

Equipment Required

- Two 905-3 NaI(Tl) 2- x 2-in. Detectors with Phototubes.
- Two 266 PMT Bases.
- Two 556 High Voltage Power Supplies.
- Two 113 Scintillation Preamplifiers.
- Two 575A Amplifiers.
- Two 551 Timing Single-Channel Analyzers.
- 480 Pulser.
- 414A Fast Coincidence.
- 427A Delay Amplifier.
- 416A Gate and Delay Generator.
- 974 Quad Timer/Counter.
- 4001A/4002D Bin and Power Supply.
- EASY-MCA-2K including USB cable and MAESTRO-32 software (other ORTEC MCAs may be substituted).
- PC-1 Personal Computer with USB port and a recent, supportable version of the Windows operating system.
- 306-AX Angular Correlation Table (1.17 m x 1.17 m x 0.76 m high), including two shielded collimators.
- TDS3032C Oscilloscope with bandwidth ≥ 150 MHz.
- Coaxial Cables and Adapters:
 - o Two C-36-12 RG-59A/U 75- Ω cables, with two SHV female plugs, 3.7-m (12-ft) length.
 - o One C-25-2 RG-58A/U 50- Ω cable, with BNC plugs, 0.61-m (2-ft) length.
 - o Two C-24-1/2 RG-62A/U 93- Ω cables, with BNC plugs, 15-cm (1/2-ft) length.
 - o Eight C-24-2 RG-62A/U 93- Ω cables, with BNC plugs, 0.61-m (2-ft) length.
 - o Two C-24-4 RG-62A/U 93- Ω cables, with BNC plugs, 1.2-m (4-ft) length.
 - o Four C-24-12 RG-62A/U 93- Ω cables, with BNC plugs, 3.7-m (12-ft) length.
 - o Two C-29 BNC Tee Connectors.
- CO-60S 1 μ Ci ⁶⁰Co source (5.27 y half life).
- GF-060-M-100 100 μ Ci ⁶⁰Co gamma-ray source (5.27 y half life). A license is required for this source.
- A small flat-blade screwdriver for adjusting screwdriver-accessible controls, or an equivalent potentiometer adjustment tool.

Purpose

In the first part of this experiment the coincidence techniques outlined in Experiments 9 and 13 are used to confirm the gamma-ray decay scheme of ⁶⁰Co. In the second part, the angular correlation is measured for the two cascading gamma rays from ⁶⁰Co, confirming the spins of the two excited states. The first part can be completed in the normal 4-hour laboratory session.

The angular correlation measurement requires a sequence of six 24-hour acquisitions, with minimal interactions from the student experimenters once per day to change the scattering angle and record the data at the end of each 24-hour measurement. Because of the 100 μ Ci ⁶⁰Co source employed for the 6-day, unattended measurement, the apparatus must be located in a secured room, with access to the locked room controlled by the Laboratory Manager.

Experiment 19

Gamma-Ray Decay Scheme and Angular Correlation for ^{60}Co

Introduction

In Experiment 19.1, a gamma-gamma coincidence experiment is performed to show that the two gamma-rays from ^{60}Co are in coincidence. Experiment 19.2 involves the measurement of the angular correlation of these two gamma-rays, the determination of the anisotropy, and the coefficients of the correlation function.

The decay scheme for ^{60}Co is shown in Fig. 19.1. Note that ^{60}Co decays to the 2.507 MeV level of ^{60}Ni via beta emission, and this state de-excites by a gamma-ray cascade through the 1.3325-MeV level. Because the lifetime of the 1.3325-MeV state is only 0.7 ps, the two gamma rays will appear to be in coincidence within the resolving time of the instrumentation. Figure 19.2 shows a NaI(Tl) spectrum from ^{60}Co .

In order to verify that γ_1 and γ_2 are in coincidence, it is necessary to use the experimental techniques that were outlined in Experiment 13. Figure 19.3 shows the geometrical setup that will be used for the angular correlation measurement in Experiment 19.2. A specific case of that geometry (without the collimators) will be adapted for the γ_1 - γ_2 coincidence verification in Experiment 19.1.

CAUTION

Exposure of personnel to the radiation from the 100 μCi ^{60}Co source used in this experiment should be minimized by limiting exposure time and maintaining at least a 1 meter distance from the source. At a 1 cm distance from the point source the exposure dose rate is approximately 1.3 R/hr. At a 10 cm distance that exposure dose rate is reduced to 13 mR/hr, and at 1 meter the exposure dose rate is approximately 0.13 mR/hr.

When moving the source from its storage shield to the mounting in the angular correlation table, the source should be gripped with tongs that maintain at least a 10-cm distance between the source and any body parts.

Radiation hazard warning signs should be posted on the angular correlation table when the source is present. During the 24-hour data acquisitions, the apparatus should be secured in a locked room to prevent access by uninformed or unauthorized people. The Laboratory Manager should be the sole person controlling access to the locked room.

Experiment operators who have been instructed in radiation safety issues and procedures can safely work with this source for prolonged periods at distances greater than 1 meter. Infrequent manipulations of the apparatus at closer distances should be limited to less than a minute for each interaction.

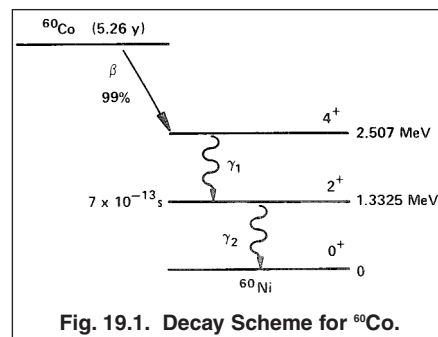


Fig. 19.1. Decay Scheme for ^{60}Co .

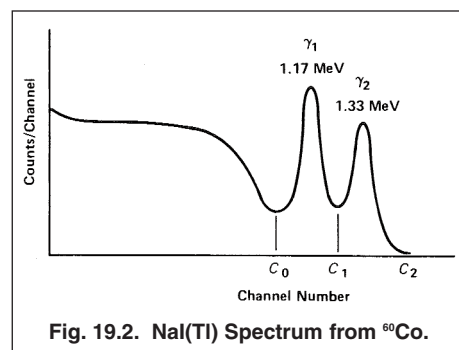


Fig. 19.2. NaI(Tl) Spectrum from ^{60}Co .

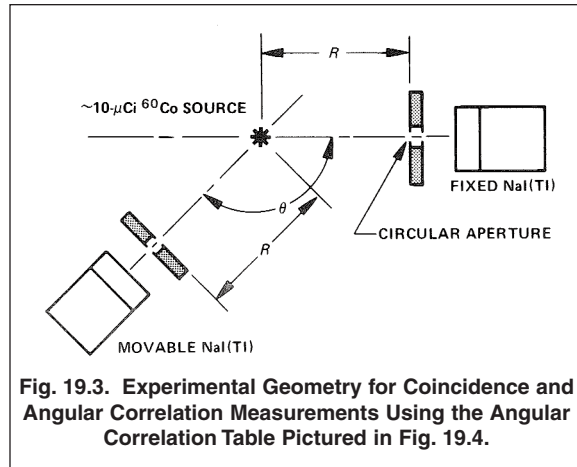


Fig. 19.3. Experimental Geometry for Coincidence and Angular Correlation Measurements Using the Angular Correlation Table Pictured in Fig. 19.4.

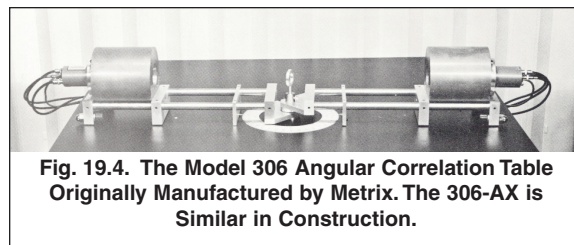


Fig. 19.4. The Model 306 Angular Correlation Table Originally Manufactured by Metrix. The 306-AX is Similar in Construction.

EXPERIMENT 19.1 Verification of the Gamma-Gamma Coincidence for ^{60}Co

Because the angular correlation of γ_1 and γ_2 is nearly isotropic (within 17%), the angle θ in Fig 19.3 can be set at any value for the coincidence verification. Usually, the most convenient angle is 180° . A typical electronics setup for the measurement is shown in Fig 19.5.

Procedure

1. If the NaI(Tl) detectors are installed in their lead shields on the angular correlation table, remove them from the shields. Secure the two detectors on the table top facing each other with a 7 cm separation. At the appropriate step number, the $1\ \mu\text{Ci}$ ^{60}Co source will be suspended midway between the two detectors on their mutual axial centerline.

Electronics Connections and Setup

2. Set up the electronics as shown in Fig. 19.5. Ensure the NIM bin power and the HV Power Supplies are turned off. The details for cable connections and instrument settings are outlined below. For both detectors and their chains of signal processing electronics, implement the following steps.
 - a. Connect the ANODE output of the 266 PMT Base to the INPUT of the 113 Scintillation Preamplifier using a 15-cm C-24-1/2 RG-62A/U 93- Ω cable. Set the INPUT CAPacitance switch on the 113 to 100 pF.
 - b. Connect the 113 Preamplifier power cable to the PREAMP POWER connector on the rear panel of the supporting 575A Amplifier. Check that the time constant switches accessible through the side panel of the 575A Amplifier are all set to 0.5 μs .
 - c. Insert the 575A Amplifier and the related 556 HV Power Supply side-by-side into the NIM bin.
 - d. Connect the 113 Preamplifier OUTPUT to the supporting 575A Amplifier INPUT using a 3.7-m C-24-12 RG-62A/U 93- Ω cable. Set the 575A input polarity to NEGative.
 - e. Using a 3.7-m C-36-12 RG-59B/U 75- Ω cable with two SHV female plugs, connect the OUTPUT of the related 556 HV Power Supply to the POS HV input of the 266 PMT Base. Check that the POLARITY switch on the rear panel of the 556 is set to POSitive, and the CONTROL toggle switch is set to INTernal. Set the front-panel voltage controls on the 556 to their minimum values.
 - f. Connect the Bipolar output of the 575A Amplifier to the analog INPUT of the EASY-MCA using a 1.2-m C-24-4 RG-62A/U 93- Ω cable.
 - g. Verify that the EASY-MCA is connected to the computer via the USB cable.
 - h. Turn on power to the NIM bin and the computer that supports the EASY-MCA.
 - i. Position the $1\ \mu\text{Ci}$ ^{60}Co radioactive source midway between the NaI(Tl) detectors on their mutual axial centerlines.
 - j. Set the 556 high voltage to the value that is recommended for the related scintillation detector. Turn on the 556 HV POWER.
 - k. Set the 575A Amplifier gain for a bipolar output amplitude of approximately +6 V on the 1.33-MeV gamma-ray photopeak pulses, as observed on the 1 M Ω input of the oscilloscope. Check that the FOCUS control on the related 266 PMT base has been adjusted to maximize the above pulse height.

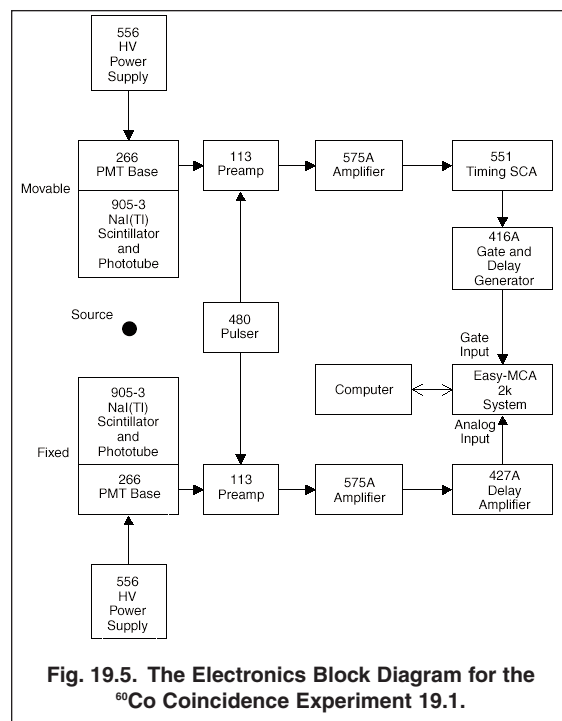


Fig. 19.5. The Electronics Block Diagram for the ^{60}Co Coincidence Experiment 19.1.

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- l. Reconnect the 575A Bipolar OUTPUT to the analog INPUT of the EASY-MCA.
 - m. Via the Acquire menu and the ADC tab in the MAESTRO-32 software that operates the EASY-MCA, select the Gate Off option. Select the analog-to-digital conversion range to be 512 channels for a 0 to +10-V input. Adjust the Upper Level discriminator to its maximum value. Adjust the Lower Level discriminator as low as possible without causing excessive counting rate on the noise. It may be useful to temporarily turn off the 556 High Voltage for the Lower Level discriminator adjustment. Under the Preset tab, clear all data fields, and do the same for the MDA Preset option (if supported). Clearing those fields will default to manual control for starting and stopping spectrum acquisition. Familiarize yourself with the software controls for setting up, acquiring and erasing spectra.
 - n. Verify that the ^{60}Co peaks accumulate at circa 60% of full scale in the energy spectrum on the MCA. The spectrum should look like that shown in Fig. 19.2.
 - o. Connect the UNipolar OUTPUT of the 575A Amplifier to the 1-M Ω input of the oscilloscope. Per the procedure taught in Experiment 3, adjust the PZ ADJ on the 575A Amplifier to make the pulses on the UNipolar OUTPUT return to baseline as quickly as possible without undershooting the baseline between pulses.
 - p. From the spectrum acquired on the MCA, confirm that the counting rate in the total spectrum is between 5,000 and 10,000 counts per second. If it is not in this range adjust the source to detector distance to achieve that goal. Make sure that the source-to-detector distance is the same for both detectors.
3. Repeat the above steps 2a) through 2p) for the other NaI(Tl) detector and its signal processing electronics.

Delay Alignments for Coincidence Gating

4. Determine which of the two 575A amplifiers has the higher gain setting. Using a 3.7-m C-24-12 RG-62A/U 93- Ω cable, connect the ATTENUated output of the 480 Pulser to the TEST PULSE input of the 113 Preamplifier associated with that higher gain amplifier. Using the same length of coaxial cable, connect the DIRECT output of the 480 Pulser to the TEST PULSE input on the other 113 Preamplifier.
5. Set the 480 Pulser output polarity to NEGative and turn on the pulser. Remove the ^{60}Co source.
6. Adjust the PULSE HEIGHT and/or CAL controls on the 480 Pulser so that the pulse height at the output of the lower-gain amplifier is approximately +5 V.
7. Adjust the ATTENUATOR toggle switches on the 480 Pulser so that the pulse height at the output of the higher-gain amplifier is within the range of +3.5 V to +7.1 V. If you cannot achieve this latter requirement, you may need to interchange the DIRECT and ATTENUated connections and repeat steps 6 and 7.
8. Identify the 575A Amplifier associated with the detector that will be moved from 90° through 180° when finally installed in the shielded collimator. Using a 0.61 m C-24-2 RG-62A/U 93- Ω cable, connect the Bipolar output of that amplifier to the DC INPUT of the 551 Timing SCA. On the SCA, select the NORmal mode and the 0.1 – 1.1 μs delay range. Turn the DELAY dial to 0.500 μs , and lock the dial. Check that the LL REF and STROBE toggle switches on the rear panel are both set to the INTernal mode. Set the UPPER LEVEL to maximum (10 V), and the LOWER LEVEL to 0.1 V.
9. Using a 0.61-m C-24-2 RG-62A/U 93- Ω cable, connect the 551 POSitive OUTPUT to the POSitive INPUT of the 416A Gate and Delay Generator.
10. Identify the 575A Amplifier that is associated with the detector that will remain at a constant angle setting when eventually installed in the shielded collimator (Fixed Detector). Using a 0.61-m C-24-2 RG-62A/U 93- Ω cable, connect the Bipolar output of that amplifier to the input of the 427A Delay Amplifier.
11. Confirm that the Pulser is still turned on. Connect the Delay Amplifier OUTPUT to the Channel 1 input (1 M Ω) of the oscilloscope. Trigger the oscilloscope from the leading edge of this bipolar pulse on Channel 1. Simultaneously, observe the POSitive DELAYED OUTPUT of the 416A on the oscilloscope Channel 2 input (1 M Ω), while triggering on Channel 1.
12. Set the DELAY controls on the 416A to their minimum values. Adjust the 416A POSitive DELAYED OUTPUT logic-pulse amplitude to approximately +5 V.

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- Adjust the DELAY switches on the 427A Amplifier so that the maximum amplitude of the analog output pulse from the 427A arrives 500 ns after the leading edge of the logic pulse from the 416A. The DELAY dial on the 416A can be used to fine tune this arrival relationship.
- Adjust the WIDTH control on the 416A so that the logic pulse from the 416A extends 500 ns past the maximum amplitude point of the analog pulse. See Fig. 19.6 for a pictorial representation of this gating relationship. Lock the DELAY dial on the 416A to prevent unintended changes. This adjustment sets the coincidence resolving time to 1.0 μs .
- Using 1.2-m C-24-4 RG-62A/U 93- Ω cables, connect the POSITIVE DELAYED OUTPUT of the 416A to the GATE Input of the EASY-MCA, and connect the 427A OUTPUT to the analog INPUT of the EASY-MCA.
- Verify that the EASY-MCA will accumulate the Pulser spectrum.
- Via the Acquire menu and the ADC tab in the MAESTRO-32 software that operates the EASY-MCA, select the Gate On option. Confirm that the EASY-MCA will still acquire the Pulser spectrum.
- Disconnect the 416A output from the EASY-MCA GATE input. Confirm that this prevents the acquisition of the pulser spectrum. Reconnect the 416A output to the EASY-MCA GATE input, and turn off the 480 Pulser.

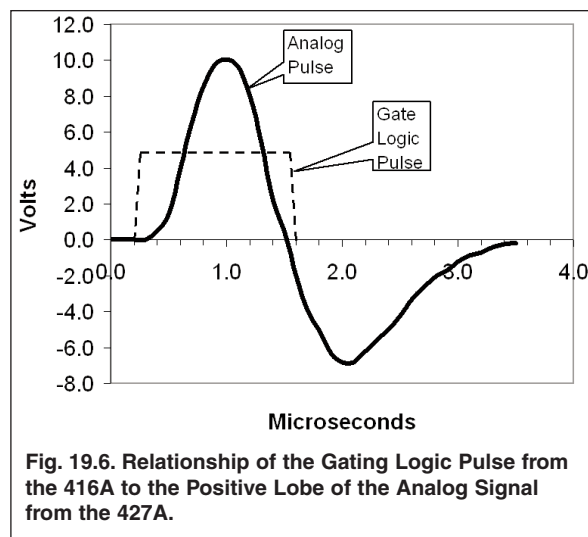


Fig. 19.6. Relationship of the Gating Logic Pulse from the 416A to the Positive Lobe of the Analog Signal from the 427A.

Setting the Energy Window

- Disconnect the 427A INPUT from the Fixed-detector 575A Amplifier Bipolar output. Connect the Movable-detector 575A Amplifier UNipolar output to the 427A INPUT.
- With the 1- μCi ^{60}Co mid-way between the two detectors, acquire a spectrum on the EASY-MCA. Identify the 1.17-MeV gamma-ray peak in the spectrum. Check that the EASY-MCA has the Gate On option selected in the MAESTRO-32 software controls. If the MCA will not properly collect the gated spectrum with the UNipolar signal, it may be necessary to increase the DELAY on the 551 SCA from the 500 ns setting to 700 ns to compensate for the 200 ns later peaking time of the UNipolar pulse.
- Switch the 551 SCA to the WINDOW mode. Raise the LOWER LEVEL control and lower the WINDOW dial until the gating provided by the 551 restricts acquisition on the EASY-MCA to the 1.17-MeV peak. Make fine adjustments so that the acquired spectrum contains the complete 1.17-MeV peak, but excludes the 1.33-MeV peak and the Compton continuum. Lock the dials on the 551 at this setting. This setup ensures that the EASY-MCA will acquire a spectrum only when a 1.17-MeV gamma-ray has been detected in the movable detector.
- Disconnect the 427A INPUT from the 575A UNipolar output that is associated with the Movable-detector signal processing chain. Connect the 427A INPUT to the Bipolar output of the 575A Amplifier associated with the Fixed-detector signal processing chain. If the 551 DELAY dial was changed in step 20, return the dial to the original 500 ns setting.

Measuring the γ γ Coincidence Spectra

- Turn off the Gate on the MCA and acquire a spectrum. Confirm that the total counting rate in the spectrum is between 5,000 and 10,000 counts/second. If this condition is not met, adjust the equal values of R for both detectors to achieve this goal.
- Turn on the coincidence gate requirement on the EASY-MCA. Accumulate a spectrum in the MCA. This spectrum should include only the 1.33-MeV peak and its Compton continuum from the Fixed detector. The 1.17-MeV peak of Fig 19.2 will be virtually eliminated.¹ This result shows that the 1.17- and 1.33-MeV gamma rays are in coincidence, because a 1.17-MeV gamma-ray was required in the SCA in order to acquire each 1.33-MeV pulse in the spectrum.

¹The 1- μs coincidence resolving time should allow accidental coincidence events in the 1.17-MeV photopeak amounting to circa 3.7% of the counts in the 1.33-MeV photopeak.

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25. Save the spectrum for later use in your report.
26. Repeat the experiment with the 551 Timing SCA set to bracket the 1.33-MeV peak. Under these conditions, only the 1.17-MeV peak and its Compton continuum should appear in the MCA spectrum. These two measurements verify that γ_1 and γ_2 in Fig 19.1 are prompt, sequential gammas.
27. Save the spectrum from step 26. Export both spectra and an ungated spectrum to a transportable memory device such as a CD, memory stick or external hard drive. If the spectra are exported as ASCII text, they can be imported into an Excel spreadsheet using space and tab delimiters. You can include graphs of the spectra from Excel in your report. Alternatively, you can photograph the MAESTRO-32 spectrum display with a high-resolution digital camera, and include the photo in your report.

EXPERIMENT 19.2. Measuring the $\gamma_1 \gamma_2$ Angular Correlation for ^{60}Co .

NOTE: Experiment 19.2 should be set up near the end of the laboratory period spent on Experiment 19.1. Subsequently, a series of six 24-hour measurements will be made over the following 6 days to collect the data to evaluate against the theoretical angular distribution for the two gamma rays from ^{60}Co . For safety, the room containing the apparatus with the 100 μCi ^{60}Co source will be locked to prevent access by unauthorized and untrained personnel. Access to the secure room will be provided via the Laboratory Manager once per day for the students to record the data and change the angle.

Relevant Information

The Table of Isotopes (ref. 4) gives the spins of most of the nuclear levels that have been measured. Many of these spin assignments were made on the basis of angular correlation measurements. In the case of gamma-gamma angular correlation, an experimental arrangement similar to Fig. 19.3 is used. The fixed detector is set to measure only γ_1 , and the movable detector observes γ_2 . The number of coincidences between γ_1 and γ_2 is determined as a function of θ (the angle between the two detectors). A plot of the number of coincidence events per unit time as a function of the angle, θ , is called the measured angular correlation. The detection of γ_1 in a fixed direction selects nuclei for which the subsequent γ_2 emissions have a non-isotropic angular distribution. This is a result of the non-isotropic distribution of spin orientations in ^{60}Co . Figure 19.1 shows that ^{60}Co decays by β^- emission to the 2.507-MeV (4+) state, which cascades through the 1.3325 MeV (2+) state to the ground state (0+) of ^{60}Ni . The numbers in parentheses in the previous sentence, e.g. (4+), denote the spins for the specific states.

These angular momenta (spins) determine the shape of the correlation function of the isotope. A complete discussion of the theoretical arguments associated with the angular correlation measurements is presented in ref. 1 and 2. The theoretical correlation function, $w(\theta)$, for ^{60}Co is given by

$$w(\theta) = a_0 + a_2 \cos^2\theta + a_4 \cos^4\theta \quad (1)$$

where $a_0 = 1$, $a_2 = 1/8$, and $a_4 = 1/24$.

Table 19.1 shows the calculated values for $w(\theta)$ for angles between 90° and 180° in 10° increments for ^{60}Co . It can be seen from the table that the correlation function, $w(\theta)$, changes by only 17% from 90° to 180° . Therefore, $\sim 1\%$ counting statistics² should be targeted when the experiment is performed. Table 19-A.1 in the Appendix provides guidance on the detector-to-collimator distances required to achieve 1% counting statistics in a 24-hour data acquisition interval. $R = 20$ cm for both detectors should yield $< 1\%$ statistics in 24 hours, while offering an angular resolution of 7.3° .

θ (deg)	$w(\theta)$
90	1.00000
100	1.00381
110	1.01519
120	1.03385
130	1.05876
140	1.08770
150	1.11719
160	1.14287
170	1.16042
180	1.16667

²If N counts are accumulated in alive time t_L , the estimated percent standard deviation in the counts is $100\%/N^{1/2}$. Therefore, 1% statistics requires $N = 10,000$ counts.

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The anisotropy associated with an angular correlation measurement is defined as

$$\text{Anisotropy} = \frac{w(180^\circ) - w(90^\circ)}{w(90^\circ)} \quad (2)$$

A comparison of the experimental anisotropy with the theoretical value will reveal that angular correlation measurements are capable of rather high precision.

In this experiment, the measured angular correlation, $w(\theta)$, will be compared to Eq. (1) and the values shown in Table 19.1. Additionally, the calculated and measured anisotropy will be compared via Eq. (2).

Procedure

DO NOT INSTALL THE 100 μCi ^{60}Co SOURCE ON THE ANGULAR CORRELATION TABLE UNTIL ELECTRONICS INTERCONNECTIONS HAVE BEEN COMPLETED. Until the source is needed for data acquisition, keep it in its storage shield.

1. Starting with the setup in Fig. 19.5, ensure that procedure steps 2 through 8 of Experiment 19.1 have been completed.
2. Install the NaI(Tl) detectors in their respective shielded collimators on the arms of the angular correlation table. Make sure that the front surfaces of the scintillation detectors are touching the back sides of their collimator apertures.

Modifying the Electronics System

3. Modify the electronics setup to match Fig. 19.7. More specifically:
 - a. Turn off the NIM Bin power and the HV power supplies.
 - b. Remove the two 556 High-Voltage Power Supplies from the bin to make room to insert another 551 Timing SCA, the 414A Fast Coincidence and the 974 Quad Timer/Counter modules. Reconnect the power cords for the 556 HV supplies to the 117 V ac power source. (The 556 HV power supplies do not have to be mounted in the bin to perform their function.)
 - c. Ensure that the settings on both 551 Timing SCAs are identical to those in step 8 of Experiment 19.1.
 - d. Make sure that both 575A Amplifiers have their Bipolar output connected to the DC INPUT of their associated 551 Timing SCA. Use 0.61-m C-24-2 RG-62A/U 93- Ω cables for these two connections.
 - e. Place BNC Tees on COINC inputs A and B of the 414A Fast Coincidence module. Turn the A and B switches to IN, and switches C and D to OUT. Set the RESOLVING TIME dial to $2\tau = 100$ ns.
 - f. Using 0.61-m C-24-2 RG-62A/U 93- Ω cables, connect the POS OUTPUT of the 551 Timing SCA associated with the movable detector to the BNC Tee on the A COINC input of the 414A. Similarly, connect the POS OUTPUT of the 551 Timing SCA associated with the fixed detector to the BNC Tee on the B COINC input of the 414A.
 - g. Using 0.61-m C-24-2 RG-62A/U 93- Ω cables, connect the Tee on the A COINC input of the 414A to COUNTER INPUT 2 of the 974. Similarly, connect the Tee on the B COINC input of the 414A to COUNTER INPUT 4 of the 974. Connect one OUTPUT of the 414A to COUNTER INPUT 3 of the 974.
 - h. The dashed lines in Fig. 19.7 will be used for tuning the SCAs to select the 1.17-MeV and 1.33-MeV gamma-ray peaks from their respective detectors.

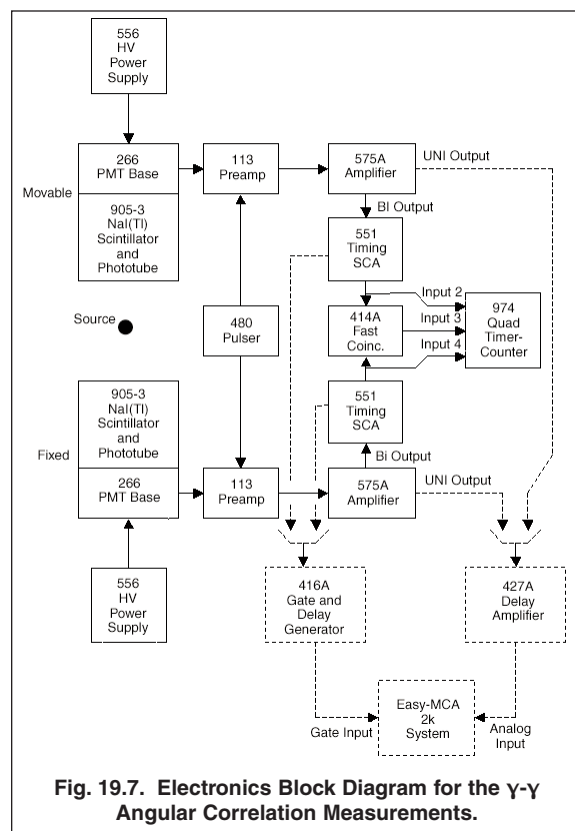


Fig. 19.7. Electronics Block Diagram for the γ - γ Angular Correlation Measurements.

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- On the 974 Quad Timer-Counter, turn the DWELL knob to its maximum clockwise position. This will ensure the counts are displayed for approximately 15 seconds before resetting and starting a new counting interval.
- Push the TIME BASE SELECT button to select the 0.1-SEC. time base. Push the M PRESET button to select $M=1$. Push the N button to choose $N=1$. This will set a preset counting time of $0.1 \text{ s} \times M \times 10^N = 1 \text{ second}$. Press the DISPLAY SELECT button to choose displaying counter 1 on the top display. In sequence, press the STOP, RESET then COUNT buttons. Counter 1 should accumulate up to 10 counts (1 second) pause for 15 seconds, then reset and repeat the cycle.
- Remove any sources from the vicinity of the detectors, and turn on the 480 Pulser. Select Counter 2 for display on the 974. Confirm that Counter 2 accumulates 60 counts in 1 second, displays that result for approximately 15 seconds, then resets to zero and repeats the cycle. (If the ac line frequency is different from 60 Hz, then the number displayed should be identical to the line frequency.)
- Repeat step 6, while displaying Counter 4.
- Select Counter 3 for display. Adjust the DELAY dial on either 551 SCA to maximize the counting rate from Input 3 on the 974 Quad Timer-Counter. This maximum should be 60 counts for a 60-Hz ac line frequency, (or at least equal to your line frequency, if not 60 Hz). If there is a range of DELAY settings for which the counting rate is 60 counts/s in counter 3, choose the final DELAY setting at the middle of this range. This step ensures that the delays are the same from the input to each preamplifier through to the input to the 414A Coincidence module. Lock the DELAY dials on both 551 SCAs to avoid changing this adjustment.

Setting the Energy Windows

- Turn off the 480 Pulser and place a $1\text{-}\mu\text{Ci } ^{60}\text{Co}$ source in front of the fixed-position detector.
- Identify the 551 SCA that serves the fixed detector.
 - Connect the NEGative OUTput of that SCA to the NEGative INPUT of the 416A Gate and Delay Generator using the 0.61-m C-25-2 RG-58A/U 50- Ω cable.
 - Connect the UNIpolar output of the 575A Amplifier that supports the fixed detector to the INPUT of the 427A Delay Amplifier using a 0.61-m C-24-2 RG-62A/U 93- Ω cable.
 - Check that the OUTPUT of the 427A Delay Amplifier is still connected to the analog INPUT of the EASY-MCA, and the POSitive DELAYED OUTPUT of the 416A is still connected to the GATE input of the EASY-MCA.
 - Check that the amplitude and DELAY adjustments on the 427A and 416A still satisfy the pulse alignment conditions in steps 12, 13 and 14 of Experiment 19.1. If not, make the adjustments to satisfy those requirements. For this experiment (19.2), the coincidence resolving time set by the gate pulse is not as critical as it was in experiment 19.1. Consequently, the gate pulse can precede the peak amplitude of the analog pulse by 0.5 to 1.0 μs , and the gate pulse can last 0.5 to 1.0 μs after the peak amplitude.
 - Select the Coincidence Mode of operation for the EASY-MCA, and acquire a spectrum. The full ^{60}Co spectrum should be observed.
 - Select the WINdow mode on the 551 SCA. Adjust the LOWER LEVEL and WINDOW dials until the spectrum acquired by the EASY-MCA contains only the 1.17-MeV full-energy peak (or the 1.33-MeV peak, when repeating this step for the movable detector). Lock the dials to preserve this setting.
- Repeat steps 9 and 10 for the 551 SCA and 575A Amplifier serving the movable detector. But, place the $1 \mu\text{Ci } ^{60}\text{Co}$ source in front of the movable detector, and set the SCA window to straddle the 1.33-MeV full-energy peak.

Setting up the 24-hr Data Acquisitions

- Remove the $1 \mu\text{Ci } ^{60}\text{Co}$ source and set the value of R for each detector to 20 cm.
- Ask the Laboratory Manager to install the $100 \mu\text{Ci } ^{60}\text{Co}$ source in the center of the angular correlation apparatus, so that that the source is at 45° to the line between the two detectors, and the two detectors are 180° apart.

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14. Set the DWELL knob on the 974 Counter-Timer to the OFF position to enable manual control of the stop/reset/count sequence. Set the value of N for the preset time to $N = 4$ to achieve a 1000-second preset time. Reset the 974 Counter-Timer and initiate a preset counting interval. When counting stops note the number of counts recorded in counter 3.
15. Based on the result in step 14, calculate the time required to accumulate 10,000 counts in counter 3. The answer should be circa 17 hours. Set the M and N preset time parameters to count for slightly less than 24 hours. This will ensure a standard deviation for the coincidence counts in counter 3 that is less than 1%. It should also allow you to return in exactly 24 hours to record the results of the data acquisition, and to start the data collection for the next angle.
16. Set the angle, θ , carefully at 180° (Fig 19.3). Reset the 974 counter and start the 24-hour counting interval. When the 24-hour counting time limit is reached, record the counts from counters 2, 3 and 4 as N_2 , N_3 and N_4 , respectively. Also record the actual counting time, t , from counter 1. N_2 and N_4 are the counts for the gamma-rays in the movable and fixed detectors before the coincidence requirement is applied. N_3 represents the sum of the true and accidental coincidence counts. To determine the true coincidence rate, a correction must be made for the number of accidental coincidence counts. Determine the accidental rate, N_{acc}/t , from the formula

$$\frac{N_{\text{acc}}}{t} = 2\tau \left(\frac{N_2}{t} \right) \left(\frac{N_4}{t} \right) \quad (3)$$

Where $2\tau = 100$ ns is the coincidence resolving time selected on the 414A Coincidence module. Consequently, the angular correlation value $w(\theta)$ is

$$w(\theta) = N_3 - N_{\text{acc}} \quad (4)$$

17. At 24-hour intervals, read and record the values of θ , t , N_2 , N_3 and N_4 . Repeat the measurements in step 16 and determine $w(\theta)$ for the six angles, $\theta = 180^\circ, 160^\circ, 140^\circ, 120^\circ, 100^\circ$ and 90° .

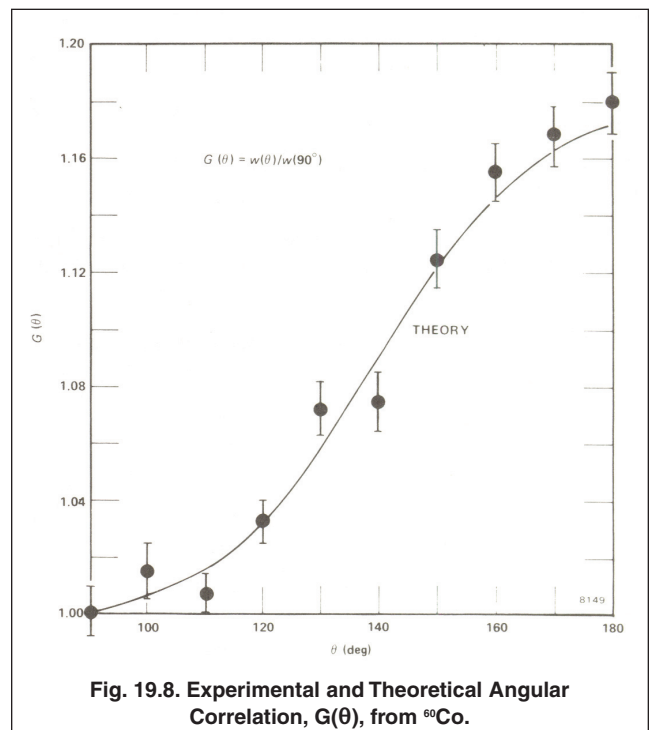
EXERCISES

- a. In order to easily compare the experimental values with the theoretical values given by Eq. (1), it is more convenient to plot $G(\theta)$ vs. θ , where $G(\theta)$ is calculated by

$$G(\theta) = \frac{w(\theta)}{w(90^\circ)} \quad (5)$$

Plot the experimental $G(\theta)$ as a function of θ . Do the same for the theoretical $G(\theta)$ from the data in Table 19.1. Figure 19.8 shows a typical set of experimental and theoretical data for this experiment. To your measured data points, add the error bars signifying the standard deviation due to counting statistics.

- b. Determine the anisotropy from the experimental data. How does this compare to the theoretical value?
- c. Make a least-squares-fit to your data points and determine the experimental coefficients to the correlation function. How do your values compare with those in Eq. (1)?
- d. What effect does the finite angular resolution have on your results?
- e. No attempt was made to correct for dead time in this experiment. How does that affect your results?



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- f. What effect does the correction for accidental coincidences have on the standard deviation due to counting statistics in $w(\theta)$?
- g. What is the modification to equation (A-3) to incorporate the angular correlation function?
-

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APPENDIX 19-A. Guidelines for Source-to-Detector Distances, Counting Rates and Counting Times.

The following tables provide guidance on adjusting the source-to-collimator distances, R , to achieve reasonable counting rates and viable counting times with a $100\ \mu\text{Ci}$ ^{60}Co source. The distance R should be the same for both the fixed and the movable detector.

The predicted singles counting rate (counts per second) is computed from equation (A-1).

$$\text{CPS}_{\text{singles}} = A \eta f (\epsilon_{\text{T}1.17} + \epsilon_{\text{T}1.33}) \frac{\Delta\Omega}{4\pi} \quad (\text{A-1})$$

Where

A is the source activity in μCi ,

$\eta = 3.7 \times 10^4$ is the number of disintegrations per second per μCi ,

$f = 0.999$ is the fraction of the decays that result in a 1.17-MeV/1.33-MeV cascade of gamma rays,

$\epsilon_{\text{T}1.17}$ is the total intrinsic detection efficiency for the 1.17 MeV gamma-ray,

$\epsilon_{\text{T}1.33}$ is the total intrinsic detection efficiency for the 1.33 MeV gamma-ray,

$\Delta\Omega$ is the solid angle subtended by the collimator aperture at the point source, and

4π is the total solid angle in the sphere of radius R surrounding the point source.

The fractional solid angle can be expressed as

$$\frac{\Delta\Omega}{4\pi} = \frac{\pi \left(\frac{d}{2}\right)^2 / R^2}{4\pi} = \frac{\left(\frac{d}{2}\right)^2}{4R^2} \quad (\text{A-2})$$

Where d is the diameter of the collimator aperture.

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The true coincidence counting rate (counts per second) for the 1.17 MeV and 1.33 MeV photopeaks is calculated from equation (A-3).

$$\text{CPS}_{\text{coinc}} = A \eta f \epsilon_{\text{P1.17}} \epsilon_{\text{P1.33}} \left(\frac{\Delta\Omega}{4\pi} \right)^2 \quad (\text{A-3})$$

Where

$\epsilon_{\text{P1.17}}$ is the photopeak intrinsic detection efficiency for the 1.17 MeV gamma ray, and

$\epsilon_{\text{P1.33}}$ is the photopeak intrinsic detection efficiency for the 1.33 MeV gamma ray.

Equation (A-3) assumes the angular correlation of the two gamma rays is isotropic. That is an adequate approximation for estimating the counting rates for set-up purposes, because the actual angular correlation varies by only 17% over the range of possible angles. For true coincidences, both detected gamma rays come from the same atom. Thus, true coincidences are also known as correlated coincidences.

For practical counting rates, there is always a finite probability that the 1.17 MeV gamma ray will be detected from the decay of one atom, while the 1.33 MeV gamma-ray is detected at the same time from the decay of a different atom. Such events are labeled accidental, chance or uncorrelated coincidences. The 414A measures the total coincidences, i.e., the sum of the true and accidental coincidences. Therefore, the accidental coincidence rate must be calculated in the experiment from the measured singles rate and the known coincidence resolving time. This deduced accidental coincidence rate is subtracted from the total coincidence rate to determine the measured true coincidence rate.

For guidance in planning the experiment, the accidental coincidence rate, CPS_{acc} , can be forecast from equation (A-4).

$$\text{CPS}_{\text{acc}} = 2\tau \left\{ A \eta f \epsilon_{\text{P1.17}} \left(\frac{\Delta\Omega}{4\pi} \right) \right\} \left\{ A \eta f \epsilon_{\text{P1.33}} \left(\frac{\Delta\Omega}{4\pi} \right) \right\} \quad (\text{A-4})$$

By dividing equation (A-3) into equation (A-4), it can be seen from equation (A-5) that the ratio of the accidental coincidence counting rate to the true coincidence counting rate depends primarily on the activity of the source, A , and the coincidence resolving time, 2τ . That is why the larger resolving time in Experiment 19.1 requires a lower source activity.

$$\frac{\text{CPS}_{\text{acc}}}{\text{CPS}_{\text{coinc}}} = 2\tau A \eta f \quad (\text{A-5})$$

As can be seen in Table 19-A.1, the accidental coincidence rate is about 37% of the true coincidence rate in Experiment 19.2, with a 100 ns resolving time and the 100 μCi source activity. For Experiment 19.1, the accidental coincidence rate for the photopeak is approximately 3.7% of the true photopeak coincidence rate, because the source activity is 1 μCi , and the coincidence resolving time is 1 μs .

The $d = 2.54$ cm apertures in the lead collimators in front of each 2 inch x 2 inch NaI(Tl) detector improve the ratio of the counts in the photopeak to the counts in the total spectrum by eliminating the Compton scattering interactions that would otherwise take place near the outer diameter of the scintillator. This eliminates many of the Compton scattered photons that can escape the scintillator without terminating in a photoelectric absorption. The total linear absorption coefficient can be used in equation (A-6) to calculate the total intrinsic efficiency of the collimated NaI(Tl) detector.

$$\epsilon_{\text{T}} = (1 - e^{-\mu T_{\text{scint}}}) \quad (\text{A-6})$$

Where μ is the total linear absorption coefficient for NaI at the photon energy, and T_{scint} is the thickness of the scintillator.

The collimation improves the peak-to-total ratio for the collimated 2 inch x 2 inch NaI(Tl) detector to approach that of an uncollimated 3 inch x 3 inch detector. Consequently, the total intrinsic detection efficiency from equation (A-6) can be multiplied by the tabulated peak-to-total ratios for a 3 inch x 3 inch detector to estimate the intrinsic photopeak efficiency. Alternatively, the peak-to-total ratio can be measured on the actual collimated detectors and multiplied by the total intrinsic efficiency to determine the intrinsic photopeak efficiency. The former method was used for the estimates in the following tables. However, the latter method is more accurate.

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Table 19-A.1 estimates the angular resolution, the singles counting rate, and the coincidence counting rate of the collimated detectors as a function of the source-to-collimator distance, R. It also includes the counting time required to achieve 1% counting statistics in the coincidence mode of Experiment 19.2. To avoid gain shifting with counting rate, it is generally advisable to keep the counting rate below 10,000 counts/second with a NaI(Tl) detector. Consequently, a source-to-collimator distance greater than 13 cm is necessary for Experiment 19.2.

For Experiment 19.2, smaller values of R yield 1% counting statistics in a shorter time period. However, the angular resolution degrades at lower values of R. The R = 20 cm distance highlighted in green in Table 19-A.1 is a reasonable compromise between angular resolution and counting time for the angular correlation measurement.

The parameters used for computing the results in Table 19-A.1 are summarized in Table 19-A.2.

Table 19-A.1. Angular Resolution and Counting Rates Versus Source-to-Collimator Distances.

Source-to-Collimator Distance, R (cm)	Angular Resolution (Degrees)	Singles Counting Rate (cps)	True Coincidence Counting Rate, $\text{CPS}_{\text{coinc}}$ (counts/s)	Coincidence Counting Time for 1% Std. Dev. (hours)	Accidental Coincidence Counting Rate, CPS_{acc} (counts/s)
30	4.8	2020	0.024	115.9	0.0089
28	5.2	2319	0.032	88.0	0.0117
26	5.6	2690	0.042	65.4	0.0157
24	6.1	3157	0.058	47.5	0.0216
22	6.6	3757	0.083	33.5	0.0306
20	7.3	4546	0.121	22.9	0.0448
18	8.1	5612	0.185	15.0	0.0683
16	9.1	7103	0.296	9.4	0.1095
14	10.4	9277	0.505	5.5	0.1868
12	12.1	12627	0.936	3.0	0.3460

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Table 19-A.2. Source, Geometry and Detector Parameters for Table 19 A.1.	
Source	<p>100 μCi = ^{60}Co source activity 3.70E+04 = disintegrations per second per μCi 0.999 = fractions of disintegrations yielding 1.17 and 1.33-MeV gamma cascade</p>
Geometry	<p>R = source to collimator distance 2.54 cm = diameter of collimator aperture</p>
Detector: 2-inch x 2-inch NaI(Tl) Collimated to 2.54-cm Diameter	
	<p>0.62 = total intrinsic efficiency for 1.17-MeV gamma ray 0.60 = total intrinsic efficiency for 1.33-MeV gamma ray 0.31 = peak to total ratio for 1.17 MeV 0.28 = peak to total ratio for 1.13 MeV 0.19 = peak intrinsic efficiency for 1.17-MeV gamma ray 0.17 = peak intrinsic efficiency for 1.13-MeV gamma ray 10000 = maximum permissible counts per second to avoid spectrum shifting</p>
Coincidence	<p>1.00E-07 = 2τ resolving time (sec.)</p>

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