$M1$ Admixtures of Transitions in ^{156}Gd

J. H. Hamilton, P. E. Little,* A. V. Ramayya, and E. Collins
Physics Department, Vanderbilt University,† Nashville, Tennessee 37203

and

Noah R. Johnson, J. J. Pinajian, and A. F. Kluk
Oak Ridge National Laboratory,‡ Oak Ridge, Tennessee 37830
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γ-γ directional-correlation measurements were carried out with a NaI-Ge(Li) detector system on the transitions in ^{156}Gd whose levels are populated from the decay of ^{156}Eu. Directional correlations of the 88.95-keV γ ray with 11 transitions which directly feed and 4 which involve a skipped transition to the 88.95-keV state were simultaneously measured. A δ value of $-5.9^{+1.4}_{-2.8}$ was measured for the 1040.44-keV, $2^+_\beta \to 2^+_g$ transition which is thus $(97.2^{+1.5}_{-2.1})\%$ $E2$. The 1065.14-keV, $2^+_\gamma \to 2^+_g$ transition has a $\delta = -18 \pm 3$ and a $(99.7 \pm 0.1)\%$ $E2$ component. Three $1^+ \to 2^+_g$ transitions of 1877.03, 1937.71, and 2097.70 keV have $E2$ admixtures of $(13.8^{+3.0}_{-2.9})$, $(24.5^{+2.0}_{-1.9})$, and $(59.0^{+25.2}_{-9.0})\%$, respectively, while the 811.77-keV, $1^+ \to 2^+_\gamma$ transition is $(0.1^{+0.4}_{-0.1})\%$ $E2$.

I. INTRODUCTION

As discussed in our recent work[1,2] on ^{178}Hf, more information is needed on the properties of β-type vibrational bands in highly deformed nuclei to help resolve the problem of the anomalous branching ratios reported[3-10] from such levels in ^{152}Sm, ^{154}Gd, and ^{156}Gd. Unfortunately, none of the $K^\pi = 0^+$ levels in ^{178}Hf have the collective character[11] to be classified as β vibrations. The β-vibrational states in ^{152}Sm, ^{154}Gd, and ^{156}Gd have known[12] collective character. While no sizable $M1$ admixtures which could bring branching ratios into agreement with theory have been found[13,14] in the $2^+_\beta \to 2^+_g$ transitions in ^{152}Sm and ^{154}Gd, the possible existence of such an $M1$ admixture in this transition in ^{156}Gd has not been tested by direct measurement of the multipole admixtures. As one goes from ^{152}Sm to ^{156}Gd the properties of the octupole bands are in better agreement with the rotational model[15] as is expected, since one is going more into the region of well-deformed nuclei. Thus, from ^{156}Gd we hope to obtain a clearer picture of the properties of β-vibrational states in more highly deformed nuclei and also to test Mottelson's[16] expectation of large $M1$ admixtures in $2^+_\beta \to 2^+_g$ transitions in such cases.

The levels in ^{156}Gd are populated by the negatron decay of ^{156}Eu, which has a 0^+ ground state and a half-life of 15 days, and by the positron decay of ^{156}Tb which has a 3^- ground state and a 5.4-day half-life. Recent studies of the level properties of ^{156}Gd have been performed from the ^{156}Eu decay[9,10] from ^{155}Eu(n,γ) work,[17] and from the ^{156}Tb decay.[6] In both the ^{156}Tb and ^{156}Eu studies[6,9] it was found that the branching ratios could be brought into agreement with theory if the $2^+_\beta \to 2^+_g$ transition is $(64.3 \pm 2.4)\%$ $M1$.

It is the primary purpose of the present work to determine the $M1$ admixture in the $2^+_\beta \to 2^+_g$ transition which depopulates the $K^\pi = 0^+$ state at 1129.41 keV. This transition can be studied under more favorable conditions from the decay of ^{156}Eu.

In Fig. 1 is given the decay scheme proposed by Kluk, Johnson, and Hamilton.[10] All energies in this paper are from that work. In the later figures these energies are rounded off. When referring to cascades, only integer numbers are used. 15 correlations were measured simultaneously in our experiment so that considerable information on $E2/M1$ admixtures of transitions and spins of levels in ^{156}Gd was obtained.

II. SOURCE PREPARATION

The sources were prepared by neutron bombardment of a $^{154}Sm_2O_3$ target (enriched to greater than 96% purity in ^{154}Sm) in a neutron flux of 2×10^{14} n/cm^2 sec in the research reactor at the Oak Ridge National Laboratory. The ^{156}Eu was produced by double neutron capture from the following reactions:

$$\underset{5\,\mathrm{b}}{^{154}\mathrm{Sm}(n,\gamma)}{}^{155}\mathrm{Sm} \xrightarrow[T_{1/2}=22\ \mathrm{min}]{\beta^-} \underset{13\,\mathrm{kb}}{^{155}\mathrm{Eu}(n,\gamma)}{}^{156}\mathrm{Eu}.$$

Ion-exchange techniques and standard precipitation procedures were employed in purifying different sources. Both methods proved adequate in that the only extraneous γ rays observed were those of ^{155}Eu.

However, the highest-energy transition in the ^{155}Eu decay is below 110 keV; hence, the only effect the ^{155}Eu contaminant had on the correlations was to decrease the true-to-chance ratio by increasing the counts in the 89-keV gate. By operating at a suitable true-to-chance ratio, then, the presence of the ^{155}Eu caused no problems.

III. EXPERIMENTAL PROCEDURES

The experiment involved a measurement of the γ-γ directional correlations of the 88.95-keV, $2_g^+ \to 0_g^+$ transition with the $2_\beta^+ \to 2_g^+$ and $2_\gamma^+ \to 2_g^+$ transitions and with as many other transitions that feed the 88.95-keV state as possible. The equipment included a movable NaI(Tl)-Ge(Li) fixed detector arrangement with a 4096-channel analyzer for data storage.[18]

A 2-in. × 2-in. NaI detector was used to gate on the 88.95-keV ground-state transition and on the Compton background in the region just above the 89-keV peak. A 0.02-cm cadmium absorber shielded this detector to suppress the 92-keV sum peak that arises from the 43- and 49-keV x rays.

The Ge(Li) detector had a 35-cm^3 active volume with a photopeak efficiency of 3.5% relative to a 3-in. × 3-in. NaI detector for a transition energy of 1.3 MeV. The resolution was 2.8 keV for the 1332-keV peak, while the peak-to-Compton ratio was 16 : 1. A lead-cadmium-copper graded shield was used to attenuate the low-energy portion of the spectrum. The source, which was positioned 7 cm from the NaI detector and 5 cm from the Ge(Li) detector, was centered to within 1%.

The electronics consisted of a Nuclear Data 161 4096-channel analyzer with dual analog-to-digital-converter units, two coincidence units, and a routing circuit. A coincidence event established between a Ge(Li) signal and one of the two NaI gate signals opened a 4096-channel memory operated in a 2 × 2048 mode for storage of events in the Ge(Li) detector in coincidence with the 89-keV photopeak in the first 2048 channels and with the Compton background in the second 2048. In this mode it was possible to make a simultaneous measurement of the directional correlations of all γ rays coincident with the 88.95-keV, $2_g^+ \to 0_g^+$ transition and with the Compton background just above the 89-keV peak. The γ-ray singles spectrum from the Ge(Li) detector is shown in Fig. 2. [A post-biased amplifier was used to reject all pulses below about 560 keV from the Ge(Li) detector for improved resolution.]

The coincidence measurements were taken for 23 h at each angle in the sequence 90, 135, 180, 225, and 270°. 10-min live-time singles runs were taken before and after each coincidence run for use in determination of accidental coincidences in each peak and to check the performance of the system.

A typical 23-h coincidence spectrum is shown in Fig. 3. From the 1965.95- and 2026.65-keV ground-state transitions which lead to pure chance peaks in the coincidence spectra, the resolving time of the coincidence unit was computed to be 75 nsec. This was used to correct for other random events.

20 cycles, where each cycle was for 70 h and included a 23-h run at 90, 135, and 180°, were recorded. Periodic interruptions were required to increase the source strength and to fill the Ge(Li) detector Dewar with nitrogen. After each interruption the single-channel window set on the 89-keV peak was checked and reset if a drift was observed. Up to about $\frac{1}{2}$ channel drifts in the gain and zero were observed in some of the individual Ge(Li) coincidence spectra. This gave rise to a slight peak broadening when the data were summed.

Besides the double cascades which occur in ^{156}Gd, there are also several triple cascades in which the initial level is populated strongly enough to provide adequate statistics for the analysis of a one-three correlation with the intermediate transition unobserved. The analysis of the correlations in ^{156}Gd will be presented under two headings – double and one-three correlations.

IV. RESULTS AND DISCUSSIONS OF DOUBLE CORRELATIONS

A. Spin of the 1168.11-keV Level and the Attenuation Coefficients

The level at 1049.45 keV in ^{156}Gd is known to be a 0^+ state. As reported earlier,[19] we, in addition to Nielsen, Rud and Wilsky,[20] measured the spin of the level at 1168.11 keV to be 0. The two γ transitions which depopulate these levels are 960.50 and 1079.16 keV, respectively. By using the right half of the 1079-keV photopeak we were able to calculate the anistropy coefficients for the 1079 → 89-keV, 0 → 2 → 0 cascade without including a 1 → 2 → 0 cascade which results from the double-escape peak from the 2097.70-keV transition. This latter cascade had about a 10% weighting factor in the correlation coefficients calculated from the total areas of the 1079-keV peaks. The coefficients for these two 0 → 2 → 0 correlations uncorrected for solid angle and attenuation effects across the 88.95-keV state are: 961 → 89-keV correlation:

$$A_2' = 0.230 \pm 0.012\,, \quad A_4' = 0.443 \pm 0.014\,;$$

1079 → 89-keV correlation:

$$A_2' = 0.215 \pm 0.010\,, \quad A_4' = 0.435 \pm 0.010\,.$$

From a comparison of the average of these two re-

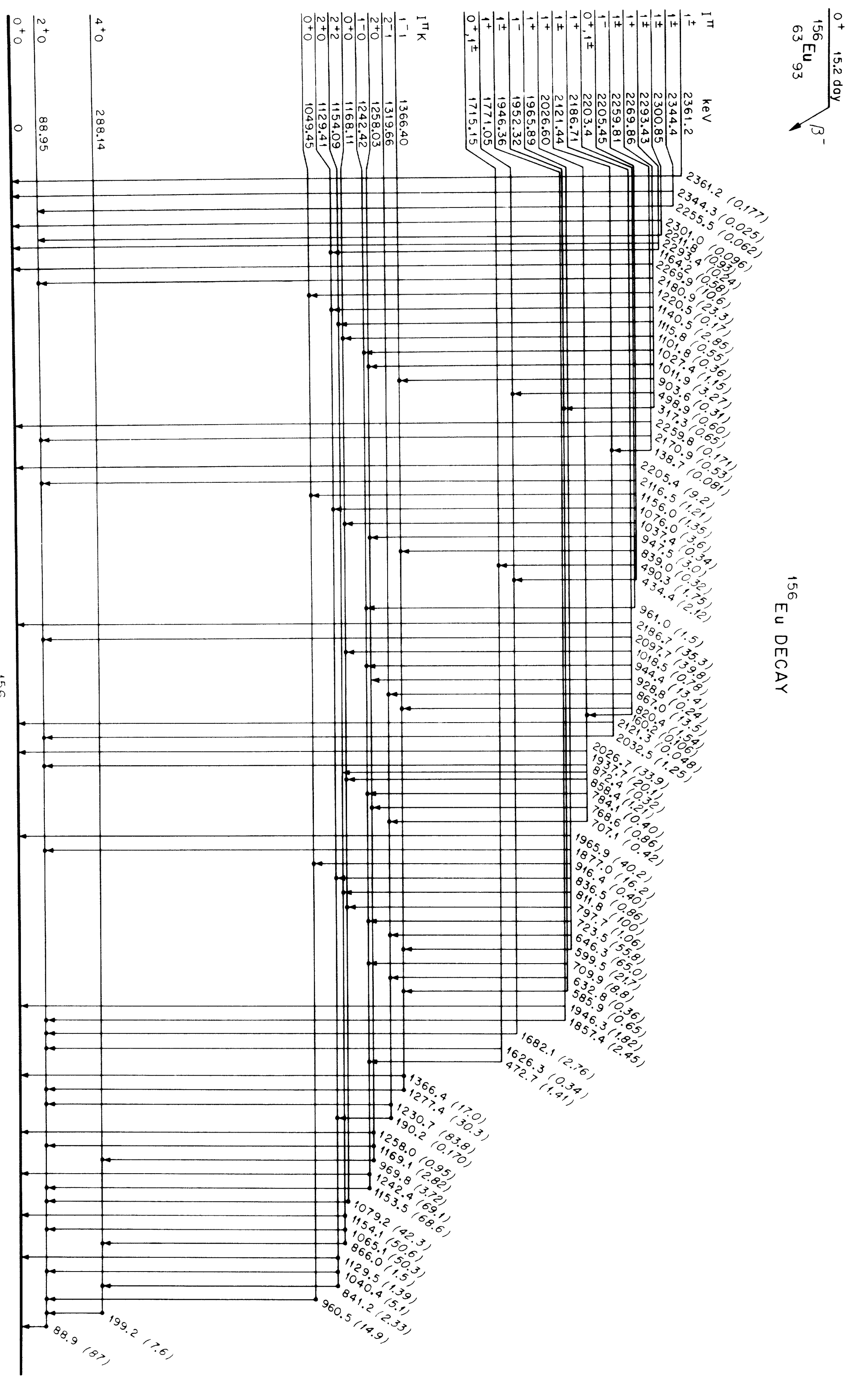

FIG. 1. The decay scheme of ^{156}Eu from Ref. 10. The transition energies of Ref. 10 are rounded off in the figure.

sults and the unique correlation coefficients for $0 \to 2 \to 0$ cascades, $A_2 = 0.357$ and $A_4 = 1.14$, the following attenuation-correction coefficients are obtained: $G_2Q_2 = 0.624 \pm 0.021$ and $G_4Q_4 = 0.385 \pm 0.008$. A summary of these and the other double-correlation results is given in Table I. These coefficients include solid-angle corrections for both detectors and correction for attenuation which arises because of the relatively long life of the 88.95-keV state.

B. 1040→89-keV Correlation

The 1040.44-keV transition originates from the 2^+ level at 1129.41 keV in the $K^\pi = 0^+$ β-vibrational band. This cascade is the one of primary consideration here. Figure 4 shows the three-angle data for this correlation. After correcting for solid angle and source attenuation, the A_k coefficients are $A_2 = 0.054 \pm 0.043$ and $A_4 = 0.25 \pm 0.09$. These coefficients overlap for a mixing ratio of $\delta = -5.9^{+1.4}_{-2.8}$ which corresponds to an $E2$ component of $(97.2^{+1.5}_{-2.1})\%$. The determination of the $E2$ component is illustrated in Fig. 5. The δ sign convention is that of Krane and Steffen.[21]

Table II gives the branching ratios from the 2^+ level at 1129.41 keV. The intensities of the γ rays used in this table were taken from the decays of ^{156}Tb and ^{156}Eu, Refs. 6 and 9, respectively. Consistent branching ratios for a single value of Z_β from the 2^+ level are obtained when an $M1$ component of $(64.3 \pm 2.4)\%$ based on an average of the ^{156}Tb and ^{156}Eu work[6,9] is assumed in the $2^+_\beta \to 2^+_g$ transition. This is in obvious disagreement with the experimentally measured value of $(2.8^{+2.1}_{-1.5})\%$ $M1$ admixture in this transition. Hence, here, as in ^{152}Sm and ^{154}Gd, theoretical and experimental

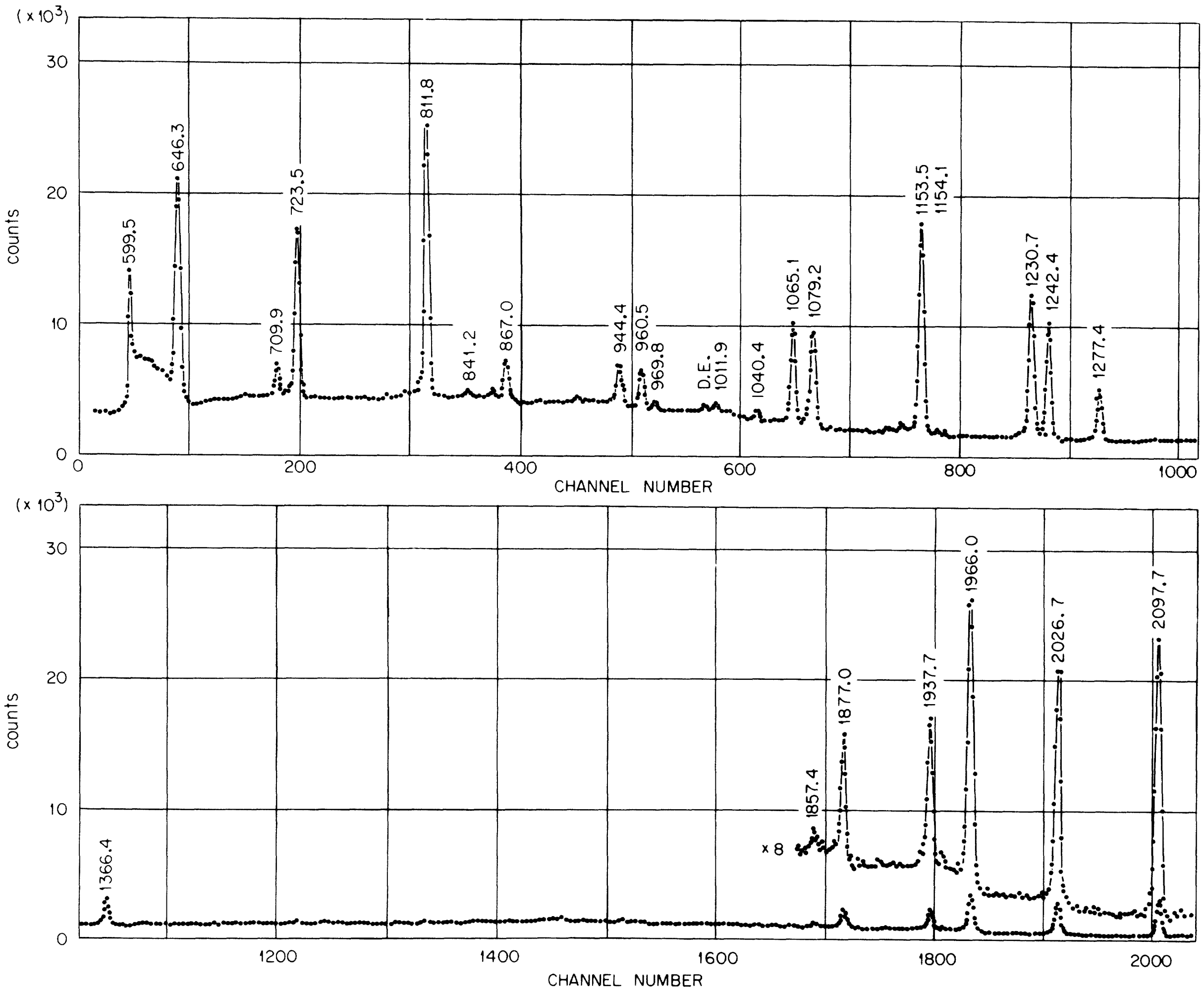

FIG. 2. The singles spectrum of ^{156}Eu taken with the Ge(Li) detector and a post-biased amplifier to cut out the region below 560 keV.

branching ratios do not agree for a single, Z_β mixing parameter. A two-parameter mixing of the β, γ, and ground-state bands does not bring about agreement between theory and experiment for the data from either ^{156}Tb or ^{156}Eu. The band-mixing problem is considered in detail in Ref. 9.

C. 1169 → 89-keV Correlation

A second $K^\pi = 0^+$ band is reported[6,10,17,19] in ^{156}Gd with the 0^+, 2^+, and 4^+ members at 1168.11, 1258.03, and 1462.3 keV, respectively. To obtain consistent branching ratios from the 2^+ level, a 43% $M1$ component (^{156}Tb data) must be assumed in the $\Delta I = 0$ transition. Since the 1258.0-keV level is very weakly populated in the ^{156}Eu decay, our γ-$\gamma(\theta)$ measurements involving the 1169.11-keV transition from this state are of poor statistical quality. We obtain $A_2 = -0.15 \pm 0.11$ and $A_4 = 0.25 \pm 0.19$ for the 1169 → 89-keV $2^+ \to 2^+ \to 0^+$ cascade. While these coefficients overlap best for a nearly pure $E2$ transition, the error limits on the A_k coefficients are so large that within a 2σ variation in A_k almost any value of δ is allowed.

D. 1065 → 89-keV Correlation

The 2^+ member of the γ-vibrational band lies at 1154.09 keV. A 1065.14-keV transition depopulates this level to the 2^+ member of the ground-state rotational band. The three-angle correlation data for the 1065 → 89-keV, $2_\gamma^+ \to 2_g^+$ correlation are also shown in Fig. 4. One observes that the 1065.14-keV transition lies on the Compton edge of the 1277.43-keV transition which is also in coincidence with the 88.95-keV ground-state transition. This circumstance makes it more difficult to obtain accurate areas of the peaks and, hence, introduces somewhat larger errors in the correlation coefficients than otherwise would have oc-

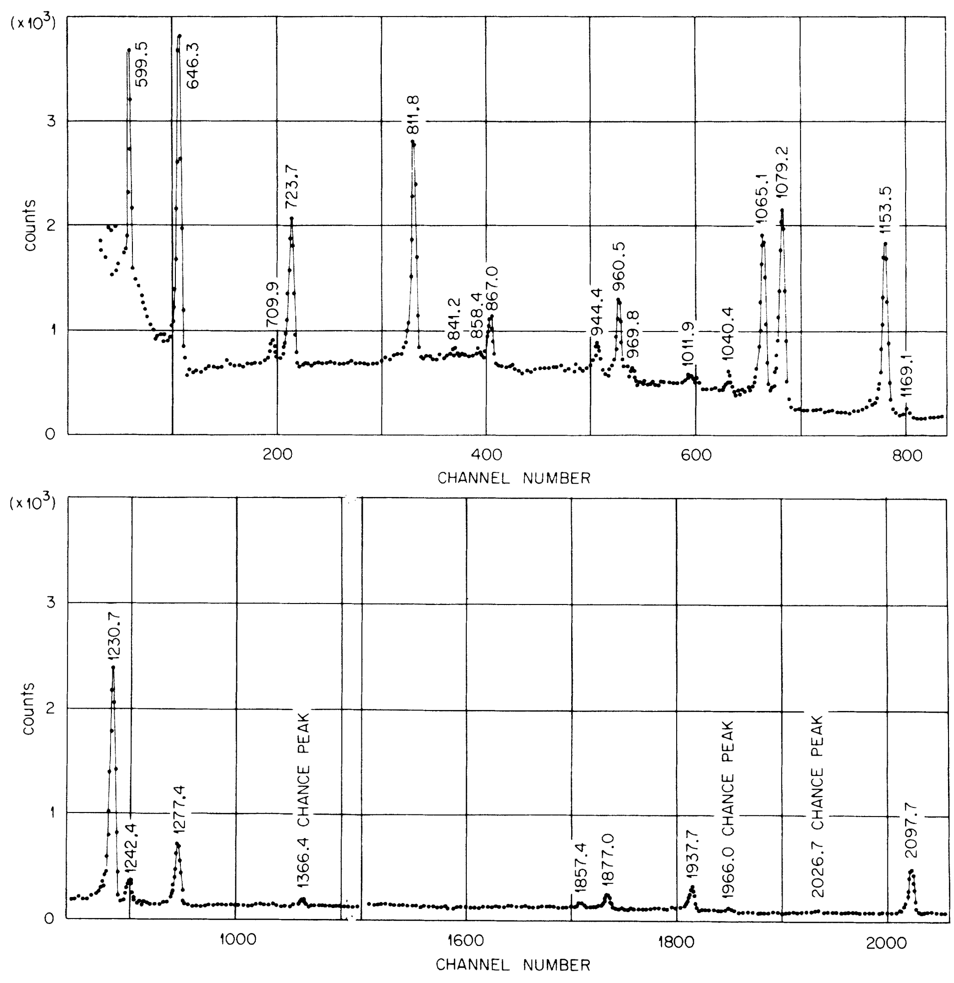

FIG. 3. A typical spectrum in coincidence with the 89-keV transition in the decay of ^{156}Eu. The counting time was 23 h.

TABLE I. The results of a directional-correlation study of the consecutive cascades in ^{156}Gd. The gating transition was the 88.95-keV, $2^+ \rightarrow 0^+$ ground-state transition.

Energy (transition) (keV)	Spin sequence ($x \rightarrow 2_g^+ \rightarrow 0_g^+$)	A_2 [a,b]	A_4 [a,b]	δ [c]	Admixture (%)
961.0	0^+	0.357 [d]	1.14 [d]	...	$E2$ 100
1040.44	2_β^+	0.054(43)	0.25(9)	$-5.9^{+1.4}_{-2.8}$	$E2$ $97.2^{+1.5}_{-2.1}$
1065.14	2_γ^+	−0.035(6)	0.337(12)	-18 ± 3	$E2$ 99.7 ± 0.1
1079.16	0^+	0.357 [d]	1.14 [d]	...	$E2$ 100
1153.47	1^-	−0.254(10)	0.004(9)	$\lvert\delta\rvert < 0.023$	$E1$ >99.95
1230.71	2^-	0.260(10)	0.002(9)	$0.018^{+0.018}_{-0.010}$	$E1$ $99.97^{+0.03}_{-0.05}$
1277.43	1^-	−0.237(12)	−0.016(15)	-0.01 ± 0.01	$E1$ $99.99^{+0.01}_{-0.03}$
1857.42	1	−0.22(9)	−0.12(16)	$-0.03^{+0.03}_{-0.07}$	$\sigma 1$ $99.91^{+0.09}_{-0.90}$
1877.03	1^+	−0.580(28)	−0.126(34)	0.40 ± 0.05	$E2$ $13.8^{+3.0}_{-2.9}$
1937.71	1^+	0.321(21)	−0.198(27)	-0.57 ± 0.03	$E2$ $24.5^{+2.0}_{-1.9}$
2097.70	1^+	0.581(22)	−0.410(20)	-1.2 ± 0.2	$E2$ $59.0^{+25.2}_{-9.0}$

[a] The last digit of the error, in parentheses, occurs in the third decimal place.

[b] $G_2\Omega_2 = 0.624 \pm 0.021$, $G_4\Omega_4 = 0.385 \pm 0.008$.

[c] There are small differences in a few cases between these values and those reported (J. H. Hamilton, invited paper) at the 1970 Delft Conference on Angular Correlation (See Ref. 19). The more accurate present results are based on computer calculations.

[d] Theoretical values which were compared with the experimental values given in the text to obtain the G_2Q_2 and G_4Q_4 values of footnote b.

curred. However, the errors are still small on an absolute scale.

The A_k coefficients for this correlation are $A_2 = -0.035 \pm 0.006$ and $A_4 = 0.337 \pm 0.012$. Within 1 standard deviation on both A_k coefficients, $\delta = -18 \pm 3$ is obtained. Hence, the $E2$ component present in this $2_\gamma^+ \rightarrow 2_g^+$ transition is $(99.7 \pm 0.1)\%$.

E. 1153 → 89-keV Correlation

The 1242.42-keV level in ^{156}Gd has been established[22-24] as the 1^- member of a $K^\pi = 0^-$ octupole band and is populated very strongly in the decay of ^{156}Eu. The 1153.47-keV transition depopulates this level to the 89-keV 2^+ level. The coincidence peaks sit on flat backgrounds and have extremely good statistics. The data yield $A_2 = -0.254 \pm 0.010$ and $A_4 = 0.004 \pm 0.009$. The mixing ratio allowed by these coefficients is $|\delta| < 0.023$. The $E1$ component is thus greater than 99.95%.

F. 1231 → 89-keV Correlation

The 2^- member of a $K^\pi = 1^-$ octupole band[20-22] is assigned at 1319.66 keV. This state decays to the 88.95-keV level via a 1230.71-keV transition.

The A_k coefficients for this $2^- \rightarrow 2^+ \rightarrow 0^+$ cascade are $A_2 = 0.260 \pm 0.010$ and $A_4 = 0.002 \pm 0.009$. These

TABLE II. Branching ratios from the 1129.41-keV level in ^{156}Gd.

Energy (transition) (keV)	spin sequence	γ intensity ^{156}Tb [a]	^{156}Eu [a]	Weighted ave.	Experimental relative $B(E2)$ values [b] $M1=0\%$	$M1=3\%$	$M1=64.3\%$ [c]	Theoretical relative $B(E2)$ values for Z_β values of: 0	0.020	0.027	0.030
841.16	$2_\beta^+ \rightarrow 4_g^+$	36.4 ± 4.4	45.7 ± 3.5	42.1 ± 2.7	122 ± 8	126	342 ± 22	180	295	342	380
1040.44	$2_\beta^+ \rightarrow 2_g^+$	100	100	100	100	100	100	100	100	100	100
1129.47	$2_\beta^+ \rightarrow 0_g^+$	24.3 ± 3.2	27.3 ± 2.5	26.5 ± 2.0	17.6 ± 1.3	18.1	49.2 ± 3.7	70	54	49.2	47

[a] Taken from Refs. 6 and 10 for ^{156}Tb and ^{156}Eu decays, respectively. The errors in the 841.16- and 1129.41-keV transition also contain the statistical errors of the 1040.44-keV one.

[b] Values for different $M1$ components in the $2_\beta^+ \rightarrow 2_g^+$ transition as indicated. The weighted average γ-ray intensities were used to calculate the relative $B(E2)$ values.

[c] Overlap occurs for ±2.4%.

yield a mixing ratio of $\delta = 0.018^{+0.018}_{-0.010}$ and, hence, the $E1$ admixture in the 1231-keV transition is $(99.97^{+0.03}_{-0.05})\%$.

G. 1277 → 89-keV Correlation

In addition to the 2^- member of the $K^\pi = 1^-$ octupole band at 1319.66 keV, the 1^- member at 1366.40 keV is also strongly populated and is depopulated via a 1277.43-keV transition in coincidence with the 89-keV transition. For the 1277 → 89-keV correlation, we find $A_2 = -0.237 \pm 0.012$ and $A_4 = -0.016 \pm 0.015$. These coefficients allow a mixing ratio of $\delta = -0.01 \pm 0.01$ which indicates an $E1$ component of $(99.99^{+0.01}_{-0.03})\%$.

It is noted[6] that the interpretation of these levels at 1319.66 and 1366.40 keV as being the respective 2^- and 1^- members of a $K^\pi = 1^-$ octupole band is somewhat tentative, since the spin sequence is inverted and the $B(E1)$ ratio[6] (0.46 ± 0.02) from the 1366.40-keV level does not overlap the theoretical prediction of the adiabatic symmetric-rotor model for a $K = 1$ band. However, spin-sequence inversion has been observed[25] previously in ^{154}Gd and band mixing can noticeably alter the branching ratios. This is discussed in more detail by Meyer.[25]

H. 1857 → 89-keV Correlation

The coefficients for the 1857.42-keV transition are $A_2 = -0.22 \pm 0.09$ and $A_4 = -0.12 \pm 0.16$. When we compare these numbers with theory for $x \to 2 \to 0$ cascades with $x = 1$, 2, 3 and 4, we find that these data can only fit a $1 \to 2 \to 0$ spin sequence. Hence, the spin of the 1946.36-keV level is assigned a value of 1. With these coefficients, the mixing ratio is determined to be $\delta = -0.03^{+0.03}_{-0.07}$ which allows a dipole component of $(99.91^{+0.09}_{-0.90})\%$. This value of the mixing ratio is consistent with either a positive- or negative-parity assignment, since both essentially pure $E1$ and $M1$ transitions are observed in this decay scheme.

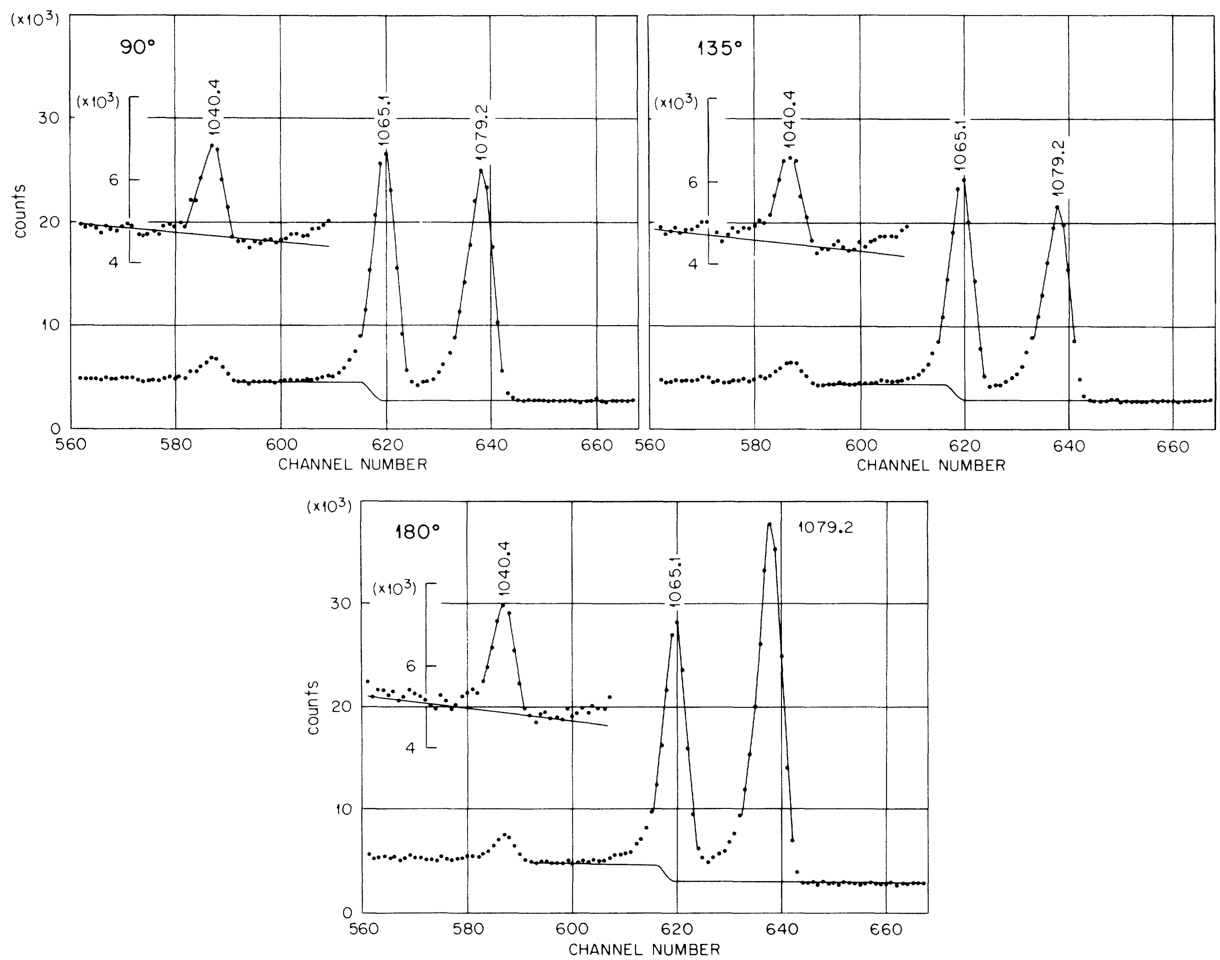

FIG. 4. The three-angle data for the 1040 → 89-, 1065 → 89-, and 1079 → 89-keV correlations in ^{156}Gd.

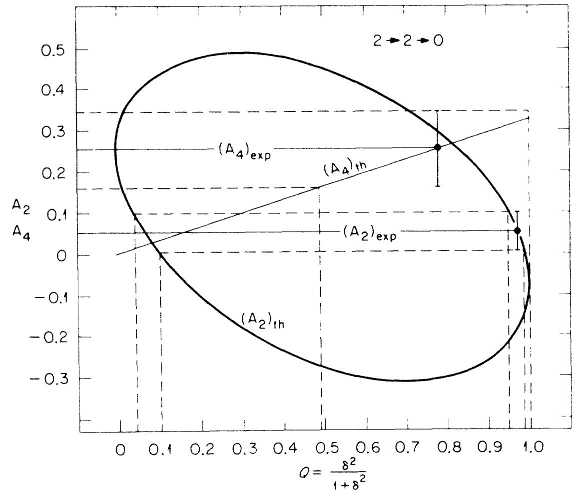

FIG. 5. Theoretical A_2 and A_4 coefficients vs $Q=\delta^2/(1+\delta^2)$ are given by the ellipse and straight line. From a comparison of the experimental data for the 1040→89-keV correlation with these curves, the mixing ratio of the 1040.44-keV transition was determined.

I. 1877→89-keV Correlation

The 1^+ level at 1965.89 keV is depopulated by a ground-state transition, an 1877.03-keV transition to the 2^+ level at 88.95 keV, and several lower energy transitions whose correlations are discussed later. The 1877.03-keV transition lies on the Compton edge of the 2097.70-keV transition so that a careful analysis of the background with this edge included is required. The A_k coefficients are $A_2 = -0.550 \pm 0.028$ and $A_4 = -0.126 \pm 0.034$ which permit a δ value of 0.40 ± 0.05. This limits the $E2$ component in the 1877.03-keV transition to $(13.8^{+3.0}_{-2.9})\%$.

J. 1938→89-keV Correlation

The 1937.71-keV transition depopulates a 1^+ level at 2026.60 keV. This peak lies on a relatively flat background and has, on the average, about 5000 counts in the peak channel of the summed data at each angle. From the experimental values of $A_2 = 0.321 \pm 0.021$ and $A_4 = -0.198 \pm 0.027$, we obtain $\delta = -0.57 \pm 0.03$ which corresponds to an $E2$ component of $(24.5^{+2.0}_{-1.9})\%$.

K. 2098→89-keV Correlation

The last double correlation to be considered is the 2098→89-keV one. The 2097.70-keV transition depopulates a 1^+ level at 2186.71 keV. The anisotropy coefficients, $A_2 = 0.581 \pm 0.022$ and $A_4 = -0.410 \pm 0.020$, yield a mixing ratio of $\delta = -1.2 \pm 0.2$ and, hence, the $E2$ component is $(59.0^{+25.2}_{-9.0})\%$. This result differs considerably from that of Bauer and Deutsch[26] who obtain $A_2 = 0.27 \pm 0.02$ and $A_4 = -0.15 \pm 0.02$ with a δ value of -0.5 ± 0.1 and a 20% $E2$ admixture. Both works are consistent with internal-conversion studies.[23] The lower correlation coefficient values of Bauer and Deutsch[26] are probably explained by competition from the 2181→89-keV correlation, since the then unknown 2180.91-keV transition must have been included in their NaI gate at 2098 keV.

V. RESULTS AND DISCUSSIONS OF ONE-THREE CORRELATIONS

Although it has been known[27] for some time that γ-γ directional correlations on the one-three (intermediate transition unobserved) cascades could be used to obtain multipolarities of transitions and level spins, practical use has been hindered by the complexity of the γ spectra and the poor resolution or efficiency of earlier detectors. With present Ge(Li) detectors such measurements are routinely carried out while doing direct cascade measurements with multichannel analysis. In our work on ^{156}Gd, we encountered several such cascades and generated a set of tables and graphs[28] to assist in the analysis of these cascades.

The four one-three correlations discussed below all depopulate the 1^+ level at 1965.89 keV. The

TABLE III. Results of a directional-correlation study of several one-three correlations in ^{156}Gd. The gating transition was the 88.95-keV, $2^+ \to 0^+$ ground-state transition.

Energy (transition) (keV)	Spin sequence ($x \to y \to 2_g^+ \to 0_g^+$)	A_2 [a, b]	A_4 [a, b]	δ	Admixture (%)
599.47	$1^+ \to 1^-$	0.149 (36)	−0.005 (67)	$-0.036^{+0.036}_{-0.044}$	$E1$ $99.87^{+0.13}_{-0.51}$
646.29	$1^+ \to 2^-$	−0.136 (07)	0.003 (12)	-0.025 ± 0.014	$E1$ $99.94^{+0.04}_{-0.02}$
723.47	$1^+ \to 1^-$	0.152 (11)	−0.011 (18)	$-0.038^{+0.011}_{-0.014}$	$E1$ $99.86^{+0.07}_{-0.09}$
811.77	$1^+ \to 2_\gamma^+$	0.045 (07)	−0.012 (13)	-0.035 ± 0.035	$E2$ $0.1^{+0.4}_{-0.1}$

[a] The last digit of the error, in parentheses, occurs in the third decimal place.
[b] $G_2Q_2 = 0.624 \pm 0.021$, $G_4Q_4 = 0.385 \pm 0.008$.

spins and parities of the levels in the cascades are discussed in the level-structure work.[10] A summary of the results of the analysis of these one-three correlations is given in Table III.

A. 599 → (1277) → 89-keV Correlation

The spin sequence of this triple cascade is $1^+ \to 1^- \to 2^+ \to 0^+$. The 599.47-keV peak (Fig. 6) lies on a high background. In addition, the post-biased amplifier stretcher was used to place this peak in the first 50 channels of the analyzer. This explains the unusual background on the low-energy side of the peak (caused by the threshold setting of the analyzer). Our A_k coefficients for this cascade are $A_2 = 0.149 \pm 0.036$ and $A_4 = -0.005 \pm 0.067$.

For this spin sequence the theoretical A_4 value for a one-three correlation vanishes identically for all values of the mixing ratio. Since our experimental A_4 term overlaps zero, the mixing ratio is not limited by the A_4 coefficient and is completely determined by the A_2 coefficient for this $1^+ \to 1^- \to 2^+ \to 0^+$ cascade. Such a determination yields two values of the mixing ratio. The larger value of $\delta = 23$ corresponds to practically pure $M2$. The K conversion coefficient[10] of the 599.47-keV transition excludes this case. The second value, $\delta = -0.036^{+0.036}_{-0.044}$, corresponds to an $E1$ component of $(99.87^{+0.13}_{-0.51})\%$, which is in agreement with the conversion coefficient.[10]

B. 646 → (1231) → 89-keV Correlation

This correlation has the spin sequence $1^+ \to 2^- \to 2^+ \to 0^+$. Again the reader is referred to Fig. 6 for a graphic presentation of the three-angle data

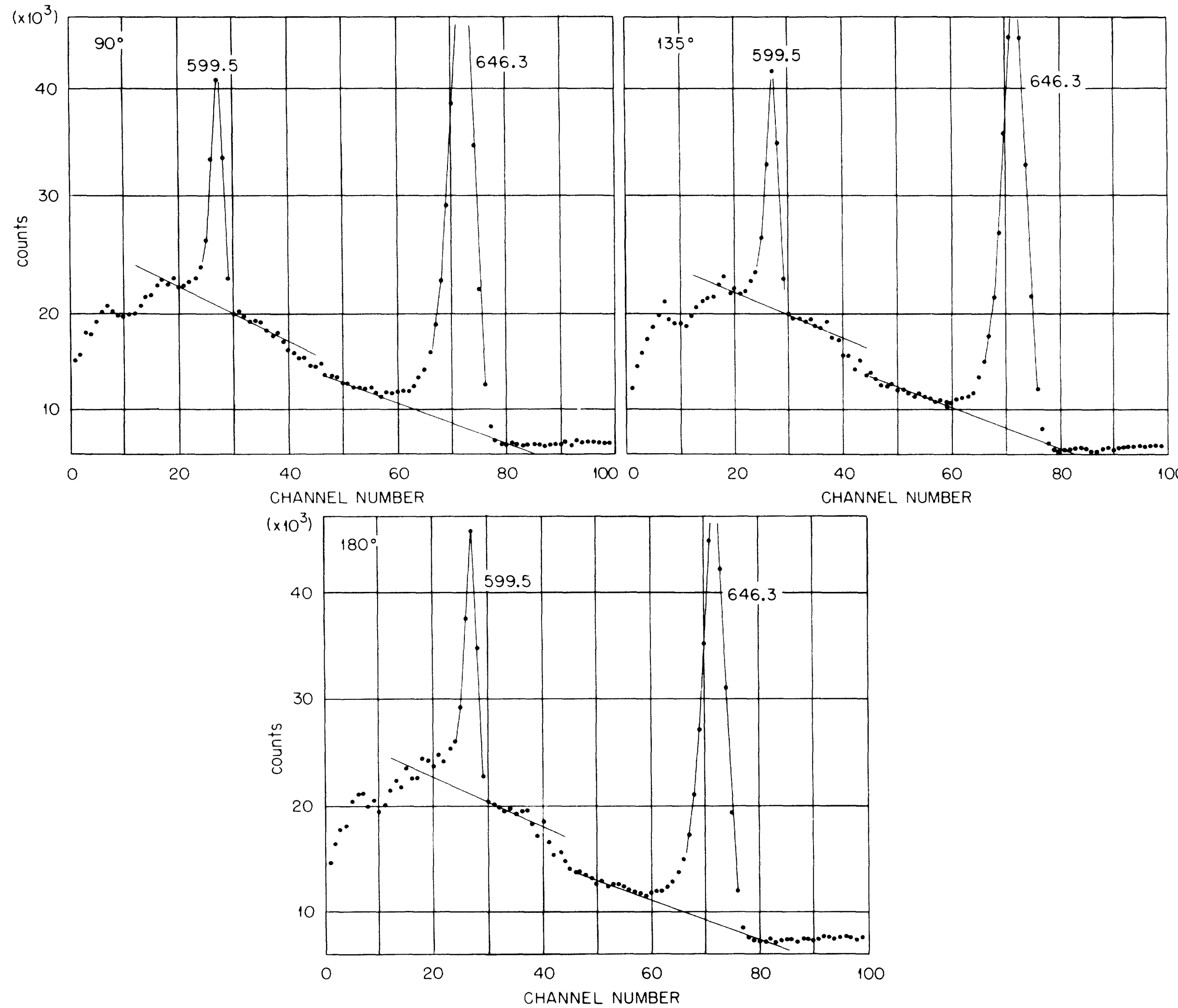

FIG. 6. Three-angle data for the 599 → (1277) → 89-keV and 646 → (1231) → 89-keV, one-three correlations in ^{156}Gd.

for this correlation. The top of the peak (45 000 counts above background for the peak channel in the 90° plot) is omitted to allow a meaningful presentation of the less-intense 599.47-keV transition. For the 646.29-keV transition, the peak-to-background ratio is very large so the sloping background is relatively unimportant. The A_k coefficients obtained from the analysis of these peaks are $A_2 = -0.136 \pm 0.007$ and $A_4 = 0.003 \pm 0.012$. The determination of the mixing ratio for this one-three correlation is illustrated in Fig. 7. We obtain $\delta = 0.025 \pm 0.014$. This δ value yields an $E1$ component of $(99.94^{+0.04}_{-0.08})\%$. Figure 7 illustrates the accuracy possible with one-three correlations.

C. 723→(1153)→89-keV Correlation

Like the 599→(1277)→89-keV correlation, this correlation has a spin sequence of $1^+ \to 1^- \to 2^+ \to 0^+$. But here the peaks are well determined with no problems introduced by the background. Our A_k coefficients for the correlation are $A_2 = 0.152 \pm 0.011$ and $A_4 = -0.011 \pm 0.018$. Again, the experimental A_4 coefficient overlaps zero so the mixing ratio is determined solely by the A_2 coefficient. Two values of δ are permitted by such a determination. The larger value, $\delta = 22$, allows essentially pure $M2$ radiation but this choice is excluded by the K conversion coefficient of the 723.47-keV transition.[10] The other value, $\delta = -0.038^{+0.011}_{-0.014}$, allows $(99.86^{+0.07}_{-0.09})\%$ $E1$.

D. 812→(1065)→89-keV Correlation

This correlation arises from a $1^+ \to 2^+_\gamma \to 2^+_g \to 0^+_g$ spin sequence. Again, good statistics (30 000 counts in the peak channel) and a small background correction permit low error limits on the anisotropy coefficients: $A_2 = 0.045 \pm 0.007$ and $A_4 = -0.012 \pm 0.013$. The value of the mixing ratio, $\delta = -0.035 \pm 0.035$, allows an $E2$ component of $(0.1^{+0.4}_{-0.1})\%$. It is most surprising to find an essentially pure $M1$ transition in these nuclei; this is the first such case reported.

VI. CONCLUSIONS

Although ^{156}Gd is more strongly deformed than ^{152}Sm and ^{154}Gd, and hence may be considered a more likely candidate to be described by the Bohr-Mottelson model, we again find disagreement between theory and experiment for the β band. Our measured $(97.2^{+1.5}_{-2.1})\%$ $E2$ component in the 1040.44-keV, $2^+_\beta \to 2^+_g$ transition differs considerably from

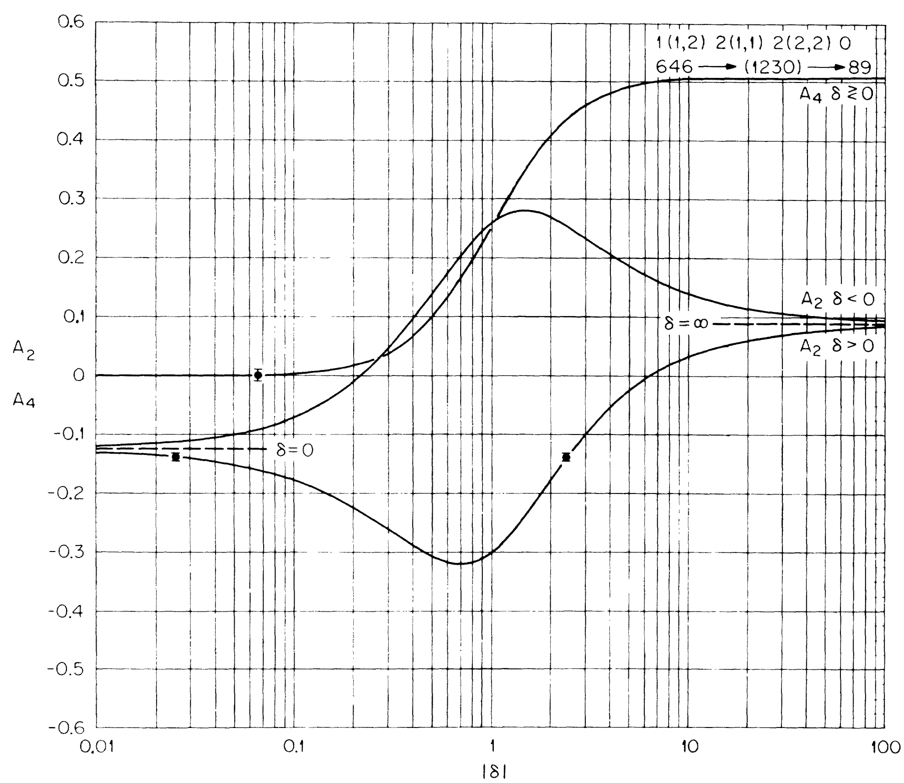

FIG. 7. A comparison between the experimental and theoretical A_2 and A_4 coefficients for the 646→(1231)→89-keV cascade in ^{156}Gd.

the $(35.7 \pm 2.4)\%$ $E2$ component predicted by the branching ratios[6,9] for a one-parameter (Z_β) band mixing of the ground-state and β band. Hence, again we have a clear discrepancy between theory and experiment for the branching ratios. The problem of two-parameter fits to the β- and γ-band branching ratios is considered in detail in our work[9] on ^{156}Eu and ^{158}Eu. At this time, then, there is still no evidence to confirm the possibility of large $M1$ admixtures in the $2_\beta^+ \to 2_g^+$ transitions from a β-vibrational band to the ground-state band.

In ^{178}Hf, a large $M1$ admixture is found in the $2^+ \to 2_g^+$ transition from a $K^\pi I = 0^+2$ state at 1276 keV, but we have shown that this $M1$ admixture does not bring about agreement with a single-parameter fit to the branching ratios as had been thought earlier.[29] Moreover, there are no collective β-vibrational levels observed in ^{178}Hf.

However, we have now shown that the transitions from three 1^+ states at 1965.89, 2026.60, and 2186.71 keV in ^{156}Gd to the ground band are predominantly $M1$. These data are the first such information on the properties of $K^\pi I = 1^+1$ quasiparticle excitations. Note that the δ values in the $1^+ \to 2_g^+$ transitions have different signs as well as magnitudes. Thus these results provide sensitive tests of any microscopic theory of such excitations. These data also suggest that the $K^\pi = 0^+$ states with no collective strength in ^{178}Hf are quasiparticle states. Admixtures of $K = 1$ states in these $K = 0$ ones in ^{178}Hf could give rise to large $M1$ admixtures as are observed from the 1^+ states in ^{156}Gd. The absence of any sizable $M1$ admixture in the $2^+ \to 2_g^+$ transitions in ^{156}Gd would argue against $K = 1$ admixtures as a source of the anomalous branching ratios for the β band.

Now that second $K^\pi = 0^+$ bands are being observed in such nuclei as ^{156}Gd and ^{158}Gd, one must be careful in interpreting the character of a band without evidence from Coulomb excitation as to its collective nature. Our results indicate that a second clue to the character of these $K^\pi = 0^+$ bands is the $M1$ strength in the $2 \to 2_g$ transition, where sizable $M1$ strength would be associated with quasiparticle excitations.

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*Present address: Physics Department, Eastern Kentucky State University, Richmond, Kentucky 40475. Also a National Science Foundation summer research participant at Vanderbilt, 1971.

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