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GAMMA-GAMMA DIRECTIONAL CORRELATIONS IN ^{154}Gd

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Gamma-gamma directional correlation measurements have been made for the following cascades in ^{154}Gd: 723-873 keV, $A_2 = -0.101(8)$, $A_4 = 0.006\ (10)$; 723–(873)–123 keV, $A_2 = -0.049(11)$, $A_4 = 0.004(16)$; 873-123 keV, $A_2 = -0.002\ (6)$, A_4 (attenuated) $= 0.246(6)$; 1274-123 keV, A_2 (attenuated) = 0.188(7), and A_4 (attenuated) = 0.005(12). Multipole mixing parameters consistent with the experiments are: $\delta(723) = 0.00 \pm 0.04$, $\delta(873) = -10.2 \pm 0.8$.

[RADIOACTIVITY ^{154}Eu; measured $\gamma\gamma(\theta)$; deduced, δ.]

INTRODUCTION

The nucleus ^{154}Gd lies in the transitional region where deviations from the rotational model and coupling between the $\beta-$ and $\gamma-$ vibrational bands and the ground state rotational band are expected. This allows magnetic dipole (MI) admixtures in transitions from the $\beta-$ and $\gamma-$ vibrational bands which otherwise would be pure electric quadrupole (E2) transitions according to the predictions of the collective model. Measurements of the admixtures to these transitions give valuable information for the understanding of the collective motion.

Prior experimental investigations of these admixtures have usually been based, at least in some essential respects, on γ - γ directional correlation measurements performed with NaI(Tl)-NaI(TI) or NaI(Tl)-Ge(Li) detector systems. Hence, it was considered desirable to investigate the decay of ^{154}Eu, with particular emphasis on a systematic study of cascades involving the 2^+ (873 keV)2^+ transtition, employing Ge(Li) detectors in both channels. Furthermore, interpretation of some of the correlation experiments hinges upon a knowledge of the attenuation coefficient due to the finite lifetime of the 123 keV level in ^{154}Gd. In the present work, data relevant to this attenuation are obtained using the same radioactive source, Ge(Li) detectors, and procedures as used in the correlation experiments involving the 873 keV radiation. The experiments reported here are a part of an investigation which will include triple gamma-ray correlation experiments, work that is still in progress [1].

The principal features of the level scheme in ^{154}Gd, according to the work of R. A Meyer [2] and J.B. Gupta *et al.* [3], are shown in Fig. 1. Gamma-gamma directional correlation measurements have been made for the 723-873, 723-(873 unobserved)-123, 873-123, and 1274-123 keV cascades. The M1 admixture in the 873 keV $2^+ - 2^+$

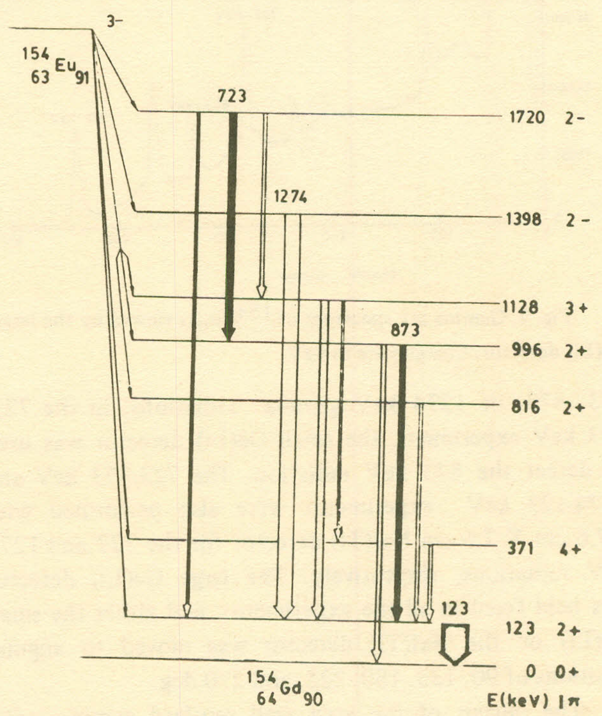

Fig. 1. Principal features of the energy level scheme for ^{154}Gd, following the beta decay of ^{154}Eu.

transition and a limit on the M2 admixture in the 723 keV $2^- - 2^+$ transition have been deduced. Measurement of the 1274-123 keV cascade has also been carried out in order to provide information on the attenuation of correlations due to the relatively long life (1.2 ns) of the 123 keV level.

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EXPERIMENTAL PROCEDURE AND RESULTS

Two solid state Ge(Li) detectors and a NaI(T1) scientillation detector were used in conjunction with standard fast-slow coincidence circuits, with resolving time of about 20 ns, and a 4096 channel dual analog-to-digital converter (ADC). A digital computer was used for on-line data collection and control of the experiment. The radioactive source used in the experiments was prepared by evaporation of an HC1 solution of $EuCl_3$ to dryness.

A schematic representation of the γ-ray spectrum accompanying the decay of 8.8-yr ^{154}Eu is shown in Fig. 2. A Ge(Li) detector of about 15 cm^3 active volume was used to detect the 123 keV gamma, and a Ge(Li) detector of 73 cm^3 active volume was used to detect the

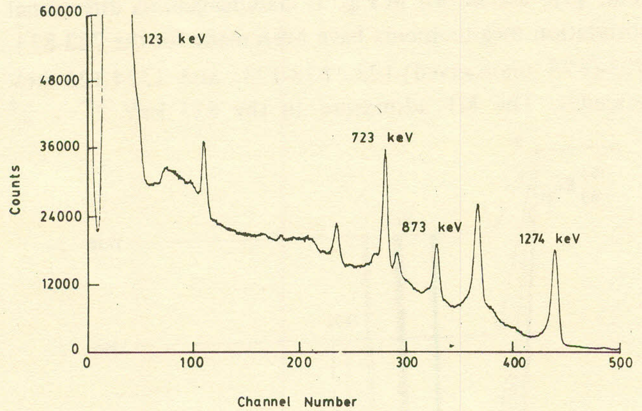

Fig. 2. Gamma ray spectrum of ^{154}Eu, as viewed by the large Ge(Li) detector. Energies are in keV.

723, 873, or 1274 keV gamma radiations; in the 723-873 keV experiment, the small Ge(Li) detector was used to detect the 873 keV radiation. The 723-873 keV and 1274-123 keV experiments were also performed with a 7.6 cm X 7.6 cm NaI(Tl) detector for the 723 and 1274 keV radiations, respectively. The large Ge(Li) detector was held fixed in all the experiments, and either the small Ge(Li) or the NaI(Tl) detector was moved to angular positions of 90, 135, 180, 225, and 270 deg.

The output of the least well resolved gamma radiation in each experiment was routed to the ADC and this coincidence spectrum was analysed by fitting to a linear background plus one to three Guassian distributions. In this manner, effects due to interfering cascades, scattering, etc., were minimized. In the experiments performed, the radiation not sent to an ADC but selected by a single channel pulse height analyzer was relatively well resolved from interference in the coincidence spectrum. The radiations sent to the ADC for spectrum analysis were: 723 keV in the 723-873 keV experiments; the 123 keV and the 723 keV radiations in two versions of the 723-(873)-123 experiment, with corresponding adjustments in the width of the energy window which selected the other radiation; 123 keV in the 873-123 keV experiment; 1274 keV in the 1274-123 keV experiments.

Corrections for imperfect source centring, for slight variations in the solid angle subtended by the movable detector, and for small drifts in electronics were made by normalizing the coincidence data to the product of the singles counting rates of the two detectors. This over-corrects for decay of the radioactive source with time, but the effect is negligible here. The data were corrected for accidental coincidences arising from the finite resolving time of the coincidence circuit by subtracting results of accidental coincidenc. runs from the total coincidences channel by channel. Corrections for the finite angular resolution of the detectors were made by using tables of Yates [4] and Camp and Van Lehn [5] for the NaI(Tl) and Ge(Li) detectors respectively.

The lifetime of the 123 keV level is relatively long. This causes attenuation of the correlation in the cascades proceeding through this level. The attenuation factor G_2 has been determined for liquid sources by study of the 1274-123 keV correlation by Steining and Deutsch [6], Rud and Nielson [7], Gupta *et al.* [3], and Sarper *et al* [8]. The attenuation coefficient G_4 has been determined by Gupta *et al.* [3] from the 873-123 keV cascade, again using a liquid source.

For the solid source that was used here, G_2 was determined from the results of the 1274-123 keV cascade, which gave $A_2 = 0.188 \pm 0.007$. On the basis of previous work [3,8], we take $A_2 = 0.235 \pm 0.005$ for the unattenuated correlation. The attenuation factor is then $G_2 = 0.80 \pm 0.03$. A precise knowledge of the A_4 correlation coefficients is not required in the interpretation of our results. However, a value $G_4 = 0.76 \pm 0.03$ can be inferred on the basis of results for the 873-123 keV correlation. The G_2 and G_4 factors for the solid source represent a few per cent greater attenuation than found in the liquid source studies.

The experimental results are summarized in Table 1. The indicated error limits are mainly statistical counting errors, with some allowance for systematic errors in solid angle and attenuation correction factors. The NaI(Tl)-Ge(Li) experiments were conducted for comparison with the corresponding Ge(Li)-Ge(Li) experiments in order to investigate possible discrepancies due to the poorer energy resolution of the NaI(Tl) detector. In the 1274-123 keV

Table 1. Results of directional correlation measurements
(uncorrected values for A_2 and A_4 lack finite angular resolution and attenuation corrections)

Cascade (energies in keV)	Detectors	Uncorrected			
		A_2	A_4	A_2	A_4
723-873	Ge-Ge	– 0.093 (15)	0.003 (16)	– 0.102 (16)	0.004 (32)
	NaI-Ge	– 0.089 (5)	0.004 (5)	– 0.101 (8)	0.006 (10)
723-(873)-123	Ge-Ge	– 0.036 (8)	0.003 (8)	– 0.049 (11)	0.004 (16)
873-123	Ge-Ge	– 0.001 (5)	0.192 (5)	– 0.002 (6)	0.323 (1)[a)]
1274-123	Ge-Ge	0.168 (6)	0.003 (7)	0.235 (5)[b)]	0.006 (14)
	NaI-Ge	0.150 (5)	0.004 (5)	0.220 (7)	0.008 (10)

a) A_4 compatible with measures A_2.
b) Unperturbed A_2 taken from previous work [3, 8].

experiment performed with the NaI(Tl)-Ge(Li) detector system, the measured A_2 is low. A very weak 1246 keV gamma radiation is not resolved in the NaI(Tl) detector. This gamma is in coincidence with the 123 keV radiation. An approximate correction can be made for the effect of this interfering cascade. The A_2 coefficient for the 1274-123 keV NaI(Tl)-Ge(Li) experiment is thereby raised by about 0.01, which brings the two experiments into reasonable agreement.

INTERPRETATION OF RESULTS

1274-123 keV Correlation. This correlation was measured in order to determine the G_2 attenuation coefficient applicable to cascades proceeding through the 123 keV level. The correlation was measured using both NaI-Ge and Ge-Ge detector systems, and some discrepancy between the results was noted. Only the Ge-Ge result was used in the determination of the attenuation coefficient; the experiment gave $A_2 = 0.188 \pm 0.007$, corrected for finite angular resolution. Calculation of the G_2 coefficient has been outlined above. The discrepancy found between the two sets of measurements is indicative of systematic errors that can occur because of relatively small interference effects which accompany the use of NaI(Tl) detectors. It is to be noted that if the G_2 attenuation coefficient were based on the NaI-Ge experiment, systematic errors would be introduced in the interpretation of other experiments.

873-123 keV Correlation. The large A_4 value for this correlation is indicative of the dominant electric quadrupole character of the 873 keV radiation. The observed A_2 value delimits the M_1 admixture in the 873 keV transition according to $\delta = -10.2 \pm 0.8$, where the mixing parameter is defined according to the conventions of Krane and Steffen [9]. A value of δ (873) = 0.33 is also consistent with the observed A_2 coefficient; however, the corresponding A_4 coefficient would be nearly zero, which is preclauded by the experiment. Lange *et al.* [10] have measured $A_2 = -0.007 \pm 0.13$, using two Ge(Li) detectors. Cupta *et al.* [3], using a NaI-Ge detector system, found $A_2 = 0.004 \pm 0.006$; they also present a tabulation of prior results.

Corresponding to the mixing parameter determined from the A_2 coefficient, the expected A_4 coefficient is 0.323 ± 0.001. The observed A_4 coefficient, corrected for finite angular resolution of the detectors, is 0.246 ± 0.006. Comparison of this experimental result for A_4, and the A_4 required for consistency with the observed A_2, the correction for attenuation of the correlation due to the lifetime of the 123 keV level is found to be $G_4 = 0.76 \pm 0.03$.

723-873 keV correlation. The spin sequence is known to be $2^- - 2^+ - 2^+$, with the 723 keV and the 873 keV transitions dominantly electric dipole (E1) and electric quadrupole (E2), respectively. No significant difference was found between the experimental results obtained using the Ge-Ge and, the NaI-Ge detector system. The use of a NaI detector in one channel facilitates the reduction of the statistical contribution to the error limits, but there is greater uncertainty in the correction for unwanted interference in the correlation. The observed small value of A_4 is consistent with the dominant dipole character of the 723 keV transition. Rud and Nielson [7], using NaI detectors, found $A_2 = -0.114 \pm 0.010$ and an A_4 coefficient consistent with zero.

With the limitation placed on the multipole mixing of the 873 keV radiation by the results of the 873-123 keV correlation, the results here may be used to delimit the M_2 admixture in the 723 keV radiation. The observed A_2 coefficient for the 723-873 keV correlation then delimits this admixture according to δ (723) = 0.00 ± 0.04; the admixture of M_2 radiation in the 723 keV transition is limited to 0.16%. Small limits on the M_2 admixture have also been reported by Rud and Nielson [7], Varnell *et al.* [11], and Ober *et al.* [12], who have reported limits of 0.09, 0.25, and 0.64%, respectively.

723-(873)-123 KeV Correlation. This correlation, with the intermediate 873 keV transition unobserved, provides less opportunity for precise determination of mixing parameters because the mixing parameter for the 873 keV transition enters into the directional coorrelation only as the square. However, the experiment is useful in establishing consistency among various experiments performed with the same apparatus and procedures. If δ (873) = −10.2, in accordance with 873-123 keV correlation, and if δ (723) = 0, in accordance with the 723-873 keV correlation, then the expected results for the 723–(873)–123 correlation are A_2 = 0.052 and A_4 = 0. These expected results are in excellent agreement with the experimental results, A_2 = 0.049 ± 0.011 and A_4 = 0.004 ± 0.016. Gupta *et al.* [3], using a NaI-Ge detector system, found A_2 = − 0.045 ± 0.007 and A_4 = 0.033 ± 0.010; their A_2 coefficient is consistent with and their A_4 coefficient is slightly higher than the present results.

DISCUSSION

The limitation on the mixing parameters for the 723 and 873 keV transitions which are consistent with all of the present experimental results are: δ (723) = 0.00 ± 0.04 expresses the possible admixture of M_2 radiation in the dominantly electric dipole 723 keV transition, and δ (873) = − 10.2 ± 0.8 expresses the admixture of some M_1 radiation in the dominantly electric quadrupole 873 keV transition. Based on his analysis of available data, Krane [13] lists δ (873) = − 9.3 ± 0.5.

Krane [14], in a review of E_2/M_1 multiple mixing ratios, has tabulated the results of experimental measurements and theoretical calculations. Greiner [15] has employed a collective model in which the neutrons and protons have differing deformations to calculate [δ] (873) = 12.4. Bes *et al.* [16] have employed a microscopic model in which excited states are viewed as collective rotations and intrinsic excitations described in terms of pairs of quasiparticles to calculate [δ] (873) = 7.3. Krane [14] discusses the problem of comparison of signs of mixing parameters.

Kumar *et al* [17] have obtained reasonable agreement with experimental values for many observables by use of two versions of their microscopic model. Their dynamic pairing plus quadrupole model (DPPQ) gives δ (873) = − 41, while their more recently developed dynamic Nilsson, Strutinsky, Belyaev model (DNSB) gives δ (873) = − 16.3. Although the latter model gives better agreement with experiment in this instance, there are other instances where the older model gives better results. The DNSB model permits use of a much extended configuration space and the model is almost parameter free in the sense that few, if any, parameters need to be adjusted for each nuclide. In view of the sensitivity of an observable such as a mixing parameter to details of the nuclear wave functions, the reasonable agreement between model results and experiment is impressive and indicative of a model that provides a realistic description of the nucleus.

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