Equipment Required

• Two 905-3 2-in. x 2-in. NaI(Tl) Scintillation Detector Assemblies.

• Two 266 Photomultiplier Tube Bases.

• Two 113 Scintillation Preamplifiers.

• Two 556 High Voltage Power Supplies.

• 480 Pulser.

• 855 Dual Spectroscopy Amplifier.

• Two 551 Timing Single-Channel Analyzers.

• 418A Universal Coincidence.

• 996 Timer and Counter.

• 427A Delay Amplifier.

• 416A Gate and Delay Generator.

• 567 Time-to-Amplitude Converter and SCA.

• 4001A/4002D NIM Bin and Power Supply.

• EASY-MCA-2K System including USB cable and MAESTRO-32 software (other ORTEC MCAs may be substituted).

• Personal Computer with USB port and recent, supportable version of the Windows operating system.

• TDS3032C Oscilloscope with bandwidth ≥150 MHz.

• Cables and Connectors

  • Two C-36-12 RG-59A/U 75-Ω Coaxial Cables with SHV Female Plugs, 12-ft. (3.7-m) length.

  • Two C-24-0.5 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 1/2-ft. (15-cm) length.

  • Four C-24-12 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 12-ft. (3.7-m) length.

  • Four C-24-1 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 1-ft. (30-cm) length.

  • One C-24-2 RG-62A/U 93-Ω Coaxial Cable with BNC Plugs, 2-ft. (61-cm) length.

  • Two C-24-4 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 4-ft. (1.2-m) length.

  • Two C-25-2 RG-58A/U 50-Ω Coaxial Cables with BNC Plugs, 2-ft. (61 cm) length.

• GF-022-D-50 ^{22}Na radioactive source with 50 µCi activity. A license is required for this source.

• 306-AX Angular Correlation Table (1.17 m x 1.17 m x 0.76 m high), including two collimators with 2.54 cm diameter apertures, one source holder, and 2 rotating arms for the NaI(Tl) detectors.

• Small, flat-blade screwdriver for tuning screwdriver-adjustable controls.

Purpose

In this experiment, two 511 keV annihilation gamma rays are radiated from a ^{22}Na source in coincidence with each other. The purpose of the experiment is to verify that these quanta emanate from the source with an angular separation of 180°. The experiment constitutes an introduction to gamma-gamma angular correlation measurements.

Introduction

^{22}Na is an excellent source for a simple gamma-gamma coincidence experiment. The decay scheme for this isotope is shown in Fig. 13.1. From the diagram, it can be noted that 99.95% of the time the decay occurs by positron emission or electron
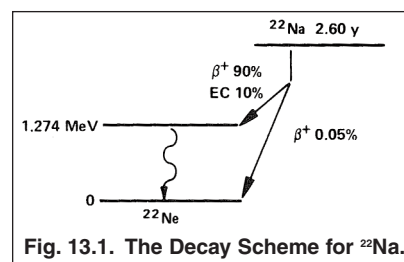
Fig. 13.1. The Decay Scheme for ^{22}Na.

Experiment 13
Gamma-Gamma Coincidence
with Angular Correlation

capture through the 1.274 MeV state of ^{22}Ne. Ninety percent of these decay events involve emission of a positron, which subsequently annihilates, producing a pair of 0.511 MeV gamma rays. Because this positron decay feeds the 1.274 MeV excited state of ^{22}Ne, the resulting 511 keV annihilation gamma rays will be in coincidence with the 1.274 MeV gamma-ray that takes ^{22}Ne to the ground state. Note that 0.05% of the decays go directly to the ground state of ^{22}Ne by positron emission. These positrons also generate 511 keV annihilation gamma-rays, but they will not be in coincidence with a 1.274 MeV gamma ray. Moreover, the electron capture (EC) decays produce a 1.274 MeV gamma-ray, but no annihilation radiation.

Fig. 13.2 shows a typical gamma-ray spectrum for ^{22}Na obtained with a NaI(Tl) detector. The 0.511 MeV peak will usually be substantially more intense than the 1.274 MeV peak, due primarily to the detector efficiency differences at the two energies (see Experiment 3), and the fact that two 511-keV photons are generated for each positron decay.

Fig. 13.3 shows a typical instrument configuration for measuring gamma-gamma coincidences. The ^{22}Na source is usually covered with a thin absorber such as a piece of metal or plastic. The overwhelming majority of the β$^+$ decays are to the 1.274 MeV excited state, and the endpoint energy for those positrons is 0.545 MeV. A 1-mm thickness of pure aluminum, or 2-mm of a polycarbonate (e.g., Lexan), is adequate to stop 0.545 MeV positrons, in order to generate annihilation radiation in the immediate vicinity of the source.

The NaI(Tl) detectors will see an approximate point source of radiation. When the positrons are annihilated, two 0.511 MeV gamma-ray photons will leave the source with an angular separation of 180°. Experimentally, this pair of photons is detected and measured with one fixed-position detector and another detector that can rotate about the source. Fig. 13.4 shows some of the details of the rotating assembly used for the experiment.

The ^{22}Na coincidence experiment will use three different electronic system configurations. In the first, the photons that enter the two detectors will have to produce pulses that overlap each other to indicate that a coincidence exists. The counter will tally the number of coincidences that are sensed during its timed counting interval. In the second experiment, a pulse from the moveable detector will enable the gate of the Multichannel Analyzer, and any corresponding pulse from the fixed detector that arrives within the gate width interval will be considered coincident and will be recorded in the spectrum. In the third configuration, the 567 Time-to-Amplitude Converter (TAC) and SCA will be used to measure the variations in time at which the coincident events are sensed by the two detectors. The counter will record all of the coincident events that occur within a selected time range, and the MCA will acquire a spectrum of the precise timing variations.
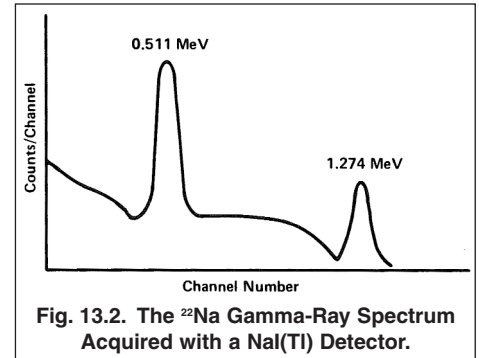

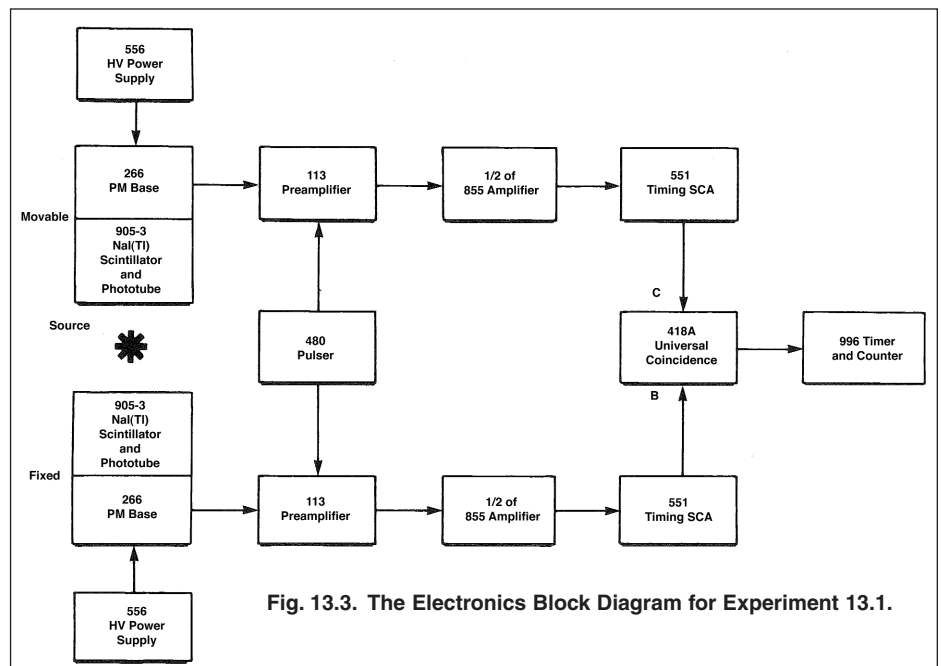**Fig. 13.2. The ^{22}Na Gamma-Ray Spectrum Acquired with a NaI(Tl) Detector.**

Fig. 13.3. The Electronics Block Diagram for Experiment 13.1.

R ≅ 30.48 cm (12.0 in.)
Diameter of Aperture ≅ 2.54 cm (1.0 in.)
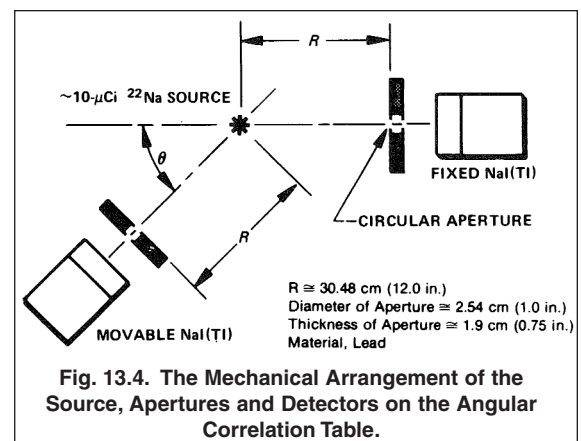Thickness of Aperture ≅ 1.9 cm (0.75 in.)
Material, Lead

Fig. 13.4. The Mechanical Arrangement of the Source, Apertures and Detectors on the Angular Correlation Table.

The student should complete Experiment 9 before starting this experiment, and should be somewhat familiar with the principles of coincidence measurements.

EXPERIMENT 13.1. The Overlap Coincidence Method for Measuring Gamma-Gamma Coincidences with ^{22}Na

Procedure

1. Install the NaI(Tl) detectors with attached 266 PMT Bases on the angular correlation arms, with the lead collimators providing 2.54 cm apertures centered on the axis of the detector. The collimator should be located close to the front surface of its associated detector. See Figure 13.4. for the appropriate source-to-collimator distance.

2. Turn off power to the NIM Bin and the 556 HV Power Supplies. Install the modules in the bin.

3. On the rear panel of each 556 Power Supply, ensure that the POSitive POLARITY is selected and the CONTROL switch is set to INTernal.

4. Connect the HV OUTPUT of one 556 Power Supply to the POS HV input of one of the 266 PMT Bases installed on a NaI(Tl) detector. Set the front panel controls for the voltage recommended by the manufacturer for the specific NaI(Tl) detector.

5. Repeat step 4 for the other 556 and 266.

6. Using a 15-cm, 93-Ω coaxial cable, connect the ANODE output of one 266 PMT Base to the INPUT of one of the 113 Scintillation Preamplifiers. Set the INPUT CAPacitance to 200 pF.

7. Repeat step 6 for the other detector.

8. Check that the SHAPING TIME is set to 0.5 µs and the NEGative input polarity is selected on both halves of the 855 Amplifier (circuit board jumpers).

9. Connect the power cables from the preamplifiers to the PREAMP POWER connectors on the rear panel of the 855 Amplifier.

10. Using 3.7 m, 93-Ω coaxial cables, connect each preamplifier OUTPUT to an available INput on the 855 Amplifier.

11. Turn on the NIM Bin power and the power to the two 556 HV Power Supplies.

12. Place the ^{22}Na source in the central source holder between the two detectors. Adjust the gain of the amplifier serving that detector to achieve a +7 V pulse height from the UNIpolar output on the 1.274 MeV gamma-rays as observed on the oscilloscope. Lock the FINE GAIN dial to prevent accidental changing of the gain.

13. Employing the procedure taught in Experiment 3, adjust the Pole-Zero (P/Z) cancellation on the 855 Amplifier to make the output pulses return to baseline as quickly as possible without undershooting.

14. Repeat steps 12 and 13 for the section of the 855 Amplifier serving the other detector.

15. Using short, 93-Ω coaxial cables, connect each UNIpolar output of the 855 Amplifier to an available DC INPUT on the 551 Timing SCAs.

16. On each 551 Timing SCA set the rear panel switches to INTernal. Select the INTegral position for the front-panel INT/NOR/WIN switch. Choose the 0.1 to 1.1 µsec delay range. Set the LOWER LEVEL dial to 40/1000 (i.e. 400 mV), and turn the DELAY dial to its minimum value (fully counter-clockwise). Lock the dials to avoid accidental changes of the settings.

17. Using a short, 93-Ω coaxial cable, connect the POSitive OUTput of the 551 serving the fixed-position detector to the B INPUT of the 418A Universal Coincidence. Connect the POSitive OUTput of the other 551 to the C INPUT of the 418A. On the 418A, set the COINCIDENCE REQUIREMENTS to 2, the B and C switches to COINCidence, and all the other switches to OFF.

18. Connect the 418A OUTPUT to the POSitive INput of the 996 Timer and Counter.

19. Identify the half of the 855 Amplifier that has the higher gain. Using a 3.7 m, 93-Ω coaxial cable, connect the ATTENuated OUTPUT of the 480 Pulser to the TEST PULSE input of the 113 Preamplifier served by the higher-gain amplifier.

20. Connect the DIRECT OUTPUT of the 480 Pulser to the TEST PULSE input on the other preamplifier. Set the Pulser polarity to NEGative, and turn on the pulser. Remove the ^{22}Na source to make it easier to see the pulser signals on the oscilloscope.

21. For the half of the 855 Amplifier set to the lower gain, connect the UNIpolar output to the Channel 1 input of the oscilloscope, and trigger the oscilloscope from Channel 1. Adjust the PULSE HEIGHT dial on the 480 Pulser to achieve a pulse height of 4.5 to 5.5V on the oscilloscope. Lock the dial to prevent unintended changes.

22. Add the UNIpolar output of the other half of the 855 Amplifier to the Channel 2 input of the oscilloscope. Adjust the ATTENUATOR switches on the 480 Pulser to achieve a pulse height on Channel 2 within the range from 2 to 8V.

23. Reconnect both 855 UNIpolar outputs to their respective 551 DC INPUTs. Connect the POSitive OUTputs from the two 551 SCAs to the oscilloscope on Channels 1 and 2, respectively. Trigger the oscilloscope from Channel 1. Adjust the DELAY dial on either 551 so that the output pulses from the two SCAs arrive at the same time (within 50 ns) on the oscilloscope display. This ensures that the intrinsic delays through the two signal processing chains are approximately the same. The difference in delays through the two photomultiplier tubes will normally be less than 50 ns.

24. Reconnect the 551 POSitive OUTputs to their respective INPUTS on the 418A. Turn off the 480 Pulser.

25. Place the ^{22}Na Source in the central source holder between the two detectors, and position the movable detector at θ = 0°.

26. On the 996 Timer Counter, set the preset counting time to an interval that is long compared to a few minutes.

27. Start an acquisition on the 996, and move the detector for small angular deflections on both sides of θ = 0° to verify that the counting rate is highest at θ = 0°, and drops off rapidly on both sides of 0°. If the 996 does not count the events, turn the COINCIDENCE REQUIREMENTS switch on the 418A to 1. If the 996 still does not count events, turn the THRESHold ADJustment fully counter-clockwise. Next turn the control 2.75 turns clockwise. This should set the threshold at +1.4 V. If the 996 still does not count events, look for another error in the set-up. Return the COINCIDENCE REQUIREMENTS switch on the 418A to 2 before proceeding with the next step.

28. Choose a preset counting time on the 996 that will ensure a 1-sigma uncertainty from counting statistics that is no larger than 3% for the highest counting rate at 0°.

29. Using the preset time determined in step 28, acquire counts at the angles specified in Table 13.1, and record the results in that table.

- -
EXERCISE

a. Plot the data from Table 13.1 on linear graph paper as illustrated in Fig. 13.5.

b. Plot the ±1 σ error bars from counting statistics on the data points. If the counting rate is defined as

Table 13.1. The Variation of Counting Rate with Angle for the Two 511 keV Annihilation Photons

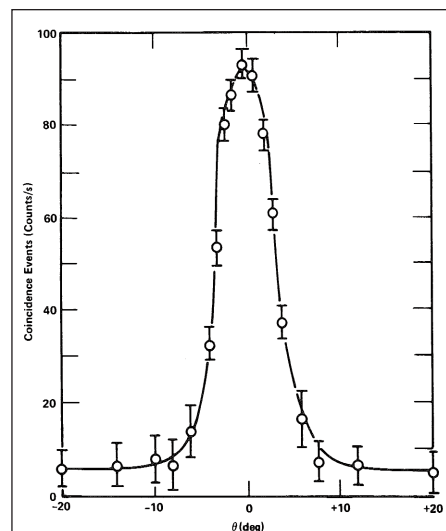| θ (deg) Positive	Counts/s	θ (deg) Negative	Counts/s
0		0	
1		1	
2		2	
3		3	
4		4	
5		5	
6		6	
7		7	
8		8	
10		10	
14		14	
20		20	
25		25	

Fig. 13.5. The Angular Variation of the Annihilation γ-γ Coincidence Counting Rate Acquired with an Overlap Coincidence.

$$R_{cps} = \frac{N}{t} \tag{1}$$

Where N is the number of counts recorded in the time, t, then the predicted standard deviation in the counting rate, R_{cps}, due to counting statistics is

$$\sigma_{Rcps} = \frac{\sqrt{N}}{t} = \sqrt{\frac{R_{cps}}{t}} \tag{2}$$
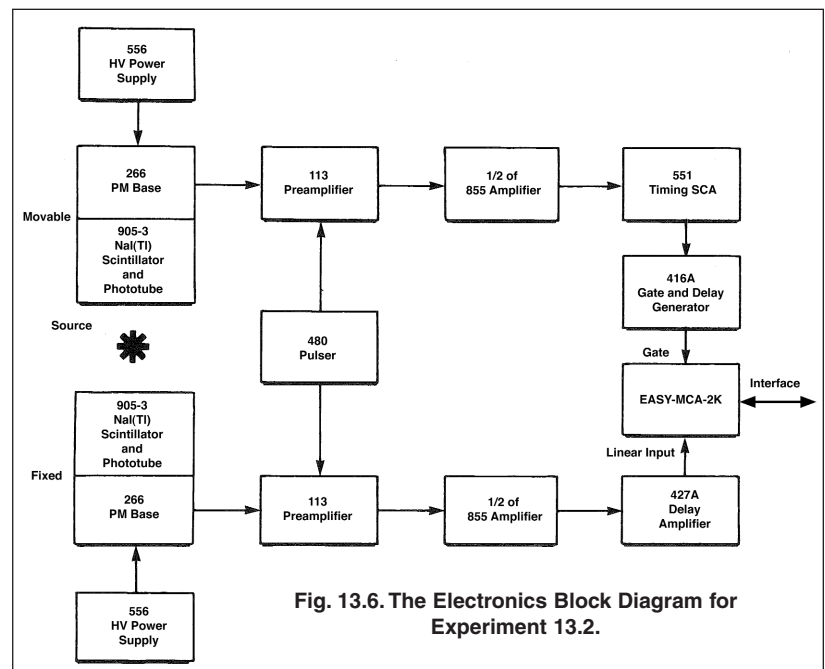
The percent standard deviation is

$$\%\sigma_{Rcps} = \frac{\%\sigma_{Rcps}}{R_{cps}} \times 100\% = \frac{100\%}{\sqrt{N}} \tag{3}$$

c. From your graph, what are the measured limits on the deviation of the angle between the two 511 keV gamma rays from 180°? What limit do the finite diameters of the collimator apertures contribute to this measurement?

EXPERIMENT 13.2. The Linear Gate Method for Measuring the Angular Correlation of 511 keV Annihilation Photons

Procedure

1. Continue with the same system and calibration as used in Experiment 13.1. Make the changes specified below.

2. Turn off the Bin power. Add the 416A Gate and Delay Generator and the 427A Delay Amplifier to the Bin. Turn on the Bin power.

3. For the 551 Timing SCA serving the movable detector, connect the POSitive OUTput to the POSitive INPUT of the 416A Gate and Delay Generator, using a short, 93-Ω coaxial cable. Connect the POSitive DELAYED OUTput of the 416A to the GATE input of the EASY-MCA-2K using a 93-Ω coaxial cable. Set the 416A DELAY to its minimum value.

4. Identify the half of the 855 serving the fixed detector. With a short, 93-Ω coaxial cable, connect the UNIpolar output of that half to the INPUT of the 427A Delay Amplifier. Connect the OUTPUT of the 427A to the linear, analog INPUT of the EASY-MCA-2K with a 93-Ω coaxial cable.

Fig. 13.6. The Electronics Block Diagram for Experiment 13.2.

5. Make sure the EASY-MCA-2K is connected to the supporting computer via the USB cable, and MAESTRO-32 is running on the computer.

6. Via MAESTRO-32, set the MCA conversion gain to 512 channels, the upper level discriminator to 512 channels, and the lower level discriminator to 20 channels. Set the coincidence requirement to OFF.

7. Acquire a spectrum on the MCA. It should look similar to that illustrated in Fig. 13.2. If it does not, you may need to check connections and settings to correct the problem.

8. Remove the ^{22}Na source to make it easier to see the pulser signals on the oscilloscope.

9. Turn on the 480 Pulser with exactly the same settings used in Experiment 13.1.

10. Observe the OUTPUT of the 427A on Channel 1 of the oscilloscope, and trigger the oscilloscope on Channel 1. The pulse height should still be in the range established in Experiment 13.1.

11. While still triggering on Channel 1, connect the 416A POSitive DELAYED OUTput to the Channel 2 input of the oscilloscope. Adjust the pulse amplitude of the 416A logic pulse to be in the range of +5 to +6 V.

12. While superimposing Channels 1 and 2, adjust the 427A DELAY and the 416A DELAY so that the logic pulse arrives approximately 1 µs before the peak amplitude of the analog pulse from the amplifier. Do not use a 427A DELAY that is greater than the minimum required. Adjust the WIDTH of the logic pulse so that it lasts approximately 1 µs past the peak amplitude of the analog pulse. This properly aligns the coincidence gate with the analog pulse for the MCA.

13. Reconnect the 416A POSitive DELAYED OUTput to the GATE input of the EASY-MCA-2K, and the 427A OUTPUT to the EASY-MCA-2K analog INPUT.

14. Via MAESTRO-32 set the gating requirement to COINCIDENCE.

15. Turn off the 480 Pulser, and position the ^{22}Na source in the central holder.

16. Acquire a spectrum on the EASY-MCA-2K with the moveable detector at 0°. Set a region of interest (ROI) from circa channel 20 to the upper limit of the 511 keV peak in the spectrum. Using the MAESTRO-32 features, measure the total counts in the ROI. Determine what preset live time will be required to record sufficient counts in the ROI to ensure that the standard deviation from counting statistics is <3% at θ = 0°.

17. Acquire spectra for the preset live time determined in step 16 at the angles specified in Table 13.1, and record the counts in the ROI divided by the live time.

EXERCISE

a. Plot the data with ±1 σ error bars on linear graph paper as in Experiment 13.1. Compare the counts rates between Experiments 13.1 and 13.2 at θ = 0°.

b. In Experiment 13.2, the MCA corrects for dead time losses by acquiring counts for a preset live time. What was the percent dead time at the highest counting rate? In Experiment 13.1, there was no dead time correction applied to the counting rate. How will that affect the comparison between the two experiments?

c. With the coincidence requirement, the ratio of the counting rate in the 1.274 MeV peak to the 511 keV peak is lower than when the coincidence gate is turned off. Why?

EXPERIMENT 13.3. Time-to-Amplitude Converter Method for Measuring Gamma-Gamma Coincidence with ^{22}Na

Procedure

1. Continue with the electronics as set up and calibrated in Experiment 13.2. Turn off power to the NIM Bin, and remove the 416A and 427A modules from the bin.

2. Install the 567 Time-to-Amplitude Converter/SCA (TAC/SCA) in the bin, and turn on the NIM Bin power.

3. On the 567, set the time range to 500 ns (50 ns RANGE x 10 MULTIPLIER). Set the SCA WINDOW dial to its maximum (clockwise) value, and the SCA LOWER LEVEL to its minimum (counter-clockwise) value. Turn the DELAY screwdriver adjustment to its minimum (counter-clockwise) value. Select the INTernal STROBE mode. Set the START and STOP GATE switches to the ANTIcoincidence mode. Confirm that the circuit board jumpers have been set for NEGative NIM inputs on the START and STOP INPUTS.

4. For the 551 serving the movable detector, connect the NEGative OUTput to the START INPUT of the 567, using a 50-Ω RG-58A/U coaxial cable.

5. For the 551 serving the fixed detector, connect the NEGative OUTput to the STOP INPUT of the 567, using a 50-Ω RG-58A/U coaxial cable.

6. Using a 93-Ω RG-62A/U coaxial cable, connect the 567 TAC OUTPUT to the linear, analog input of the EASY-MCA-2K. With another 93-Ω RG-62A/U coaxial cable, connect the 567 SCA OUTPUT to the 996 Timer/Counter POSitive INput.

7. Remove the ^{22}Na source and turn on the 480 Pulser with exactly the same settings as established in Experiment 13.1.
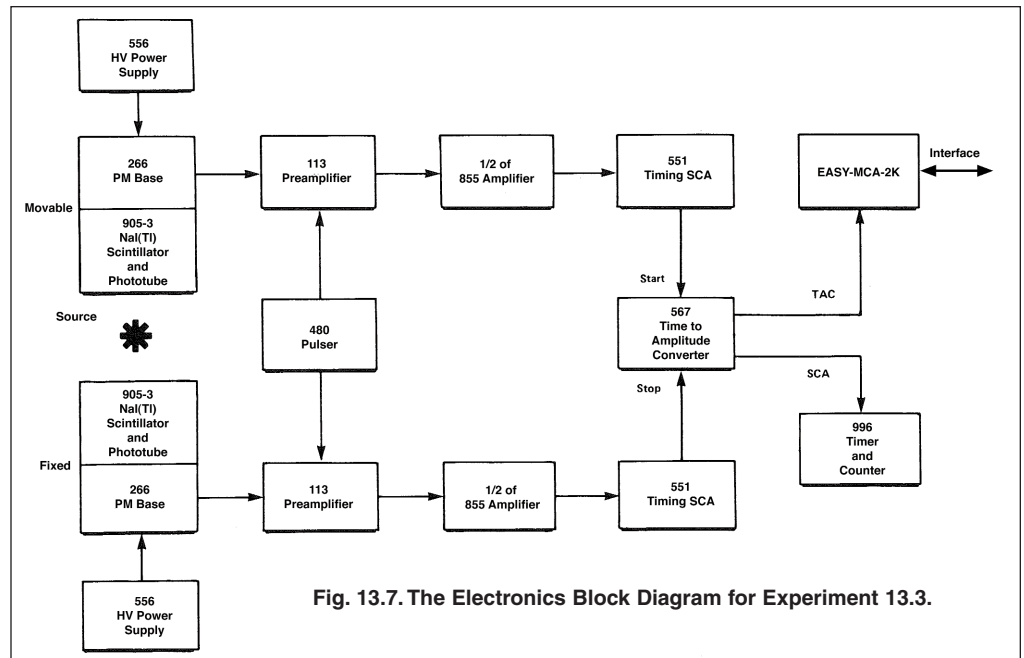

Fig. 13.7. The Electronics Block Diagram for Experiment 13.3.

8. Observe the TAC OUTPUT of the 567 on the oscilloscope.

9. Set the DELAY dial on the 551 supplying the START signal to its minimum (counter-clockwise) value and lock it. While observing the TAC OUTPUT on the oscilloscope, vary the DELAY dial on the 551 supplying the STOP signal. Note that this dial controls the pulse height from the 567 TAC. Select a dial setting that yields an amplitude of approximately +5 V. Record this value.

10. Via MAESTRO-32, turn the coincidence gating condition to OFF for the EASY-MCA-2K.

11. Re-connect the TAC OUTPUT to the linear, analog INPUT of the EASY-MCA-2K and acquire a spectrum. A fairly narrow peak should grow near channel 256.

12. Change the DELAY dial on the 551 supplying the STOP INPUT in 50 ns increments and record the peak positions in channel number versus the dial setting in nanoseconds. Cover as much of the range of the MCA channels as possible. Plot a linear calibration curve of channel number versus time, and determine the slope of the curve in nanoseconds/channel.

13. Adjust the DELAY dial to return the Pulser peak to approximately channel 256, and lock the dial. Acquire enough counts in the Pulser peak to be able to measure the FWHM of the peak.

EXERCISE

a. From the spectrum in step 13, calculate and report the FWHM time resolution in nanoseconds with the Pulser.
----

14. Turn off the 480 Pulser, and return the ^{22}Na source to its position in the central source holder. Set the movable detector at $\theta = 0°$.

15. Acquire a spectrum with sufficient counts to measure the FWHM of the time peak from the 511 keV gamma rays.

EXERCISES

b. From the spectrum in step 15, calculate and report the FWHM time resolution in nanoseconds with the 511-keV gamma rays.

c. Is the time resolution in Exercise step b. different from Exercise step a.? Why?
    ----

16. Set a region of interest (ROI) to include the entire time peak in the spectrum, but no wider than necessary. Record the counting rate (counts divided by live time) in that ROI.

17. With the 996, measure the counting rate for a similar counting time, but from the SCA OUTPUT of the 567.

    EXERCISES

d. How does the counting rate from the SCA OUTPUT compare to the counting rate from the ROI of the TAC spectrum?

e. If the two counting rates differ, why are they different?
    ----

18. Turn the TAC INHIBIT switch between the TAC and SCA OUTPUTs to the INHIBIT position, if it is not already in that position.

19. Acquire a spectrum, and raise the 567 SCA LOWER LEVEL until it begins to cut off the time peak on the lower channel side. Reduce the LOWER LEVEL dial setting just enough to ensure there is no interference with the peak. Lock the dial to prevent accidental changes. Reduce the 567 SCA WINDOW dial value until it begins to cut off the time peak on the high channel side. Increase this dial setting just enough to ensure there is no interference with the peak. Lock the dial to prevent accidental changes. With these settings, the 567 SCA is limiting the TAC OUTPUT pulse heights that are fed to the EASY-MCA-2K.

20. Erase the spectrum and acquire a new spectrum long enough to acquire statistically significant counts in the peak. Simultaneously, count the events for a similar time interval on the 996 Timer & Counter. Record the counts in the ROI and on the 996.

    EXERCISES

f. Compare the counting rates from the MCA ROI and the 996 Timer and Counter in step 20.

g. Do the two results differ less than in Exercise step d.? Why?

h. In any coincidence experiment, a much lower counting rate of uncorrelated coincidences often occurs along with a higher counting rate of correlated coincidences (ref. 11). These are sometimes referred to as random versus true coincidences, chance versus true coincidences, or accidental versus true coincidences. When the SCA is not restricting the time range being analyzed, these chance coincidences show up as a flat background under the true coincidence peak. Estimate the number of chance coincidences that were counted by the 996 when A) the SCA did not restrict the time spectrum, and B) when the SCA restricted the counts to only those in the peak (ref. 12).

i. Are the chance coincidences a significant fraction of the true coincidences in the two cases?
    ----

21. Turn the 567 TAC INHIBIT switch to the OUT position.

22. As in Experiment 13.1, measure the data to fill in Table 13.1, using the counting rate in the ROI on the MCA.

    EXERCISES

j. Plot the results from step 22 on linear graph paper.

k. How does the angular correlation graph compare to those acquired in Experiments 13.1 and 13.2?

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12. See the Introduction to Time-to-Amplitude Converters and Calibrators at http://www.ortec-online.com/Solutions/modular-electronic-instruments.aspx.