Siddiqi[24] report ⩾0.37 ± 0.04, and we find 0.37 ± 0.04. White and Siddiqi[24] gave only a lower limit because the $3 \rightarrow 2$ transition is part of a complex multiplet. We find that both the $3 \rightarrow 2$ and $3 \rightarrow 4$ transitions are complex. This ratio is obtained most accurately from coincidence data as shown in Fig. 3(b).

In ^{158}Gd a second excited $K^\pi = 0^+$ band occurs at nearly the same energy as in ^{156}Gd, but in ^{158}Gd it falls considerably below the energy of the β-vibrational state in contrast to being above the β band in ^{156}Gd. The influence of this second $K^\pi = 0^+$ band on the branching ratio is not clear at present although one would expect it would be greater in ^{156}Gd where the two bands are close in energy. Note that an earlier typographical reference error[30] in data for this band was carried over by White and Siddiqi.[24] The original error occurred in columns 4–7 of Table 11 b in Ref. 30. The data in columns 4 and 6 should have been attributed to Greenwood and Reich[16] and those in columns 5 and 7 to Kluk.[25] The $B(E2)$ ratios for the 2_0^+ level of this $K = 0$ band fall into two groups, the (n,γ) work of White and Siddiqi[24] and Baader[29] and our work and that of the much higher resolution work of Greenwood and Reich.[16] From our 763.94 keV gate seen in Fig. 3(c), the 998.47 keV $2_0^+ \rightarrow 4_g$ transition is clearly less intense than the other two out of the 2_0^+ level in marked contrast to the intensities of White and Siddiqi[24] and, further, we find that the 1180.4 and 1259.9 keV transitions are nearly equal in intensity and do not differ by their reported[24] factor of 1.93. If one assumes the $2_0 \rightarrow 2_g$ transition is pure $E2$, then the branching ratios for this band do not agree with the rotational model modified for mixing between the γ and ground bands while White and Siddiqi[24] note that their data and that of Baader[29] are in near agreement with a four-band mixing treatment of Baader.[29] However, as has been shown[31] in ^{178}Hf, it is meaningless to compare experimental results with theory without knowing exactly the $E2/M1$ ratio in the $2 \rightarrow 2$ transition. The $E2/M1$ admixture may not at all be like that measured[32] for the $2_\beta \rightarrow 2_g$ transition in ^{156}Gd.

In ^{158}Gd, the levels of the $K^\pi = 0^-$ octupole band are observed through a spin-parity of 3^-. The

TABLE IV. Reduced $B(E1)$ transition probability ratios from the octupole levels of ^{158}Gd.

Energy level (keV)	$\frac{B(E1;K_iI_i \rightarrow K_fI_f)}{B(E1;K_iI_i \rightarrow K_fI_f')}$	$\frac{E(I_i \rightarrow I_f)}{E(I_i \rightarrow I_f')}$	Experimental ratios [a]	Theoretical ratios [b] $K=0$	$K=1$	RPA with Coriolis coupling [c]
977.13	$\frac{B(E1;K1 \rightarrow 00)}{B(E1;K1 \rightarrow 02)}$	$\frac{977.14}{897.61}$	1.02 ± 0.05	0.5	2.0	0.83
1041.58	$\frac{B(E1;K3 \rightarrow 02)}{B(E1;K3 \rightarrow 04)}$	$\frac{962.09}{780.13}$	1.10 ± 0.11	0.75	1.33	0.95
1263.61	$\frac{B(E1;K1 \rightarrow 00)}{B(E1;K1 \rightarrow 02)}$	$\frac{1263.61}{1184.1}$	0.60 ± 0.11	0.5	2.0	0.49
1402.95	$\frac{B(E1;K3 \rightarrow 02)}{B(E1;K3 \rightarrow 04)}$	$\frac{1323.46}{1141.5}$	0.80 ± 0.14	0.75	1.33	0.73

[a] Transitions were assumed to be pure $E1$ multipolarity.

[b] From the predictions of the adiabatic symmetric-rotor model.

[c] From the calculations of Neergård and Vogel (Ref. 33) using the random phase approximation (RPA) equations with Coriolis coupling as given by Kocbach and Vogel (Ref. 34).

TABLE V. Properties of low-lying, negative parity states in ^{152}Sm and ^{154,156,158}Gd.

Isotope	Level energy (keV)	$(I\pi K)_i$	$(I\pi K)_f$	Transition energy (keV)	Relative intensity	Normalized $B(E1)$ values	Theory [a]
^{152}Sm	963.2 [b]	1 − 0	0 + 0	963.2	0.5	0.55 ± 0.02	0.50
		1 − 0	2 + 0	841.4	0.59	1.00	
	1041.1 [b]	3 − 0	2 + 0	919.3	1.47	0.62 ± 0.19	0.75
		3 − 0	4 + 0	674.7	0.3	1.00	
	1511.1 [c]	1 − 1	0 + 0	1511.1	0.028	0.006 ± 0.002	2.0
		1 − 1	2 + 0	1389.3	3.57	1.00	
	1529.8 [b]	2 − 1	2 + 0	1408.04	77.6		
	1579.3 [b]	3 − 1	2 + 0	1457.6	1.91	0.22 ± 0.02	1.33
		3 − 1	4 + 0	1212.8	5.11	1.00	
^{154}Gd	1241.4 [b]	1 − 0	0 + 0	1241.4	0.30	0.7 ± 0.03	
		1 − 0	2 + 0	1118.2	0.30	1.00	
	1251.6 [b]	3 − 0	2 + 0	1128.5	0.79	2.5 ± 1.2	
		3 − 0	4 + 0	880.6	0.20	1.00	
	1509.1 [d]	1 − 1	0 + 0	1510.0	50	0.19	
		1 − 1	2 + 0	1387.0	200	1.00	
	1397.6 [b]	2 − 1	2 + 0	1274.49	100		
	1617.3 [b]	3 − 1	2 + 0	1494.2	1.88	0.45 ± 0.05	
		3 − 1	4 + 0	1246.2	2.40	1.00	
^{156}Gd	1242.42	1 − 0	0 + 0	1242.42	69.1	0.81 ± 0.09	
		1 − 0	2 + 0	1153.47	68.6	1.00	
	1276.22 [e]	3 − 0	2 + 0	1187.2	1.82	1.13 ± 0.17	
		3 − 0	4 + 0	988.1	0.93	1.00	
	1366.40	1 − 1	0 + 0	1366.41	17.0	0.45 ± 0.03	
		1 − 1	2 + 0	1277.43	30.0	1.00	
	1319.66	2 − 1	2 + 0	1230.71	83.8		
	1852.1 [e]	3 − 1	2 + 0	1763.1	0.27	1.35 ± 0.51	
		3 − 1	4 + 0	1564.0	0.14	1.00	
^{158}Gd	1263.61	1 − 0	0 + 0	1263.61	7.32	0.60 ± 0.11	
		1 − 0	2 + 0	1184.1	10.1	1.00	
	1402.95	3 − 0	2 + 0	1323.46	0.76	0.80 ± 0.14	
		3 − 0	4 + 0	1141.5	0.61	1.00	
	977.13	1 − 1	0 + 0	977.14	54.3	1.02 ± 0.05	
		1 − 1	2 + 0	897.61	41.2	1.00	
	1023.69	2 − 1	2 + 0	944.15	100		
	1041.58	3 − 1	2 + 0	962.09	6.3	1.10 ± 0.11	
		3 − 1	4 + 0	780.13	3.0	1.00	

[a] From the predictions of the adiabatic symmetric-rotor mode.
[b] From Ref. 35.
[c] From Ref. 7.
[d] From Ref. 3.
[e] From Ref. 5.

$B(E1)$ ratios for the transitions from the 1^- and 3^- levels of each band are given in column 4 of Table IV. The $B(E1)$ ratios predicted by the adiabatic symmetric-rotor model for $K=0$ and 1 are listed in columns 5 and 6, respectively. In column 7, the calculations of Neergård and Vogel[33] who used the random phase approximation with Coriolis coupling are listed as given by Kocbach and Vogel.[34]

As seen in Table IV, experimental $B(E1)$ ratios for the 1263.61 keV 1^- and 1402.95 keV 3^- levels are in good agreement with the $K^\pi=0^-$ assignment for both models but the $B(E1)$ ratios for the 977.13 keV 1^- and 1041.58 keV 3^- levels do not agree with $K=0^-$ or 1^- assignments for the adiabatic symmetric rotor. However, for the latter two levels the $B(E1)$ ratios with the Coriolis coupling effect included are in somewhat better agreement with experiment. Paperiello, Funk, and Mihelich[18] assigned a value of $K^\pi=1^-$ to the 977.13 and 1041.58 keV levels as well as to the 1023.64 keV 2^- level and accounted for the $B(E1)$ ratios by a Coriolis coupling calculation involving the $K^\pi=0^-$ and 1^- bands. They also were able to explain the observed deviation of the energy spacings of the $I^\pi=1^-$, 2^-, and 3^- levels from the normal rotational spacing in terms of the Coriolis effect.

Some interesting systematic trends of the octupole levels can be noted in Table V, which is partially taken from Ref. 35. The energies of the 1^-

through 3^- levels of octupole bands with $K^\pi = 0^-$ and 1^- for the rare-earth nuclei ^{152}Sm and ^{154,156,158}Gd are listed in column 2. It is noted that the energy of the band head of the 0^- band is lowest in ^{152}Sm and increases with A while the energy of the 1^- band is highest in ^{152}Sm and decreases with A. Furthermore, the order of the bands is reversed in ^{158}Gd where the $K^\pi = 1^-$ band is lower in energy than the $K^\pi = 0^-$ band. Thus, the 0^- band which is expected[36] to be most collective in character follows the general trend of the quadrupole vibrational bands while the 1^- band does the reverse.

The effect of the Coriolis coupling is also apparent in that levels of equivalent odd spins for the $K^\pi = 0^-$ and 1^- bands are displaced away from one another. This effect is greatest in ^{154}Gd and ^{156}Gd where the two band heads are closest in energy. For these two nuclei, the normal spin sequence for the $K^\pi = 1^- (I = 1, 2, 3,$ etc.) has been inverted to $I = 2, 1, 3,$ etc. The coupling effect is evidently considerably less for ^{152}Sm and ^{158}Gd where the normal spin sequence is observed. In ^{154}Gd and ^{156}Gd, the energy spacing of the $I\pi K = 3$-0 level is strongly depressed relative to the $I\pi K = 1$-0 level when compared with the separation predicted from the levels of the ground state rotational band of each nucleus. The opposite effect occurs for the energy separation of the 3-1 level relative to the 1-1 level in these two nuclei. In ^{152}Sm and ^{158}Gd where the $K^\pi = 0^-$ and 1^- bands are farthest apart, the $B(E1)$ ratios for the $K^\pi = 0^-$ band agree well with those predicted by the symmetric-rotor model. However, the branching ratios from the $K^\pi = 1^-$ levels do not agree with the predictions of the symmetric-rotor model for any of the four nuclei.

The authors are most grateful to L. L. Riedinger for helpful discussions, to A. R. Brosi, and B. H. Ketelle for the help and use of their equipment in some of these measurements, to J. J. Pinajian and the Oak Ridge Isotopes Development Center for the use of a multichannel analyzer, and to the Operating Staff of the Oak Ridge isochronous cyclotron for their help in producing the many sources necessary for these experiments.

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†Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

‡Work supported in part by a grant from the National Science Foundation.

[1]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. Lett. 19, 1243 (1967).

[2]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. 179, 1214 (1969).

[3]R. A. Meyer, Phys. Rev. 170, 1089 (1968).

[4]L. Liu, O. B. Nielsen, P. Salling, O. Skilbreid, Izv. Akad. Nauk. SSSR Ser. Fiz. 31, 63 (1967) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 69 (1967)].

[5]L. C. Whitlock, J. H. Hamilton, and A. V. Ramayya, Phys. Rev. C 3, 313 (1971).

[6]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. C 2, 2358 (1970).

[7]L. Varnell, J. D. Bowman, and J. Trischuk, Nucl. Phys. A127, 270 (1969).

[8]A. F. Kluk, N. R. Johnson, and J. H. Hamilton, Z. Phys. 253, 1 (1972).

[9]A. F. Kluk, N. R. Johnson, and J. H. Hamilton, Phys. Rev. C 10, 1451 (1974).

[10]F. Schima and T. Katoh, Phys. Rev. 140, B1496 (1965).

[11]W. R. Daniels and D. C. Hoffman, Phys. Rev. 147, 845 (1966).

[12]L. V. Groshev, A. M. Demidov, V. A. Ivanov, V. N. Lutsenko, and V. I. Pelekhov, Izv. Akad. Nauk. SSSR Ser. Fiz. 26, 1119 (1962) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 26, 1127 (1962)].

[13]A. Backlin *et al.*, in *Proceedings of the International Symposium on Neutron-Capture Gamma-Ray Spectroscopy, Studsvik, Sweden, August 1969* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 147.

[14]L. M. Bollinger and G. E. Thomas, Phys. Rev. 2, 1951 (1970).

[15]H. A. Baader *et al.*, in *Proceedings of the International Symposium on Neutron-Capture Gamma-Ray Spectroscopy, Studsvik, Sweden, August 1969* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 363.

[16]R. C. Greenwood and C. W. Reich, Idaho Nuclear Annual Report No. IN-1218, 1968 (unpublished), p. 99; also, IN-1317, 1970 (unpublished), p. 82.

[17]Y. Y. Berzin, A. E. Legzdinya, and P. T. Prokofev, Latv. PSR Zinat. Akad. Vestis, Fiz. Teh. Zinat. Ser. No. 2, 3 (1968).

[18]C. J. Paperiello, E. G. Funk, and J. W. Mihelich, Nucl. Phys. A140, 261 (1970).

[19]D. Schroeer and P. S. Jastram, Phys. Rev. 166, 1212 (1968).

[20]R. Bloch, B. Elbek, and P. O. Tjom, Nucl. Phys. A91, 576 (1967).

[21]W. H. Shelton and R. K. Sheline, Z. Phys. 242, 368 (1971).

[22]J. Kern, O. Mikoshiba, R. K. Sheline, T. Udagawa, and S. Yoshida, Nucl. Phys. A104, 642 (1967).

[23]L. L. Riedinger, Ph.D. thesis, Vanderbilt University, 1969 (unpublished).

[24]D. H. White and T. A. Siddiqi, Nucl. Phys. A217, 410 (1973); also private communication of their γ ray intensities.

[25]A. F. Kluk, Ph.D. thesis, Vanderbilt University, 1971 (unpublished).

[26]M. A. Luddington, J. J. Reidy, M. L. Wiedenbeck, D. J. McMillan, J. H. Hamilton, and J. J. Pinajian, Nucl. Phys. A119, 398 (1968).

[27]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[28]J. T. Larsen and R. G. Lanier, Lawrence Radiation Laboratory (to be published).

[29]H. A. Baader, Dissertation, Technische Universitat Munchen, 1970 (unpublished).

[30]J. H. Hamilton, Izv. Akad. Nauk. SSSR Ser. Fiz. 36, 17 (1972) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 36, 17 (1973)].

[31]J. H. Hamilton, A. V. Ramayya, P. E. Little, and N. R. Johnson, Phys. Rev. Lett. 25, 946 (1970); Phys. Rev. C 5, 252 (1972).

[32]J. H. Hamilton, P. E. Little, A. V. Ramayya, W. E. Collins, N. R. Johnson, J. J. Pinajian, and A. F. Kluk, Phys. Rev. C 5, 899 (1972).

[33]K. Neergård and P. Vogel, Nucl. Phys. A145, 33 (1970).

[34]L. Kocbach and P. Vogel, Phys. Lett. 32B, 434 (1970).

[35]J. H. Hamilton, N. R. Johnson, L. L. Riedinger, D. J. McMillan, A. F. Kluk, and L. C. Whitlock, in *Contributions to the International Conference on Properties of Nuclear States, Montreal, Canada, August 25–30, 1969* (Univ. of Montreal Press, Quebec, 1969), p. 23.

[36]V. G. Soloviev, P. Vogel, and A. A. Korneichuk, Izv. Akad. Nauk. SSSR Ser. Fiz. 28, 1599 (1964) [transl.: Bull. Acad. Sci. USSR Phys. Ser. 28, 1495 (1964)].