FURTHER TEST OF $M1$ ADMIXTURES IN THE DECAY OF $2^{+\prime}$ BETA VIBRATIONAL STATES

J. H. Hamilton, A. V. Ramayya, and L. C. Whitlock
Physics Department,* Vanderbilt University, Nashville, Tennessee
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The γ-γ directional correlation of the 692-123 keV, $2^{+\prime} \to 2^+ \to 0^+$ cascade in ^{154}Gd was remeasured with an improved Ge(Li)-NaI system. The spectra in coincidence with the Compton background and the 123-keV photopeak were simultaneously recorded at each angle. The new results averaged with our earlier work yield $A_2 = -0.141 \pm 0.022$ and $A_4 = 0.311 \pm 0.040$. These values are consistent only with the 692-keV transition being essentially pure $E2$.

Earlier we reported[1] that γ-γ directional correlation studies on the $2^{+\prime} \to 2^+ \to 0^+$ cascade in ^{154}Gd did not support the suggestion of a large $M1$ admixture in the 692-keV transition from the $2^{+\prime}$ beta vibrational state. In order to obtain a consistent mixing parameter, Z_0, from the $2^{+\prime}$ member of the beta bands in several nuclei,[2,3] $M1$ admixtures have been proposed. The parameter Z_0 measures the mixing of the ground-state band and the beta vibrational band and is obtained from a comparison of the experimental reduced transition probabilities with theory. In ^{154}Gd an assumption of approximately 50% $M1$ admixture in the $2^{+\prime} \to 2^+$ transition is needed to give a consistent Z_0.

In the first report[1] of our directional correlation studies, the observed A_2 coefficient agreed with $\simeq$100% $E2$ or $\simeq$80% $M1$. Although the A_4 coefficient did not overlap either of these, it was closer to the 100% value. Thus, it was concluded that the $2^{+\prime} \to 2^+$, 692-keV transition was pure $E2$. Recently a second γ-γ directional correlation study[4] has been reported for the $2^{+\prime} \to 2^+ \to 0^+$ cascade in ^{178}Hf. In this case an 80% $M1$ admixture in the $2^{+\prime} \to 2^+$ transition is needed to obtain a consistent Z_0 parameter. The directional correlation studies indicate an 80% $M1$ admixture in this transition also. Thus, both the directional correlation coefficients and the relative transition probabilities are consistent with the same admixture in ^{178}Hf in contrast to the studies in ^{154}Gd.

In light of the first report[5] which indicated a discrepancy between theory and experiment in ^{154}Gd, Mottelson[6] pointed out the major crisis in the application of rotational relationships in these nuclei indicated by this discrepancy and stressed the importance of accurately determining these admixtures. At the 1968 nuclear structure conference in Dubna, the work of Nielsen, Nielsen, and Rud[4] was reported. As a result of the new work in ^{178}Hf, there were questions raised about the validity of the ^{154}Gd directional correlation work.[1] Because of the importance of these $M1$ admixtures and because of the difference between the ^{154}Gd and ^{178}Hf work, the γ-γ directional correlation of the 692-123-keV, $2^{+\prime} \to 2^+ \to 0^+$ cascade in ^{154}Gd has been remeasured under improved experimental conditions.

The system was nearly identical to that used in the previous work[1] where a 15-cm^3 Ge(Li) detector was used to measure the gamma rays in coincidence with the 123-keV gamma rays observed in a 2×2-in. NaI detector. Important changes, however, were made in the previous experiment. The source strength was reduced by a factor of 2 to improve the resolution of the system and the true-to-chance ratio. A lead-copper-cadmiun absorber was placed between the source and the Ge(Li) detector to reduce low-energy gamma rays in this detector. This reduction also improved the resolution of the system. Improved resolution (4.4 keV compared with 5.2 keV earlier[1]) gave a better separation between the 692- and 725-keV transitions and between the 692-keV transition and the 893-keV Compton edge just below the 692-keV photopeak. Thus, the accuracy of the determination of the background under the peak was improved. Finally, another single-channel analyzer and coincidence circuit and a routing circuit were added to the system so that two NaI gate signals could be used simultaneously and the spectrum in coincidence with each of the gates stored in separate halves of the 4096-channel analyzer. The spectrum above 500 keV in coincidence with the 123-keV transition was stored in the first 2048 channels and the spectrum in coincidence with the Compton background under the 123-keV peak was stored in the second 2048 channels. In the latter measurement, the gate energy was centered on 320 keV. To set the gate just above 123 keV brings in back-scattered peaks and enhances the 873-keV Compton edge. Above this is the 248-keV transition, so that the background gate was set at 320 keV. This energy was the lowest gate energy where the Compton distri-

Table I. Directional correlations of γ rays in ^{154}Gd.

$\gamma\gamma(\theta)$ (keV)	Spins and parities	Ref.	$\Omega_2 G_2 A_2$	$\Omega_4 G_4 A_4$	A_2	A_4
1274-123	$2^-, 2^+, 0^+$	Ref. 1	0.202 ± 0.004	0.003 ± 0.004		
		Present work	0.205 ± 0.012	0.007 ± 0.012		
		Average	0.203 ± 0.004[a]	0.005 ± 0.004	0.227 ± 0.006[b]	
873-123	$2^{+\prime\prime}, 2^+, 0^+$	Ref. 1	-0.011 ± 0.013	0.204 ± 0.015		
		Present work	0.016 ± 0.018	0.174 ± 0.019		
		Average	0.002 ± 0.011	0.187 ± 0.013[c]	0.002 ± 0.012[d,e]	0.323 ± 0.001[f]
692-123	$2^{+\prime}, 2^+, 0^+$	Ref. 1	-0.119 ± 0.023	0.148 ± 0.024		
		Present work	-0.134 ± 0.036	0.213 ± 0.038		
		Average	-0.126 ± 0.020	0.180 ± 0.020	-0.141 ± 0.022[d,g]	0.311 ± 0.040[g,h]

[a] $\Omega_2 G_2 = 0.894 \pm 0.029$ obtained as a ratio of this entry to that in column 6. (Ref. 1 obtained 0.89 ± 0.03.)
[b] R. Stiening and M. Deutsch [Phys. Rev. 121, 1484 (1961)], 2(1)2(2)0 theory 0.250, $M2$ admixture $\simeq 0.1\%$.
[c] $\Omega_4 G_4 = 0.578 \pm 0.040$ obtained as ratio of this entry to that in column 7. (Ref. 1 obtained 0.63 ± 0.04.)
[d] Corrected with $\Omega_2 G_2 = 0.894$.
[e] Yields $\delta = 10 \pm 2$, since $M1$ admixture is known to be small (Refs. 7 and 8) in gamma-band transitions.
[f] A_4 (theory) compatible with A_2 (experimental).
[g] A_2 and A_4 combined yield $\delta = -(10^{+5}_{-3})$ (from the lower limit on δ, $M1 \lesssim 2\%$).
[h] Corrected with $\Omega_4 G_4 = 0.578 \pm 0.040$.

butions under the 123-keV transition could be measured reliably. This energy is quite suitable to measure the flat Compton background coincidences since essentially all of the Compton background under the 123-keV peak arises from gamma rays above 590 keV.

The true correlation and the background were simultaneously measured at 90°, 135°, and 180°, respectively, for 10 cycles. Each cycle was a 23-h run at each angle. The attenuation correction which arises from the lifetime of the 123-keV state and the solid angle of the Ge(Li) detector were determined from known correlations in ^{154}Gd as before. Only now one does have a much improved correction for the contribution of the Compton distribution under the 123-keV peak to the 873- to 123-keV correlation. In the earlier work, this correction was measured only a few times at each angle. Since this is the correlation from which $\Omega_4 G_4$ is obtained, this correction is important. The new correction leads to a smaller $\Omega_4 G_4$ and thus a larger A_4 in the other correlations. There also exists the possibility of a small $M1$ admixture in the 873-keV transition. The reported[7] value of δ for the 873-keV transition is 10 ± 2 which is in agreement with the value we have determined from A_2. For the similar transition from the gamma band in ^{152}Gd, a recent report[8] gives $\delta = 3.7^{+1.2}_{-0.9}$. Since the $M1$ admixture is known to be small, our A_2 value for this cascade limits δ to greater than 7 for the 873-keV transition in ^{154}Gd. Even if a δ as small as 3.7 had been found in ^{154}Gd also, it would raise the $\Omega_4 G_4$ correction (lower corrected A_4) only 5.5% and this would not alter our conclusion.

The results of the new and the earlier[1] measurements are given in Table I. As seen in Fig. 1, the A_2 and A_4 coefficients are now consistent in their prediction of essentially pure $E2$ for the 692-keV transition from the $2^{+\prime}$ beta vibrational state. The same A_2 coefficient was obtained in both experiments. The A_4 coefficient is now larger than the pure $E2$ value while before[1] it was less than the pure $E2$ value. The increase in A_4 was primarily from the data in the 692-keV correlation itself with a smaller increase from a change in $\Omega_4 G_4$. Because of the better resolution and the improved Compton background measurements, a greater confidence is placed in the new measurements even though the statistical error is somewhat larger as a result of taking only 10 cycles as compared with 20 cycles before. Because of this greater confidence level, a straight average of the two measurements is considered better than an average based on statistical weighting according to errors. Thus we conclude that the 692-keV transition from the $2^{+\prime}$ beta vibrational level is essentially pure $E2$.

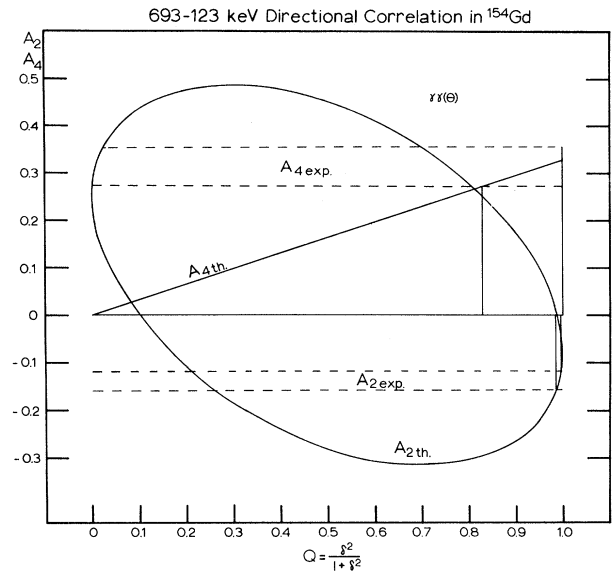

FIG. 1. Theoretical correlation coefficients A_2 and A_4 for a $2 \rightarrow 2 \rightarrow 0$ cascade. The dashed lines are the limits of the experimental values.

How one puts both the ^{154}Gd and ^{178}Hf results into a consistent scheme is an open question. It is possible, of course, that both experiments are right and that they reflect a difference in the softness of nuclear deformation in the two nuclei as ^{154}Gd lies at the beginning of this deformed region but ^{178}Hf more towards the center. In an effort to understand the possible sources of these discrepancies in Z_0, a mixing of the beta and gamma bands was tried[9] in ^{152}Gd and ^{154}Gd. While this improved the agreement in the gamma band, it did not help the consistency in the beta band. Further experiments are very important to clarify our understanding of these vibrational states where a new description may be needed.

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COULOMB DISTORTION EFFECTS IN LARGE-ANGLE $M1$ ELECTROEXCITATION*

B. T. Chertok† and W. T. K. Johnson†
The American University, Washington, D. C.
(Received 12 November 1968)

A reanalysis of inelastic electron-scattering measurements from giant $M1$ states in ^{28}Si and ^{12}C and in ^{26}Mg is made using Coulomb-distortion corrections in place of the plane-wave Born-approximation analysis. It is shown that the corrections even for light nuclei can reduce the nuclear form factors for $M1$ transitions outside the experimental error quoted in the plane-wave Born approximation analysis of electron scattering. This reduction in $B(M1,q)$ is magnified at the photon point.

Many experiments have been performed by groups at Stanford,[1] Darmstadt,[2] and the Naval Research Laboratory[3] using $100° \leq \theta \leq 180°$ electron scattering to pick out prominent magnetic-dipole transitions in light nuclei from ^{6}Li to ^{28}Si. Complementary measurements at Illinois[4] of radiative widths of some of these giant $M1$ states have been made by nuclear resonance fluorescence. The measured nuclear form factors, $B(M1,q)$, have been important theoretically[5] in understanding the role of spin-orbit coupling and particle-hole configurations in light nuclei as the $1p$, $2s$, and $1d$ shells are being filled and in determining the transition radius[6] where the magnetic-dipole transitions occur in nuclear matter. For spin-, isospin-flip transitions, $00 \rightarrow 11$, in self-conjugate nuclei ($A = 4N$), Kurath[5] has shown that the spin-orbit coupling term in the interac-