Angular-correlation measurements of small multipole admixtures in gamma-ray transitions in $^{207}Pb^{\dagger}$

Morton Kaplan and E. Jane Wilson
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
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Precise angular-correlation measurements have been made on the 1770-570-keV and 1063-570-keV γ-ray cascades in ^{207}Pb. By using energy-gated timing analysis and obtaining good counting statistics at many angles, we have derived angular-correlation coefficients with significantly smaller uncertainties than previously reported. Data for the highly anisotropic 1063-570-keV correlation confirm the presence of a small $E5$ admixture in the predominantly $M4$ ($\frac{13}{2}+\to\frac{5}{2}-$) transition. The nearly isotropic 1770-570-keV cascade exhibits considerably less anisotropy than found in earlier work and corresponds to a mixing of about 1% $E2$ into the ($\frac{7}{2}-\to\frac{5}{2}-$) $M1$ transition.

[RADIOACTIVITY ^{207}Bi; measured $\gamma\gamma(\theta)$; deduced γ-mixing ^{207}Pb transitions.]

The angular-correlation technique employing energy-gated timing analysis has been applied to the study of the ($\frac{13}{2},\frac{5}{2},\frac{1}{2}$) and ($\frac{7}{2},\frac{5}{2},\frac{1}{2}$) γ-γ cascades in ^{207}Pb. The $\frac{7}{2}-$ and $\frac{13}{2}+$ states are independently populated by electron-capture decay of ^{207}Bi, as indicated in Fig. 1 which gives the major aspects of the decay scheme[1] relevant to the present work. Previous measurements of both cascades have indicated the presence of small admixtures of higher multipole radiation in the ($\frac{13}{2}+\to\frac{5}{2}-$) $M4/E5$[2-5] and ($\frac{7}{2}-\to\frac{5}{2}-$) $M1/E2$[6] transitions. Our experimental objective was the confirmation of these higher-multipole admixtures and the derivation of the respective angular-correlation coefficients (and corresponding mixing ratios) with greater accuracy than was previously known. This was particularly important for the ($\frac{7}{2}-\to\frac{5}{2}-$) 1770-keV transition, where the single reported measurement[6] was not free of ambiguity. In addition, these quantities will be useful in the analysis of a nuclear orientation experiment[7] to measure the magnetic moment of ^{207}Bi.

The 1063-570-keV cascade presented few experimental difficulties due to the high relative intensity of each of the γ rays (see Fig. 1) and the large expected anisotropy $\epsilon=[W(\pi)-W(\pi/2)]/W(\pi/2)=0.386$. In contrast, the very nearly isotropic behavior of the 1770-570-keV cascade, $\epsilon=-0.009$, together with the low intensity of the ($\frac{7}{2}-\to\frac{5}{2}-$) transition, posed a more challenging and difficult situation.[8]

The angular-correlation measurements were performed with a three-detector system using 5.1 × 5.1-cm NaI(Tl) crystals mounted on RCA 8575 (or 8850) photomultiplier tubes. Each detector assembly was on a moveable arm attached to the 114-cm-diam angular-correlation table, and adjustments could be made radially, vertically, and circumferentially with respect to the radioactive source located at the center of the table. The central arm of the system was designated the fixed counter. The remaining two arms were set successively at various angles between 90 and 270° with respect to the fixed counter, allowing simultaneous measurements at two angles.

The timing analysis was effected by using constant fraction timing discriminators (CFTD) operating from the photomultiplier anode pulses. The discriminator output from the fixed counter provided the start signal of a time-to-amplitude converter (TAC). The TAC stop signals originated from the CFTD pulses of the moveable counters, after each was delayed by different known times in the nanosecond region in order to separate the respective timing spectra of the two detectors.

In order to minimize the accidental coincidence rate and optimize the time resolution, the timing information from the TAC was gated by energy criteria imposed on the start and stop γ-ray signals. The dynode pulses from the photomultipliers were energy analyzed and a slow coincidence was required between the selected γ-ray photopeaks from the fixed counter and each moveable counter. These energy coincidence outputs provided the enabling signals for a linear gate which passed the timing pulses from the TAC.

The time spectra from the two detector pairs were stored in a multichannel analyzer and the energy-selected singles and coincidence events were separately recorded in individual scalers. This technique of gating the timing signal with the slow energy coincidence signal minimizes the accidental coincidence rate but also provides a direct measure of this rate in the form of a flat background in the timing spectra. Thus the necessity for measuring the resolving times of various electronic units is eliminated, and the true prompt time-coincidence peak can be accurately determined even with a high chance-coincidence rate.

The radioactive source used in our experiments consisted of approximately 25 μCi ^{207}Bi in 0.5 N HNO_3. The small volume of liquid was sealed in a plexiglas ampoule and mounted in a holder in the center of the angular correlation table. Scattering and electronic saturation effects were minimal with the source strength used, and the accidental coincidence rates were relatively low. The prompt time-resolution with the ^{207}Bi source was 2.3 nsec full width at half maximum (FWHM), at a source-to-detector distance of 10 cm.

Integration of the prompt peaks in the timing spectra and subtraction of the average background due to accidental coincidences yielded the true coincidence data. In order to correct for small differences in detector efficiencies, energy windows, or other nonuniformities, the data at each angle was divided by the singles counting rates of the fixed and moveable counters. The angular correlation coefficients were determined from the experimental $W(\theta)$ vs θ data by least-squares fitting to the function

$$W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta) ,$$

where P_2 and P_4 are Legendre functions. The best-fit values A_0, A_2, and A_4, along with their associated errors, were normalized to $A_0 = 1$ to give the desired quantities. These angular correlation coefficients, after correction for the

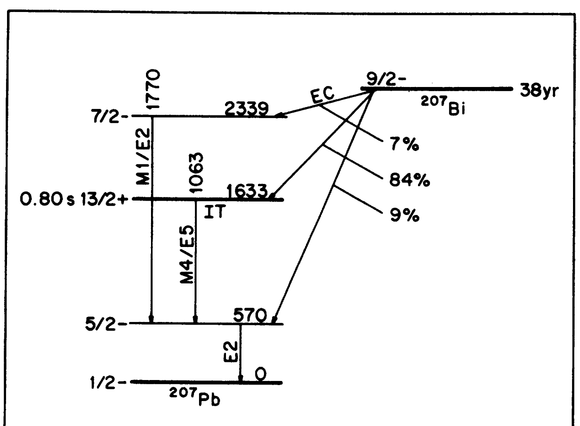

FIG. 1. Partial decay scheme of ^{207}Bi showing the γ-ray cascades in ^{207}Pb studied in the present work.

finite solid angles subtended by the detectors,[9] were compared with the theoretical F coefficients[10] for the appropriate transitions to obtain the mixing ratios for the first (mixed) member of each cascade.

The experimental data and fit curve for the 1063-570-keV, $(\frac{13}{2}, \frac{5}{2}, \frac{1}{2})$, cascade are given in the upper half of Fig. 2. Each data point represents approximately $(5-7)\times 10^4$ true coincidence counts, and the statistical error is indicated by the vertical bar. Both the fit curve and the data are normalized to $A_0 = 1$. The derived coefficients, after incorporating the solid-angle corrections, are $A_2 = 0.2202$ (28) and $A_4 = -0.0277$ (38). An additional correction must be made to compensate for the interference of the 1770-570-keV cascade. This was estimated from the relative areas in the observed γ-ray spectra, the position of the 1063-keV γ-ray window, and the 1770-570-keV correlation measurement, and amounted to 6.3%. The final results are given in Table I along with a comparison of earlier work and theoretical predictions for pure $M4$ and mixed multipolarity $\delta(E5/M4) = -0.04$ of the $(\frac{13}{2}+ \rightarrow \frac{5}{2}-)$ transition. The agreement with the previous work is quite good and confirms, with smaller error limits,

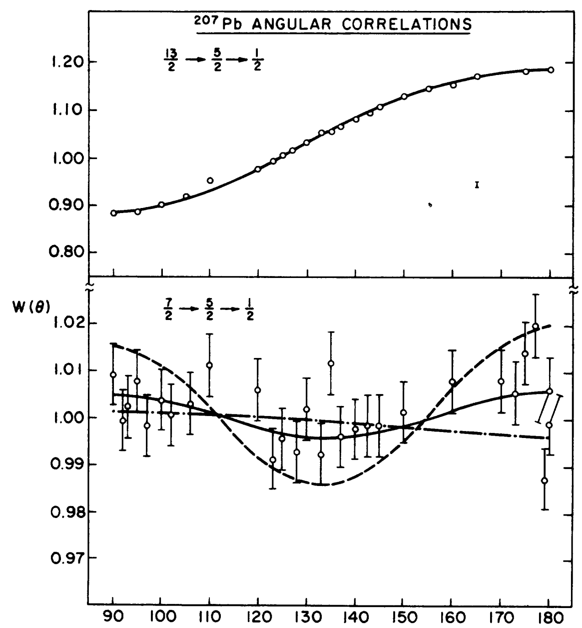

FIG. 2. Angular correlation results for γ-ray cascades in ^{207}Pb. The upper half of the figure is for the 1063-570-keV $(\frac{13}{2}, \frac{5}{2}, \frac{1}{2})$ cascade and the lower half is for the 1770-570-keV $(\frac{7}{2}, \frac{5}{2}, \frac{1}{2})$ cascade. The experimental errors are indicated by vertical bars and the solid curves are fits to the data. See text for details. Note the scale factor of 10 difference between the upper and lower parts of the figure.

TABLE I. Angular-correlation coefficients for γ-ray cascades in ^{207}Pb.

Correlation	Reference	A_2	A_4	Mixing ratio δ[a]
1063-570 keV ($\frac{13}{2}\rightarrow\frac{5}{2}\rightarrow\frac{1}{2}$)	This work	0.235 (3)	−0.029 (4)	−0.041 (9)
	Ref. 2	0.232 (7)	−0.022 (3)	−0.03[b]
	Theory $\frac{13}{2}(4+5)\,\frac{5}{2}\,(Q)\,\frac{1}{2}$	0.235	−0.025	−0.04
	Theory $\frac{13}{2}(4)\,\frac{5}{2}\,(Q)\,\frac{1}{2}$	0.221	−0.018	0
1770-570 keV ($\frac{7}{2}\rightarrow\frac{5}{2}\rightarrow\frac{1}{2}$)	This work	−0.003 (3)	0.010 (4)	−0.094 (4)
	Ref. 6	−0.0087 (89)	0.029 (14)	−0.086 (13)
	Theory $\frac{7}{2}(Q+D)\frac{5}{2}\,(Q)\,\frac{1}{2}$	−0.003	−0.0007	−0.094

[a] Amplitude $(L+1)/L$ for the first transition in each cascade.
[b] Value calculated in Ref. 1.

the admixture of approximately 0.1% $E5$ multipole intensity into the predominantly $M4$ transition.

The lower half of Fig. 2 presents the normalized experimental data for the 1770-570-keV, $(\frac{7}{2}, \frac{5}{2}, \frac{1}{2})$, cascade. Each data point represents approximately $(2-3)\times 10^4$ true coincidence counts and is the average of duplicate runs at each angle. Note that there is a scale factor of 10 between the ordinates of the upper and lower halves of Fig. 2. The solid curve is the least-squares fit to the experimental data and yields the coefficients $A_2 = -0.0033$ (32) and $A_4 = 0.0105$ (41), after correction for solid angle. The dashed curve corresponds to the angular correlation coefficients reported by Lazar and Klema.[6] It is easily seen that the present data exhibits considerably less P_4 term in the angular correlation than did the previous work, resulting in less of a depression around 135°. The dot-dashed curve in Fig. 2 represents the predicted correlation using our experimental value of A_2 and the theoretical value of A_4 which corresponds to a mixing ratio $\delta(E2/M1) = -0.094$ for the $(\frac{7}{2}- \rightarrow \frac{5}{2}-)$ transition. This is equivalent to giving full weight to the experimental A_2 and ignoring the measured A_4 value. The numerical results are summarized in Table I. Due primarily to the much improved counting statistics and the large number of angles measured, our experimental errors are significantly smaller than in Ref. 6. The observed 1770-570-keV correlation is substantially more isotropic than found earlier,[6] with both A_2 and A_4 being considerably reduced in magnitude. Note that the sign of the experimental A_4 is positive, in disagreement with the expectation from theory based upon the value of A_2 and the known spin sequence. Although our measurements have reduced the size of this discrepancy from the previous work, it has not been completely eliminated. It is probably attributable to the experimental difficulties associated with the nearly isotropic behavior of the correlation and the relatively weak intensity of the 1770-keV transition. The multipole mixing ratio for this transition, as computed from the experimental A_2 results, is slightly larger than the original estimate,[6] and corresponds to approximately 0.9% $E2$ in the intensity of this mainly $M1$ transition. This value is consistent with γ-ray polarization studies of this cascade,[11] and in excellent agreement with the Weisskopf estimate[1] $|\delta| = 0.095$.

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[1]M. R. Schmorak and R. L. Auble, Nucl. Data B5, 207 (1971).
[2]H. J. Korner, K. Auerbach, J. Braunsfurth, and E. Gerdau, Nucl. Phys. 86, 395 (1966).
[3]S. Gustafsson, K. Johansson, E. Karlsson, and A. G. Svensson, Phys. Lett. 10, 191 (1964).
[4]P. Kleinheinz, R. Vukanovic, L. Samuelsson, D. Krmpotic, H. Lindstrom, and K. Siegbahn, Nucl. Phys. A93, 63 (1967).
[5]H. E. Bosch, L. F. Gatto, M. Behar, and G. J. Garcia, Phys. Rev. C 1, 242 (1970).

[6]N. H. Lazar and E. D. Klema, Phys. Rev. 98, 710 (1955).

[7]P. D. Johnston and M. Kaplan, private communication.

[8]The anisotropy values were calculated from theory using our measured values for the mixing ratios of the first transition in each cascade.

[9]M. J. L. Yates, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964), p. 453.

[10]M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324 (1955).

[11]P. H. Stelson, W. G. Smith, and F. K. McGowan, Phys. Rev. 116, 167 (1959).