

Purpose

This experiment explores some of the basic instrument configurations for time coincidence studies, including time spectroscopy. It includes a brief discussion of typical decay schemes, because coincidence techniques are indispensable for decoding such decay sequences. Beta-Gamma coincidence measurements will be used to provide an absolute calibration of the activity for a ⁶⁰Co radioactive source.

Introduction

Time coincidence counting is a common method for detecting and identifying radioactive materials, and for calibrating their disintegration rates. The technique involves determining which events in two or more detectors occur at the same time, within a resolving time set by the signal processing electronics. The resolving time can be as small as 100 picoseconds with fast timing electronics, or as large as a few microseconds for slow timing systems. The absolute activity measurement can be made by counting two or more characteristic radiation events, such as beta and gamma, that occur either together or within a specified time relationship to each other. In this experiment, ⁶⁰Co is the isotope that is used to explore the method.

β-γ Coincidence

Many beta and gamma sources used in nuclear training laboratories are produced with nuclear reactors. Typically, a stable isotope is placed in the reactor core for a specified time period. The neutron flux in the reactor core could be as much as 10¹⁴ neutrons/cm²/second. This means that 10¹⁴ thermal neutrons bombard each cm² of the sample during each second of irradiation. As a result of this bombardment, the sample becomes radioactive.

At thermal neutron energies, the most probable reaction is neutron capture, otherwise known as the (n, γ) reaction. A simplified explanation of this reaction is that a neutron from the reactor collides with one of the stable nuclei in the

Equipment Required

- 905-3 2-inch x 2-inch (5.08-cm x 5.08-cm) NaI(Tl) Detector and PM Tube Assembly.
- 266 PhotoMultiplier Tube Base.
- Two 113 Preamplifiers.
- BA-015-050-1000 Partially-Depleted Silicon Surface-Barrier Detector
- 142A Preamplifier
- 556 High Voltage Power Supply.
- 710 Quad 1-kV Bias Supply.
- 480 Pulser.
- 855 Dual Amplifier.
- Two 551 Timing Single Channel Analyzers.
- 418A Universal Coincidence.
- 974A Quad Counter and Timer.
- 425A Nanosecond Delay.
- 567 Time-to-Amplitude Converter and SCA.
- 4001A/4002D NIM Bin and Power Supply
- Easy-MCA-2K including a 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.
- TDS3032C Oscilloscope with bandwidth ≥150 MHz.
- DETECTOR-STAND-AX NaI(Tl) Detector Stand (Down-looking) with Source and Foil Holder.
- 305-AX Thin-Window Vacuum Chamber with Source Holder for β-γ Coincidence Measurements.
- ALPHA-PPS-115 Vacuum Pump Station.
- Cables and Connectors:
 - Two C-24-0.5 RG-62A/U Coaxial Cables with BNC Plugs, 0.5-ft. (15-cm) length.
 - One C-24-1 RG-62A/U Coaxial Cable with BNC Plugs, 1-ft. (30-cm) length.
 - Seven C-24-2 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 2-ft. (0.61-m) length.
 - Six C-24-4 RG-62A/U 93-Ω Coaxial Cables with BNC Plugs, 4-ft. (1.2-m) length.
 - Four C-24-12 RG-62A/U Coaxial Cables with BNC Plugs, 12-ft. (3.7-m) length.
 - Three C-25-2 RG-58A/U 50-Ω Coaxial Cables with BNC Plugs, 2 ft. (0.61 m) length.
 - Two C-36-12 RG-59A/U Coaxial Cables with SHV Female Plugs, 12-ft. (3.7-m) length.
 - Two C-29 BNC Tee Connectors.
 - One C-27 100-Ω BNC Terminator.
- BF-060-5 5-μCi ⁶⁰Co Source with a thin Mylar window for β-spectrometry. A license is required for this source.
- Small, flat-blade screwdriver for tuning screwdriver-adjustable controls.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

sample. The neutron is absorbed into the nucleus, thus forming an isotope of the original nucleus. The new nucleus is typically in an excited state. To relax to the ground state, the excess energy is given off by the emission of prompt gamma-rays, and that is why the process is called an (n, γ) reaction. Even in the ground state, the new nucleus is usually unstable, and will decay with a finite half life by emitting a radioactive particle. For isotopes formed by (n, γ) neutron activation, the product nucleus is neutron-rich, and the most probable decay mode for a neutron-rich isotope is β^- decay. The beta decay is often followed by gamma emission from the daughter nucleus.

Figure 9.1 depicts the beta decay process for a fictitious isotope X_1 that has been formed by the (n, γ) reaction. For simplicity, the excited states of X_1 are not shown, because de-excitation to the ground state occurs promptly after neutron absorption via gamma-ray emission. In other words, the lifetimes of the excited states in X_1 are negligible. By the time the experimenter receives the sample from the reactor, X_1 is already in its ground state.

For graphically representing a decay scheme, the energy of excitation of a nucleus is plotted in the vertical direction, and a daughter isotope having a higher atomic number is shifted to the right. The possible energy levels available in the decay are shown as vertically-stacked, horizontal lines in the diagram. In Fig. 9.1, lighter reference lines (A, B and C) have been drawn to the right to label the energy levels for further discussion. These extra lines would not appear in a normal decay-scheme diagram.

Isotope X_1 decays by β^- emission to become isotope Y_1 . If the atomic number of X_1 is Z , then the atomic number of Y_1 is $Z+1$. But, the atomic mass numbers are identical for both isotopes, because a neutron in X_1 has been replaced with a proton and an emitted electron plus antineutrino for Y_1 . The equation representing this decay is:



Where the available energy from the decay is shared between the electron (β^-) and the antineutrino ($\bar{\nu}$).

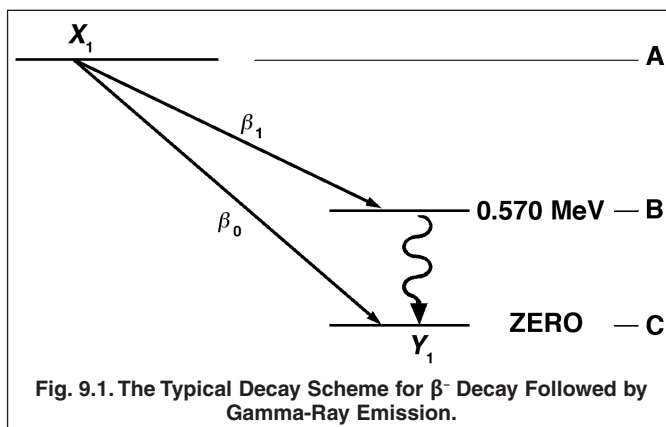
There are two possible modes for this decay, β_0 and β_1 . In other words, the excited X_1 nucleus has two possible routes to become de-excited. The β_0 mode feeds directly to the ground state of Y_1 (labeled C in Fig. 9.1), whereas the β_1 mode leaves Y_1 in the 0.570 MeV excited state (labeled B in the figure). Consequently, the beta particle and the antineutrino share 0.570 MeV less energy in the β_1 mode than in the β_0 alternative.

In the diagram, C is the zero energy state for Y_1 , and is commonly called the ground state of Y_1 . If X_1 decays into the ground state of Y_1 via the β_0 mode, no gamma rays accompany that particular decay. Alternatively, if X_1 decays to the 0.570 MeV excited state of Y_1 via the β_1 mode, the beta-particle emission is followed by release of a 0.570 MeV gamma ray to take Y_1 from the excited state to the ground state. Usually, the half life for the decay of the excited state by gamma-ray emission is in the range of 10^{-8} to 10^{-12} seconds. This is short enough to be considered prompt gamma-ray emission. The gamma-ray energy is always equal to the difference in energy between the two states involved in the transition. In the case of Y_1 , the final state happens to be labeled with zero energy, so the gamma-ray energy matches the energy of the excited state, 0.570 MeV. If the beta spectrum from X_1 is studied as in Experiment 6, two beta spectra will be observed, with a difference of 0.570 MeV in their end-point energies. However, a β - γ coincidence experiment will quickly show that only β_1 is in coincidence with the 0.570 MeV gamma ray. The coincidence technique will be used later in this experiment to determine the absolute activity of a radioactive source.

α - γ Coincidence

In order to understand α - γ coincidence, a simple, hypothetical example will be used. Let us assume that we have a radioactive isotope (A) that decays by alpha emission to a stable isotope (B) with the scheme shown in Fig. 9.2.

From the decay scheme, it can be seen that 50% of the time (A) decays by alpha emission (α_0) directly to the ground



Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

state of (B). The other 50% of the time, decay is by an α_1 - γ_1 branch, which is similar to the β_1 - γ_1 branch in the previous example. The decay is by a 5 MeV alpha (α_1) followed immediately by a 0.50 MeV gamma ray. Thus, the α_1 and γ_1 are in coincidence. For this example, every α_1 is followed by a γ_1 .

Because an alpha particle is composed of two protons and two neutrons, the atomic number of isotope (B) is $Z-2$, if the atomic number of (A) is Z , and the mass number of (B) is 4 units less than the mass number of (A). Consequently, (B) is displayed to the left of (A) in Fig. 9.2.

Fig. 9.3 shows the alpha and gamma spectra for the source as they would have been measured separately in the previous experiments with a silicon charged-particle detector and a NaI(Tl) detector, respectively. If the electronics are set up with a silicon detector looking at the alphas in coincidence with a NaI(Tl) detector measuring the gammas, it will be observed that there are no gamma rays in coincidence with α_0 .

γ - γ Coincidence

In all the examples shown thus far in this experiment, gamma decay occurs directly to the ground state of the final stable nucleus. However, it is possible for a nucleus to de-excite with a sequence of several gamma-rays, as the nucleus cascades through multiple excited states. In order to understand this, let us consider the simple decay scheme shown in Fig. 9.4.

In Fig. 9.4 the nucleus (C) decays to the nucleus (D) by β^- emission followed by gamma decay. A simple way to look at the decay is as follows: the beta emission of (C) results in the nucleus (D), which is left with an excess energy of excitation equal to 1.0 MeV. The excited (D) nucleus gives off its energy of excitation by the emission of a sequence of two gamma rays. First, the emission of γ_1 , which has an energy of 0.4 MeV, drops the nucleus into the 0.6 MeV excited state. The emission of γ_2 , which has an energy of 0.6 MeV, follows promptly, and leaves the nucleus in the ground state. Simply stated, for every γ_1 emitted, a γ_2 is also generated. The two gamma-rays occur in time coincidence.

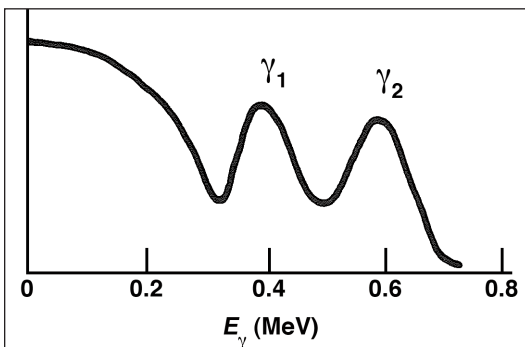


Figure 9.5. The Unrestricted Gamma-Ray Energy Spectrum Expected for the Decay Scheme in Fig. 9.4, as Recorded by a NaI(Tl) Detector.

With no coincidence requirements applied to the acquisition, the corresponding gamma spectrum from isotope (C) is shown in Fig. 9.5.

As was pointed out earlier, there would also be a coincidence between the beta particle and either of the gamma rays. Occasionally, an isotope will branch directly to the ground state without going through the intermediate states. If this happened in the above example, a gamma ray of 1 MeV energy would also be seen in the spectrum. The probabilities for gamma decay from a given state to the ground state through intermediate states relative to the direct transition to the ground state are called gamma-ray branching ratios. Branching ratios are usually listed in the decay-scheme diagrams.

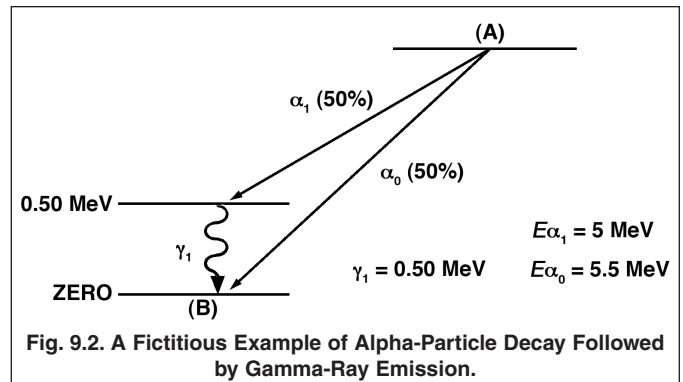


Fig. 9.2. A Fictitious Example of Alpha-Particle Decay Followed by Gamma-Ray Emission.

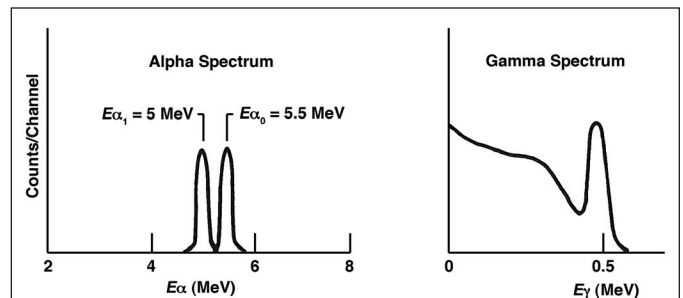


Fig. 9.3. The Individual Spectra That Would Be Recorded for the Alpha Source in Fig. 9.2. The Alpha Spectrum from a Silicon Charged Particle Detector is on the Left, and the Gamma-Ray Spectrum from a NaI(Tl) Detector is on the Right.

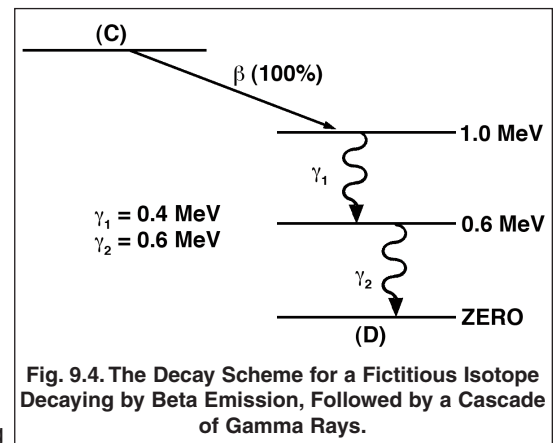


Fig. 9.4. The Decay Scheme for a Fictitious Isotope Decaying by Beta Emission, Followed by a Cascade of Gamma Rays.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

In later experiments γ - γ and α - γ coincidence measurements will be made. In this experiment, several possible electronic configurations for coincidence measurements will be considered, and a β - γ coincidence setup will be used to determine the absolute activity of a ^{60}Co source.

EXPERIMENT 9.1. A Simple Slow Coincidence System Investigated via a Pulse Generator

Relevant Information

For the coincidence system in Fig. 9.6, a pulse generator replaces the detectors that would normally feed pulses to the 113 Preamplifiers. This enables studying the properties of the coincidence scheme at much higher coincidence counting rates. Consequently, the study of the coincidence circuit can be completed in a period of time that is orders of magnitude shorter than would be possible with two detectors responding to coincident events from a common radioactive source.

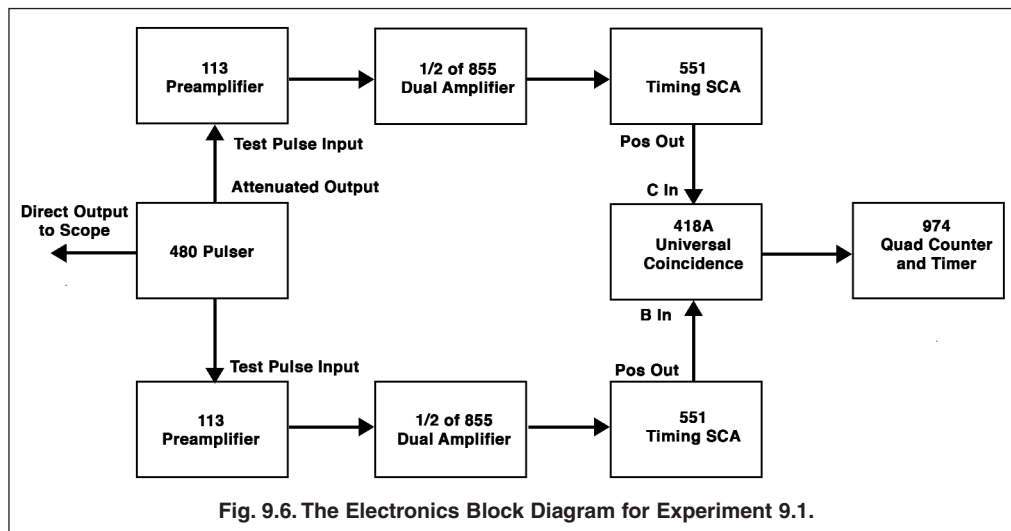


Fig. 9.6. The Electronics Block Diagram for Experiment 9.1.

In this experiment, the 551 Timing Single Channel Analyzers are primarily used to mark the arrival time of the pulses from the two chains of preamplifiers and amplifiers. The upper and lower level discriminators on the Timing SCAs will be set near their respective upper and lower limits to allow virtually all analog pulse heights to be accepted, while preventing triggering on noise near the baseline. For pulse heights occurring within the limits set by the upper and lower level discriminator thresholds, the 551 Timing SCA generates a logic output pulse when the trailing edge of the amplifier pulse falls through 50% of the maximum amplitude of the pulse. Although pulses from the detector can have varying amplitudes, the time profile of all pulses is the same. In other words, if you acquired traces of the amplifier output pulses from an oscilloscope, and normalized every pulse to the same peak amplitude, all pulses would be identical in shape. Consequently, a circuit that generates a timing signal when the analog pulse falls through the 50%-of-peak-amplitude point on the trailing edge of the pulse will always exhibit the same time delay relative to the detection of the radiation in the detector, independent of the pulse height. This circuit is known as a Trailing-Edge Constant Fraction of Pulse-Height Trigger, or more commonly, a Trailing-Edge Constant-Fraction Discriminator (ref. 12).

The 418A Universal Coincidence employs a simple, pulse-overlap method to determine when two events are coincident in time. The positive timing pulses from the Timing SCAs are nominally 500 ns in duration. The circuit in the Universal Coincidence looks to see if any portion of the output pulse from Timing SCA 1 has a time overlap with any portion of the output pulse from Timing SCA 2. If there is any overlap, the Universal Coincidence generates an output logic pulse that signals a time coincidence was detected. In the nomenclature of digital electronics, this is called an AND circuit, because an output is generated only if input 1 AND input 2 are present at the same time.

The coincidence resolving time is determined by the width of the pulses provided to the AND circuit. If both pulse widths are 500 ns, input 1 can precede input 2 by anywhere from 0 to 500 ns and still exhibit an overlap with input pulse 2. Conversely, input pulse 2 can precede input pulse 1 by up to 500 ns and still satisfy the overlap requirement. Consequently, the resolving time of the overlap circuit is $500 + 500 = 1,000$ ns. More generally, the resolving time is $\tau_1 + \tau_2$, where τ_1 is the pulse width for the first input, and τ_2 is the pulse width for the second input. Usually, $\tau_1 = \tau_2 = \tau$, in which case the total resolving time becomes 2τ .

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

INPUT A of the 418A Universal Coincidence, permits the operator to adjust the width of that input to the overlap circuit over the range of 100 ns to 2 μ s. Thus, the resolving time in this experiment can be adjusted from 100 ns + 500 ns = 600 ns to 2,000 ns + 500 ns = 2,500 ns via the RESOLVING TIME screwdriver adjustment associated with INPUT A. Note that this resolving time is not symmetric with respect to both A and B inputs. At the maximum width of 2 μ s, INPUT A can precede INPUT B by up to 2 μ s and still qualify as an overlap. But, INPUT B must precede INPUT A by less than 500 ns to satisfy the overlap requirement. To achieve symmetry, both input pulse widths must be the same.

The adjustable width on INPUT A is really intended for the case where INPUT A is used as an anti-coincidence or veto condition on other inputs to the module. For that application, the veto width must be expanded to ensure a complete overlap of the pulses presented to the other inputs. However, the width adjustment on INPUT A does permit investigating the issue of varying the resolving time in this experiment. For experiment 9.3, the resolving time will be controlled symmetrically by the 500 ns pulse widths from the Timing SCAs. See the data sheet or instruction manual for the 418A and references 1 and 11 for more information on operating principles for overlap coincidence circuits.

Coincidence circuits are often classified as either a fast or slow coincidence. Although there is no precise dividing line between the two categories, circuits with resolving times that are large compared to 50 ns are considered to be slow coincidence logic, and circuits with resolving times that are small compared to 100 ns are usually classified as fast coincidence logic. Typically, slow coincidence logic is derived from the analog signals that have been already processed for optimum energy resolution. To achieve fast coincidence logic, special wide-bandwidth amplifiers are usually used to maintain the fast rise time of the signal from the detector. The latter scheme compromises the signal-to-noise ratio for the pulse height in order to reduce the uncertainty in determining the arrival time of the signal.

The 974A Quad Counter and Timer will utilize counter 1 as a preset timer, and inputs 2, 3 and 4 will be employed to count the pulses from the Universal Coincidence and the Timing SCAs for the preset time established by counter 1.

Procedure

The modules will be connected as illustrated in Fig. 9.6. For Experiment 9.1 all coaxial cables will be 93- Ω RG 62A/U cables with BNC connectors.

1. Place all the modules, except the preamplifiers, in the 4001A/4002D NIM Bin and Power Supply.
2. Connect the DIRECT OUTPUT of the 480 Pulser to a BNC Tee on the Channel 1 Input to the oscilloscope. Place a C-27 100- Ω terminator on the other arm of that Tee. Select the 1-M Ω input impedance option on Channel 1.
3. Place a BNC Tee on the ATTENUATED OUTPUT of the 480 Pulser. Connect one arm of the Tee to the TEST PULSE input of one of the 113 Preamplifiers. Connect the other arm of the Tee to the TEST PULSE input of the other 113 Preamplifier. Ideally, an impedance matching splitter should be used in place of the Tee. However, the impedance mismatch caused by driving the two 93- Ω loads in parallel from the 93- Ω output impedance of the 480 Pulser can be tolerated with impunity, because of the large attenuation selected for the 480 output, and the internal termination in 100- Ω at each preamplifier TEST PULSE input.
4. Connect the OUTPUT of one of the 113 Preamplifiers to the INput of one section of the 855 Dual Amplifier. Duplicate this connection for the other 113 Preamplifier and the remaining INput to the other section of the 855 Dual Amplifier.
5. Connect the power cables for the 113 Preamplifiers to the PREAMP POWER connectors on the rear panel of the 855 Dual Amplifier.
6. Connect the UNIpolar output of one section of the 855 Dual Amplifier to the DC INPUT on one of the 551 Timing Single-Channel Analyzers. Duplicate this connection for the other UNIpolar output on the 855 Dual Amplifier and the other 551 Timing SCA.
7. Connect the POSitive OUTput of one of the 551 Timing SCAs to INPUT B on the 418A Universal Coincidence. Connect the POSitive OUTput of the other 551 Timing SCA to INPUT C on the 418A Universal Coincidence.
8. Connect the OUTPUT of the 418A Universal Coincidence to COUNTER INPUT 3 on the 974A Quad Counter/Timer.
9. Turn on power to the 4001A/4002D NIM Bin and Power Supply.
10. Set the INPUT CAPacitance switches to 100 pF on both 113 Preamplifiers.

Experiment 9

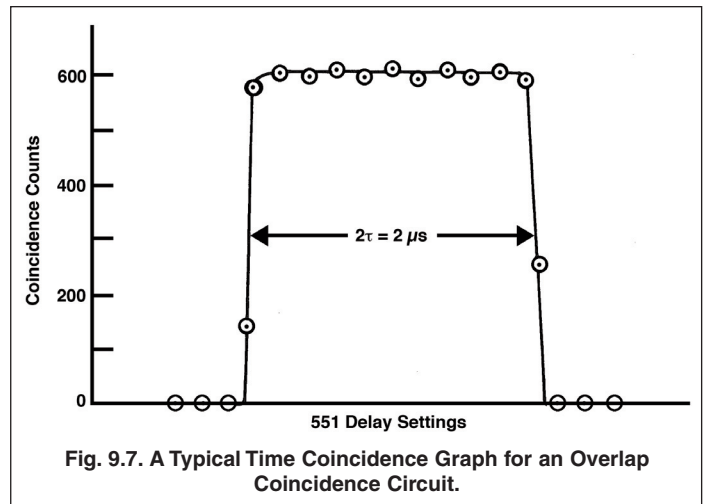
Time Coincidence Techniques Applied to Absolute Activity Measurements

11. On the 480 Pulser, set the 10-turn PULSE HEIGHT dial to its maximum (clockwise) value, choose ATTENUATOR settings of x1, x1, x10, x1, and a NEGative output polarity. Turn the Pulser ON.
12. On the 855 Dual Amplifier, set the two jumpers on the circuit board for a NEGative input polarity (one jumper for each of the two sections). Set all of the SHAPING TIME switches (accessible through the side panel) to 0.5 μ s.
13. By separately observing each Amplifier UNIpolar output on the Channel 2 input of the oscilloscope (with 1-M Ω input impedance), adjust the gain of each amplifier section to produce approximately a +5 V pulse height. For this measurement, the oscilloscope can be triggered by the DIRECT OUTPUT of the 480 Pulser on Channel 1.
14. Reconnect the Amplifier UNIpolar outputs to their respective DC INPUTs on the 551 Timing SCAs.
15. On the rear panels of both 551 Timing SCAs, ensure that the Lower Level REFERENCE toggle switches are set to the INTernal mode. Likewise, verify that the STROBE toggle switches are set to the INTernal mode.
16. On the front panels of both 551 Timing SCAs, set the INT/NOR/WIN switch to the NORmal mode. Set the output DELAY switches to the 1–11 μ s range. Set both DELAY dials to 500/1100 (i.e., 5 μ s), and lock the dials. Set both LOWER LEVEL dials to 10/1000 (i.e., 100 mV) and lock the dials. Set both UPPER LEVEL dials to 1000/1000 (i.e., 10 V) and lock the dials.
17. On the front panel of the 418A Universal Coincidence, set the COINC/OFF/ANTI switches to COINCidence for the B and C INPUTS and to OFF for the remaining inputs. Set the COINCIDENCE REQUIREMENTS to 2.
18. On the 974A Quad Counter/Timer INPUTs 2, 3 and 4 should be already set up, by default, for positive NIM input pulses. If there are problems with counting the POSitive SCA output pulses, check that the circuit board connectors are in the right position to accept positive logic pulses.
19. On the 974A front panel, turn the DWELL knob fully counter-clockwise to the OFF position. Using the TIME BASE SELECT pushbutton choose the 0.1-second time base. With the M and N PRESET pushbuttons set M = 1 and N = 2 to achieve a 10 second preset counting interval. Press the DISPLAY SELECT pushbutton the necessary number of times to cause the counts from COUNTER INPUT 3 to be displayed on the top LED display.
20. Press the STOP button, then the RESET button and finally the COUNT pushbutton. Confirm that the 974A counts for approximately 10 seconds and then stops. Check that the number of counts displayed for COUNTER INPUT 3 is approximately 600. (If the ac power frequency differs from 60 Hz, this number should be 10 times the line frequency.)
21. If step 20 is not successful, connect 974A COUNTER INPUT 3 to the POSitive OUTput from one of the 551 Timing SCAs. Repeat the 10 second count per step 20. The number of counts should be 600. If it is higher than 600, raise the LOWER LEVEL dial on the 551 until the count relaxes to 600. If it is less than 600 counts, check for improper connections or settings on the 113 Preamplifier, 855 Dual Amplifier, and 551 Timing SCA, and make sure the 480 Pulser is indeed turned on. Repeat this test for the other 551 Timing SCA POSitive OUTput.
22. Once the SCA outputs are counting correctly, restore the original connections between the Timing SCAs, the Universal Coincidence and the Counter/Timer
23. If coincidence counts are still not recorded, adjust the DELAY dial on the 551 Timing SCA whose OUTput is connected to the B INPUT on the 418A until the counting rate appears and is maximized. Lock the DELAY dial in that position.
24. For the 551 feeding the C input on the 418A, increase the DELAY dial in 100 ns steps and record the number of counts accumulated on the 974A in 10 seconds for each setting. Continue increasing the DELAY in steps of 100 ns until the coincidence counting rate drops to zero.
25. Repeat step 24 for decreasing DELAY settings in steps of 100 ns.

Experiment 9 Time Coincidence Techniques Applied to Absolute Activity Measurements

EXERCISE

- Plot the data taken in steps 24 and 25 with Counts on the vertical scale and Delay on the horizontal scale. The result should look like Fig. 9.7, except the total width, 2τ , should be about $1\ \mu\text{s}$.
- What is the 2τ resolving time from your graph?
- How does the resolving time compare to the width of the pulses from the 551 Timing SCAs?
- What is the delay setting that corresponds to half way between the two limits where the coincidence counting rate plunges to zero? Why would that point be important for setting up a coincidence counting system?



- Move the cable connection from the 418A INPUT C to INPUT A. Select the OFF condition on the COINC/OFF/ANTI switch for INPUT C, and set the switch to COINCidence for INPUT A.
- Turn the 418A RESOLVING TIME screwdriver adjustment fully clockwise.
- Repeat steps 23 through 25 and Exercise steps a and b.

EXERCISE

- How does the resolving time from your new graph relate to the width of the 551 Timing SCA output and the pulse width at the test point above the 418A INPUT A?

EXPERIMENT 9.2. Using the Time-to-Amplitude Converter for Coincidence Measurements Requiring Smaller Resolving Times

Relevant Information

The Time-to-Amplitude Converter (TAC) can be useful for coincidence measurements, particularly when one needs a much smaller resolving time than is easily achieved by employing wide logic pulses with a conventional overlap coincidence circuit. The TAC is basically an instrument that provides an analog output pulse whose amplitude is proportional to the time difference (Δt) between the start and stop input pulses that are supplied to the module. Inherent in its design is the ability to measure time differences less than a nanosecond with a time resolution of the order of 10 picoseconds. Typically a TAC has several selectable time ranges extending from 0 to 10 ns up to 0 to 2 milliseconds in duration. When the analog output from a TAC is fed to a multichannel pulse-height analyzer, that combination of functions yields a spectrum that not only indicates if two events are in time coincidence, but also shows how the coincident events are distributed in time. This capability can be useful for measuring the decay lifetimes for isotopes with very short decay times. If the multichannel analyzer is replaced with a single-channel analyzer (SCA), the pulse-height window of the SCA can be set across the prompt coincidence peak to provide nanosecond to sub-nanosecond coincidence resolving times.

The purpose of this experiment is to study some of the properties of the TAC. Additional information on the features and operation of a TAC can be found in references 1 and 11.

Procedure

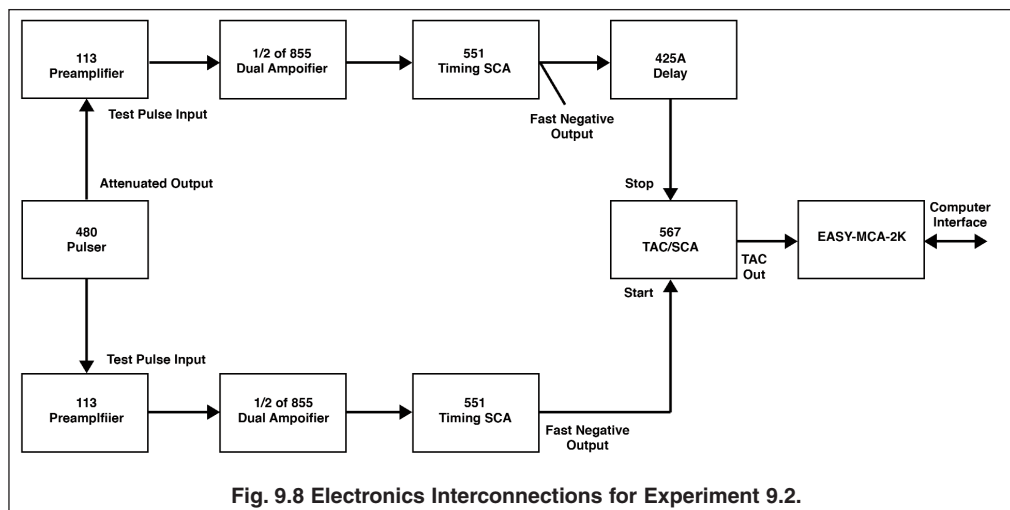
Experiment 9.2 uses the existing set-up and calibration from Experiment 9.1, with the following changes.

- Turn off the NIM Bin power, and add the 425A and 567 modules to the bin. Turn on the bin power.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

- Using RG-58A/U 50-Ω coaxial cables, connect the fast NEGative OUTPUT of one of the 551 Timing SCAs to the START INPUT of the 567 TAC/SCA. Connect the fast NEGative OUTPUT of the other 551 Timing SCA to the top (input) connector on the 425A Delay. Connect the bottom (output) connector on the 425A Delay to the STOP input on the 567 TAC/SCA. Because these three routings incorporate fast negative NIM signals, it is critical to make the



connections with 50-Ω coaxial cables. The inputs on each module supply the 50-Ω terminations necessary to prevent distortions from pulse reflections.

- Using an RG-62A/U 93-Ω coaxial cable, connect the TAC OUTPUT from the 567 TAC/SCA to the analog INPUT of the Easy-MCA-2k multichannel analyzer. Connect the Easy-MCA-2k to the supporting computer via a USB cable. Check that the computer is turned on, and that MAESTRO-32 software is operational in the computer.
- All the control settings on the 113 Preamplifiers, 855 Dual Amplifier and the 551 Timing SCAs should remain the same as established by the end of Experiment 9.1, except for those specified next.
- On both 551 Timing SCAs select the 0.1 – 1.1 μsec. delay range, and turn the DELAY dials to their minimum values. Lock the dials.
- Flip the 32-ns switch on the 425A DELAY to the DELAY IN position. Set all the other switches to the DELAY OUT position. The Model 425A is an analog delay that employs sections of 50-Ω coaxial cable of different lengths to achieve the selected delay.
- On the rear panel of the 567 TAC/SCA, check that the EXT STROBE RESET switch is set to 10 μs.
- On the front panel of the 567 TAC/SCA, select the OUT position for the TAC INHIBIT switch. Choose the ANTI-coincidence positions for the GATE switches on the START and STOP inputs. Set the STROBE switch to INTERNAL. By default, the PWB jumpers should already reside in the “negative NIM input” position. But, if the inputs do not respond correctly, you may have to check that setting. Select a RANGE of 100 ns, and a X1 MULTIPLIER. This provides a recordable time range of nominally 0 to 100 ns.
- Via the MAESTRO-32 software on the computer, select 1024 channels full scale (for pulse heights from 0 to +10 V), an upper level discriminator setting of 1024 channels and a lower level discriminator setting of 20 channels. Ensure that the coincidence/anti-coincidence gate condition is turned off.
- Ensure that the 480 Pulser is turned on and all other settings are the same as in Experiment 9.1
- Start an acquisition on the Easy-MCA. Observe the channel position at which a narrow peak begins to grow. Adjust the DELAY dial on either 551 Timing SCA to make the peak grow at circa channel 500. Increasing the output delay on the Timing SCA connected to the START INPUT will shift the peak to a lower channel number. Increasing the output delay on the Timing SCA connected to the STOP INPUT will shift the peak to the right. Once the peak is centered at mid-scale on the MCA, lock the DELAY dials on the Timing SCAs.
- Acquire a peak long enough to be able to measure the full width at half maximum height (FWHM) with adequate precision. Measure the FWHM in channels and record it as ΔC_1 . If the FWHM is less than 5 channels, change the MCA conversion gain to 2048 channels, with an upper level discriminator set to 2048, and a lower level discriminator set to 40. If ΔC_1 was greater than 20 channels, reduce the MCA conversion gain to 512 channels, with an upper

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

level discriminator set to 512, and a lower level discriminator set to 10. Repeat the FWHM measurement and continue with the conversion gain that was finally selected.

13. For each 425A delay setting in Table 9.1, acquire a peak in the time spectrum with a sufficient number of counts to allow an accurate measurement of the peak position. Setting a region of interest (ROI) across the peak with the MAESTRO-32 features will permit an accurate reporting of the centroid by the software. Record the measured centroids versus delays in Table 9.1.

Stop Signal Delay (ns)	Peak Location (Channel No.)	Stop Signal Delay (ns)	Peak Location (Channel No.)
0		35	
5		40	
10		45	
15		50	
20		55	
25		60	
30		63	

EXERCISES

- Plot the data from Table 9.1 as a linear calibration curve with delay versus channel number. The result should look like Fig. 9.9, except the number of channels spanned by the data may differ.
- Determine the slope of the calibration curve, $\delta D/\delta ch$.
- Calculate the time resolution in nanoseconds from the measurement in step 12 and the slope from step b.

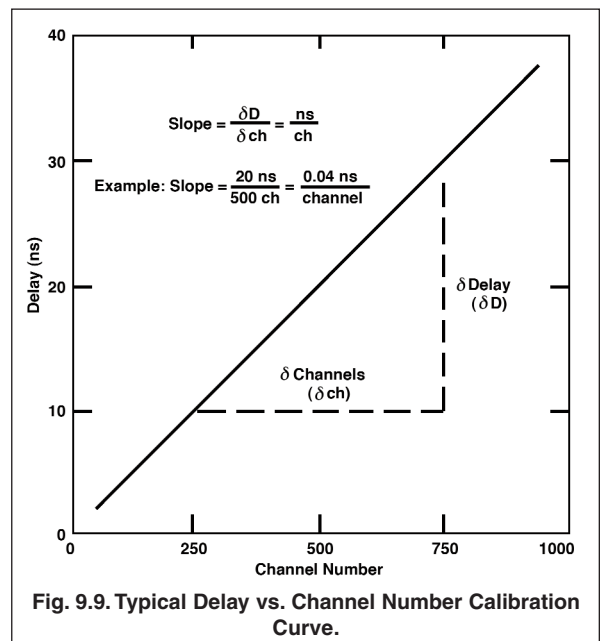
$$\Delta T_1 = \Delta C_1 \frac{\delta D}{\delta ch} \quad (2)$$

- Set all the switches on the 425A to the DELAY OUT position. Using the RANGE and MULTIPLIER switches on the 567 TAC/SCA, select a time range of 500 ns.
- Increase the MCA conversion gain to 2048 channels. Increase the upper and lower level discriminator settings to 2048 and 40, respectively.

- Turn the DELAY on the Timing SCA that feeds the START INPUT to its minimum value and lock it.

- Starting from the minimum value, increase the DELAY dial on the 551 Timing SCA that feeds the STOP INPUT in 25 ns increments and record the peak positions in a table similar to Table 9.1. You may need to find the minimum setting that is required to create a peak in the time spectrum. You can stop the increments once the peaks get close to the maximum MCA channel number.

- Measure the FWHM of one of the peaks near mid-scale on the MCA. Record that FWHM as ΔC_2 .



EXERCISES

- Draw a new calibration curve for the 500 ns range as was done previously.
- Determine the slope of the calibration curve, and use it to convert the FWHM measured in step 18 to a FWHM time resolution ΔT_2 .
- Does ΔT_2 differ from ΔT_1 ? Why?

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

EXPERIMENT 9.3 Determination of Absolute Activity by the Coincidence Method

Purpose

In this experiment, the coincidence counting method will be used to measure the absolute activity of a ^{60}Co source via $\beta - \gamma$ coincidence counting.

Relevant Information

For determining the absolute activity of the ^{60}Co source, the method consists of counting the following events:

- 1) The total counts in the gamma spectrum for the source as measured by a NaI(Tl) detector. (See Experiment 3 for additional information on this detector.)
- 2) The total counts in the beta spectrum acquired by a silicon surface-barrier detector, as outlined in Experiment 6.
- 3) The $\beta - \gamma$ coincidence counting rate for the source as previously demonstrated with a pulser in Experiment 9.1.

From item 1), the gamma counting rate, R_γ , is

$$R_\gamma = A_0 \epsilon_\gamma \quad (3)$$

Where A_0 is the true disintegration rate of the sample and ϵ_γ is the de facto efficiency of the NaI(Tl) detector.

From item 2) the beta counting rate is

$$R_\beta = A_0 \epsilon_\beta \quad (4)$$

where ϵ_β is the de facto efficiency of the beta detector.

The coincidence counting rate measured for item 3) is theoretically predicted to be

$$R_c = A_0 \epsilon_\gamma \epsilon_\beta \quad (5)$$

From equations. (3), (4), and (5), A_0 can be calculated to be

$$A_0 = \frac{R_\gamma R_\beta}{R_c} \quad (6)$$

Procedure

This experiment employs a model BA-015-050-1000 Partially-Depleted Silicon Surface-Barrier Detector for measuring the beta particles from the ^{60}Co source. Review the procedures in Experiment 6 for working with this type of detector. In particular, note the warning regarding the fragility of this type of detector.

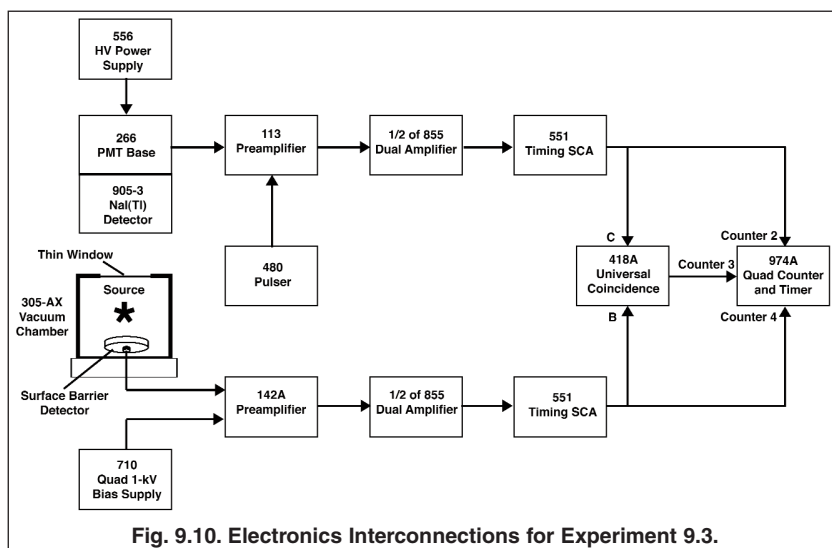


Fig. 9.10. Electronics Interconnections for Experiment 9.3.

SURFACE-BARRIER DETECTOR WARNING

Never touch the exposed surface of the non-ruggedized surface-barrier detector with any foreign material — especially your fingers. The front window is a thin layer of deposited gold which will be irreparably damaged by skin oils or any abrasive, thus destroying the function of the detector. Always handle the detector by its edges and/or in its protective case. Do not allow any foreign material to touch the front surface of the detector.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

Set up the equipment shown in Fig. 9.10. More specifically:

Installation and Connections

1. Turn off the power to the NIM Bin.
2. If the silicon surface-barrier detector is not already properly mounted in the vacuum chamber, install the detector in the chamber. The Microdot connector on the rear of the detector must be plugged into the feedthrough in the base of the chamber, and the connector retention nut must be turned finger-tight.
3. Place the ^{60}Co source on the axial centerline of the detector with approximately a 2.5 cm distance between source and detector. One side of this source has a thin Mylar film over the radioactive material to allow the beta particles to escape with minimal energy loss. The other side of the source is a disk of aluminum of circa 3 mm thickness, which is sufficiently thin to transmit the gamma rays, but will completely absorb the beta particles. Make sure that the side with the thin Mylar film faces the surface-barrier detector.
4. Install the vacuum-chamber cap over the chamber in preparation for evacuating the chamber.
5. Using the minimum feasible length of RG 62A/U 93- Ω coaxial cable, connect the portion of the feedthrough that protrudes outside the vacuum chamber to the INPUT of the 142A Preamplifier.
6. Connect the pump-out port of the vacuum chamber to the Vacuum pump using the supplied vacuum hose.
7. Mount the NaI(Tl) detector and 266 PMT Base in the Detector Stand. The scintillation crystal should be on the centerline of the vacuum chamber with minimum space between the circular face of the scintillation crystal envelop and the thin window on the vacuum chamber. Insert a thin sheet of notebook paper between the scintillation end cap and the vacuum chamber to electrically isolate one from the other. This will avoid ground loops that could introduce extraneous noise into either detector signal processing chain.
8. Using the minimum feasible length of RG-62A/U 93- Ω coaxial cable, connect the ANODE output of the 266 PMT base to the INPUT of the 113 Preamplifier.
9. Remove the 425A Delay and the 567 TAC/SCA from the NIM bin to make room to insert the 710 Quad 1 kV Bias Supply and the 556 HV Power Supply. To minimize potential ground loops, it is preferable to locate the 710 Bias Supply next to the 855 Dual Amplifier. That issue is not quite so critical for the 556 HV Power Supply, because the NaI(Tl) detector is less sensitive to ground loops.
10. Make sure the power switch on the 556 HV Power Supply is turned off. Check that the POLARITY switch on the rear panel is set to POSitive, and the CONTROL switch is set to INTernal. Set the voltage controls on the front panel to their minimum values.
11. Connect one of the OUTPUTS on the rear panel of the 556 to the POSitive HV input on the 266 PMT Base using an RG-59A/U coaxial cable with SHV plugs.
12. Turn on the NIM Bin power long enough to check the POS/NEG LEDs on the front panel of the 710 Bias Supply. You will be using the #1 output. So make sure the green LED for that section indicates a POSitive polarity for the bias voltage. Turn off the NIM Bin power.
13. On the 710 Bias Supply, turn the RANGE switches to DISABLE and the VOLTAGE dials to the minimum value for all 4 sections. Turn the MASTER switch OFF.
14. Using an RG-59A/U coaxial cable with SHV plugs, connect the #1 HV OUTput on the rear panel of the 710 Bias Supply to the BIAS input on the 142A Preamplifier.
15. Connect the power cables for the two preamplifiers to the PREAMP POWER connectors on the rear panel of the 855 Dual Amplifier.
16. Using an RG-62A/U 93- Ω coaxial cable, connect the OUTPUT of the 113 Preamplifier to one INput of the 855 Dual Amplifier. Similarly, connect the E output of the 142A Preamplifier to the other INput on the 855 Dual Amplifier.
17. Connect one UNipolar output of the 855 Dual Amplifier to the DC INPUT of one of the 551 Timing SCAs using a short RG-62A/U 93- Ω coaxial cable. Similarly, connect the other UNipolar output to the DC INPUT on the remaining 551 Timing SCA.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

18. Place BNC Tees on the #2 and #4 COUNTER INPUTS of the 974A Quad Counter/Timer.
19. Using short RG-62A/U 93- Ω cables, connect one arm of the Tee on the COUNTER 2 INPUT to the POSitive OUTput on the 551 Timing SCA that derives its signal from the NaI(Tl) detector. Connect the other arm of the Tee to the C input on the 418A Universal Coincidence.
20. Similarly, connect one arm of the Tee on the COUNTER 4 INPUT to the POSitive OUTput on the 551 Timing SCA that derives its signal from the surface-barrier detector. Connect the other arm of the Tee to the B input on the 418A Universal Coincidence.
21. With a short length of 93- Ω coaxial cable, connect the 418A OUTPUT to the COUNTER 3 INPUT of the 974A Quad Counter/Timer.

Control Settings

1. On the 418A Universal Coincidence, set the COINCIDENCE REQUIREMENTS knob to 2. Set the COINC/OFF/ANTI switches to COINCidence for the B and C INPUTs and to OFF for the rest of the INPUTs.
2. For both 551 Timing SCAs and both halves of the 855 Dual Amplifier, use the settings established in Experiment 9.1.
3. For the half of the 855 Dual Amplifier that is processing the signal from the surface-barrier detector, change the input polarity to POSitive via the POS/NEG jumper for that input on the circuit board inside the module.
4. On the 113 Preamplifier, set the INPUT CAPacitance to 100 pF.
5. Turn on the NIM Bin power.
6. From the data sheet, or from the laboratory instructor, find out the recommended bias voltage that should be applied to the NaI(Tl) detector. The manufacturer normally states the measured energy resolution for the specific detector and the voltage at which that result was measured. Set that voltage on the 556 HV Bias Power Supply, and turn on the power to that module.
7. Use the oscilloscope to monitor the pulses at the UNIpolar output of the amplifier section that is serving the NaI(Tl) detector. The positive pulses should reach maximum amplitude in approximately 1 μ s, and have a duration of a few microseconds. Adjust the gain of the amplifier so that the 1.33 MeV gamma-ray pulses have about an 8 V amplitude. Lock the FINE GAIN dial at this value to prevent accidental changes.
8. Adjust the P/Z cancellation of the amplifier according to the procedures taught in prior experiments in this series.
9. Reconnect the UNIpolar output of the NaI(Tl) amplifier to its designated Timing SCA.
10. Turn on the vacuum pump. While you are waiting for the vacuum to pump down to its limit (where the pump becomes very quiet), find out what bias voltage is specified for the surface-barrier detector on its data sheet.
11. Once the chamber is evacuated, turn on the MASTER switch on the 710 Bias Supply. Confirm that the correct voltage polarity LED is illuminated. Set the VOLTS/CURRENT switch to output 1 VOLTAGE so that the applied voltage can be monitored as it is applied. Select the appropriate RANGE for the output 1 VOLTAGE dial. Slowly turn the dial, while monitoring the displayed voltage, until the recommended bias voltage is achieved.
12. Turn the VOLTAGE/CURRENT switch to output 1 CURRENT. Note the displayed bias current. Multiply that current by 100 M Ω to determine the voltage increment that must be added to the recommended bias voltage to compensate for the voltage drop through the 100 M Ω bias resistor in the 142A Preamplifier.
13. Turn the VOLTAGE/CURRENT switch back to output 1 VOLTAGE and add the voltage increment calculated in step 12.
14. Observe the UNIpolar output pulses from the half of the 855 Dual Amplifier that is processing the signals from the surface barrier detector. The pulses should have a positive polarity, rise to peak amplitude in approximately 1 μ s, and have a duration of a few microseconds. Per the revelations in Experiment 6, there should be a continuum of pulse heights with the maximum pulse height corresponding to the 0.314 MeV end-point energy for the beta spectrum. Adjust the amplifier gain to achieve approximately a 6 V maximum pulse height for the continuum. Lock the FINE GAIN dial at this value to prevent unintended changes.

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

15. Using the procedures taught in the previous experiments from this series, adjust the P/Z cancellation of the amplifier for the signal from the surface-barrier detector.
16. Reconnect the 855 UNIpolar output to its respective Timing SCA input.
17. Set a preset time limit on the 974A Counter/Timer that will not interfere with manual starting and stopping of counting. Start a counting acquisition and confirm that all three counters are incrementing. Counters 2 and 4 should exhibit counting rates much larger than counter 3.

Timing SCA Adjustments

1. Turn the Bias voltage on the surface barrier detector to zero, vent the vacuum chamber, and remove the ^{60}Co source.
2. Close the vacuum chamber, pump down the vacuum and slowly return the detector bias voltage to its proper value.
3. Observe the counting rate on Counter 4. It should be negligible. Raise and lower the LOWER LEVEL on the 551 Timing SCA serving the surface-barrier detector to find out where the noise level is. The counting rate on Counter 4 will increase rapidly when the LOWER LEVEL encounters noise near the lower limit of the dial. Raise the LOWER LEVEL setting safely above the noise threshold and lock the dial.
4. Repeat step 3 for the Timing SCA serving the NaI(Tl) detector.
5. Ideally, one should optimize the WALK ADJ adjustment for each Timing SCA. But, unless someone has maladjusted this control, it should not require tuning for this experiment. The WALK ADJ is used to minimize sensitivity to pulse height in the time at which the POSitive and NEGative OUTputs are generated by the Timing SCA. In other words, it minimizes the systematic timing error (ref. 12).
6. Turn the surface-barrier detector bias to zero, and vent the vacuum chamber. Reinstall the ^{60}Co source with the thin window facing the silicon detector.
7. Pump down the vacuum chamber and slowly return the silicon detector bias to its proper voltage.
8. Use the procedure learned in Experiment 9.1 steps 23 through 25 and Exercise steps a) and d) to determine the resolving time graph. You will probably need an order of magnitude longer counting times to achieve sufficient statistical accuracy on the coincidence counts from the radioactive source. Be aware that there will be a flat baseline of random coincidences on which the rectangle found in Experiment 9.1 sits. Determine the mid-point of that rectangle, and set the Timing SCA DELAY to match that setting. Lock the DELAY dials on both Timing SCAs.

Measuring the Activity from the Singles and Coincidence Counts

1. Count the #2, #3 and #4 COUNTER INPUTs to complete the calculation in Equation (6). The coincidence counting rate in Counter 3 will have the lowest rate. Therefore the random error from counting statistics for that number will dominate the precision of the calculation. Count for a sufficient length of time to achieve a predicted standard deviation of <3% in the final result. The raw counts from a detector without coincidence restrictions is often called the *singles* counting rate. This term is contrasted with the *coincidence* counting rate, where events from both detectors must occur simultaneously.

EXERCISE

- a. From the data in step 1 above, calculate the activity of the ^{60}Co source using Equation (6).
 - b. How does that result compare to the known activity of the source? How does the half life affect that comparison?
 - c. Plot the coincidence resolving time graph acquired in the Timing SCA Adjustments section, step 8. What causes the flat, random background predicted to lie under the coincidence rectangle?
 - d. Draw the ^{60}Co decay scheme. What effect will the beta decays to the 2.158 MeV and 1.3325 MeV states have on the above activity measurement?
 - e. Would the coincidence method used to determine the activity of the ^{60}Co source work for the decay scheme depicted in Fig. 9.1?
-

Experiment 9

Time Coincidence Techniques Applied to Absolute Activity Measurements

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