ORTEC®

Experiment 3
Gamma-Ray Spectroscopy Using NaI(Tl)

Equipment Required

- **SPA38** Integral Assembly consisting of a 38 mm x 38 mm NaI(Tl) Scintillator, Photomultiplier Tube, and PMT Base with Stand
- **4001A/4002D** NIM Bin and Power Supply
- **556** High Voltage Bias Supply
- **113** Scintillation Preamplifier
- **575A** Spectroscopy Amplifier
- **EASY-MCA-2K** including USB cable and MAESTRO software (other ORTEC MCAs may be substituted)
- Personal Computer with a USB port and a recent, supportable version of the Windows operating system.
- **TDS3032C** Oscilloscope with a bandwidth ≥150 MHz.
- **C-34-12** RG-59A/U 75-Ω Cable with one SHV female plug and one MHV male plug, 3.7-m (12-ft) length.
- Five **C-24-1** RG-62A/U 93-Ω Coaxial Cables with BNC plugs, 30-cm (1-ft.) length.
- **C-24-12** RG-62A/U 93-Ω Coaxial Cable with BNC plugs, 3.7-m (12-ft.) length.
- Three **C-24-4** RG-62A/U 93-Ω Coaxial Cables with BNC plugs, 1.2-m (4-ft.) length
- **C-29** BNC Tee Connector
- **C-27** 100 Ω Terminator (BNC male plug)
- **RSS8*** Gamma Source Set. Includes ~1 μCi each of: ^{60}Co, ^{137}Cs, ^{22}Na, ^{54}Mn, ^{133}Ba, ^{109}Cd, ^{57}Co, and a mixed Cs/Zn source (~0.5 μCi ^{137}Cs, ~1 μCi ^{65}Zn). The first three are required in this experiment. An unknown for Experiment 3.2 can be selected from the remaining sources.
- **GF-137-M-5*** 5 μCi ±5% ^{137}Cs Gamma Source (used as a reference standard for activity in Experiment 3.5).
- **GF-057-M-20*** 20 μCi ^{57}Co Source (for Experiment 3.9).
- One each of pure metal foil absorber sets: **FOIL-AL-30**, **FOIL-FE-5**, **FOIL-CU-10**, **FOIL-MO-3**, **FOIL-SN-4**, and **FOIL-TA-5**. Each set contains 10 identical foils of the designated pure element and thickness in thousandths of an inch (Foil-Element-Thickness).
- **RAS20** Absorber Foil Kit containing 5 lead absorbers from 1100 to 7400 mg/cm^2. The 10 aluminum absorbers from 140 to 840 mg/cm^2 also included in this kit are not used in this experiment.
- Small, flat-blade screwdriver for tuning screwdriver-adjustable controls
- Additional Equipment Needed for Experiment 3.10
- **427A** Delay Amplifier
- **551** Timing Single-Channel Analyzer
- **426** Linear Gate
- **416A** Gate and Delay Generator

*Sources are available direct from supplier. See the ORTEC website at www.ortec-online.com/Service-Support/Library/Experiments-Radioactive-Source-Suppliers.aspx

Purpose

The purpose of this experiment is to acquaint the student with some of the basic techniques used for measuring gamma rays. It is based on the use of a thallium-activated sodium iodide detector. The written name of this type of detector is usually shortened to NaI(Tl). In verbal conversations, it is typically simply called a sodium iodide detector.

Gamma Emission

Most isotopes used for gamma-ray measurements also have beta-emissions in their decay schemes. The decay scheme for the isotope typically includes beta decay to a particular level, followed by gamma emission to the ground state of the final isotope. The beta particles will usually be absorbed in the surrounding material and not enter the scintillation detector. This absorption can be assured with aluminum absorbers (ref. 10). For this experiment, the beta emissions cause negligible interference, so absorbers are not specified. There is always some beta absorption by the light shield encapsulating the detector. The gammas, however, are quite penetrating, and will easily pass through the aluminum light shield.

Generally there are two unknowns that we would like to investigate about a gamma source. One is measuring the energies of the gamma rays from the source. The other is counting the number of gamma-ray photons that leave the source per unit of time. In this experiment the student will become familiar with some of the basic NaI(Tl) measurements associated with identifying a gamma-emitting radioisotope. A total time of ~6 hours is required to complete all the parts of Experiment 3 (3.1 through 3.10). Since each part is written to be fairly independent of the others, the complete series can be done in two 3-hour lab periods.

Experiment 3
Gamma-Ray Spectroscopy Using NaI(Tl)

The NaI(Tl) Detector

The structure of the NaI(Tl) detector is illustrated in Figure 3.1. It consists of a single crystal of thallium activated sodium iodide optically coupled to the photocathode of a photomultiplier tube. When a gamma ray enters the detector, it interacts by causing ionization of the sodium iodide. This creates excited states in the crystal that decay by emitting visible light photons. This emission is called a scintillation, which is why this type of sensor is known as a scintillation detector. The thallium doping of the crystal is critical for shifting the wavelength of the light photons into the sensitive range of the photocathode. Fortunately, the number of visible-light photons is proportional to the energy deposited in the crystal by the gamma ray. After the onset of the flash of light, the intensity of the scintillation decays approximately exponentially in time, with a decay time constant of 250 ns. Surrounding the scintillation crystal is a thin aluminum enclosure, with a glass window at the interface with the photocathode, to provide a hermetic seal that protects the hygroscopic NaI against moisture absorption. The inside of the aluminum is lined with a coating that reflects light to improve the fraction of the light that reaches the photocathode.

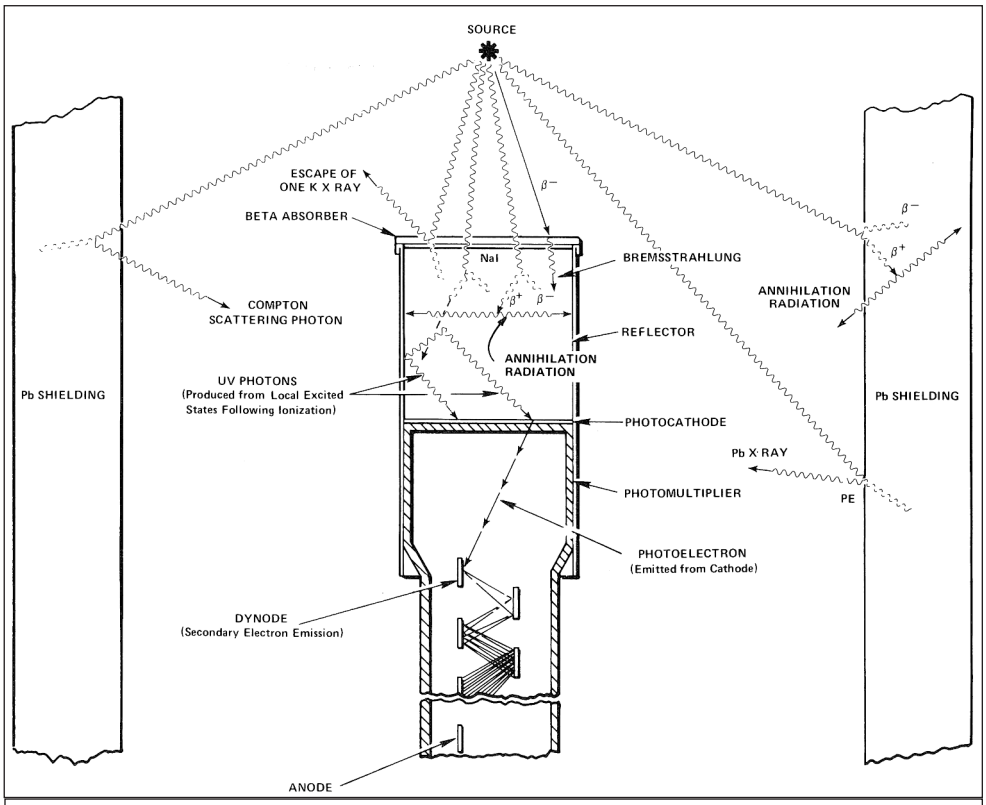

Fig. 3.1. The Structure of the NaI(Tl) Detector and Various Types of Gamma-Ray Interactions that Occur in the Typical Source-Detector-Shield Configuration.

At the photocathode, the scintillation photons release electrons via the photoelectric effect. The number of photoelectrons produced is proportional to the number of scintillation photons, which, in turn, is proportional to the energy deposited in the crystal by the gamma ray.

The remainder of the photomultiplier tube consists of a series of dynodes enclosed in the evacuated glass tube. Each dynode is biased to a higher voltage than the preceding dynode by a high voltage supply and resistive biasing ladder in the photomultiplier tube base. Because the first dynode is biased at a considerably more positive voltage than the photocathode, the photoelectrons are accelerated to the first dynode. As each electron strikes the first dynode the electron has acquired sufficient kinetic energy to knock out 2 to 5 secondary electrons. Thus, the dynode multiplies the number of electrons in the pulse of charge. The secondary electrons from each dynode are attracted to the next dynode by the more positive voltage on the next dynode. This multiplication process is repeated at each dynode, until the output of the last dynode is collected at the anode. By the time the avalanche of charge arrives at the anode, the number of electrons has been multiplied by a factor ranging from 10^4 to 10^6, with higher applied voltages yielding larger multiplication factors. For the selected bias voltage, the charge arriving at the anode is proportional to the energy deposited by the gamma ray in the scintillator.

The preamplifier collects the charge from the anode on a capacitor, turning the charge into a voltage pulse. Subsequently, it transmits the voltage pulse over the long distance to the supporting amplifier. At the output of the preamplifier and at the output of the linear amplifier, the pulse height is proportional to the energy deposited in the scintillator by the detected gamma ray. The Multichannel Analyzer (MCA) measures the pulse heights delivered by the amplifier, and sorts them into a histogram to record the energy spectrum produced by the NaI(Tl) detector. See Figure 3.2 for the modular electronics used with the NaI(Tl) detector.

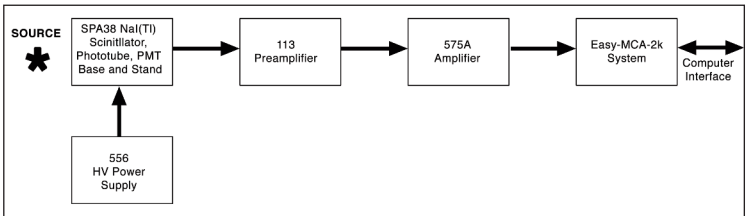

Fig.3.2. Electronics Block Diagram of Gamma-Ray Spectroscopy System with NaI(Tl) Detector.

For an ideal detector and supporting pulse processing electronics, the spectrum of 662-keV gamma rays from a ^{137}Cs radioactive source would exhibit a peak in the spectrum whose width is determined only by the natural variation in the gamma-ray energy. The NaI(Tl) detector is far from ideal, and the width of the peak it generates is typically 7% to 10% of the 662-keV gamma-ray energy. The major source of this peak broadening is the number of photoelectrons emitted from the photocathode for a 662-keV gamma-ray. For a high-quality detector this is on the order of 1,000 photoelectrons. Applying Poisson statistics (ref. 1 and 11), 1,000 photoelectrons limit the full width of the peak at half its maximum height (FWHM) to no less than 7.4%. Statistical fluctuations in the secondary electron yield at the first dynode and fluctuations in the light collected from the scintillator also make a small contribution to broadening the width of the peak in the energy spectrum. Because the broadening is dominated by the number of photoelectrons, and that number is proportional to the gamma-ray energy, the FWHM of a peak at energy E is approximately described by

$$\% \text{ Resolution (FWHM)} = \frac{\delta E}{E} \times 100\% \approx \frac{k \times 100\%}{\sqrt{E}} \qquad (1)$$

Where

E is the energy of the peak,

δE is the FWHM of the peak in energy units, and

k is a proportionality constant characteristic of the particular detector.

Equation (1) indicates that the percent energy resolution of the NaI(Tl) detector improves as the gamma-ray energy increases.

Because the scintillation has a 250-ns decay time constant, it is important to collect the resulting charge pulse from the photomultiplier tube for at least four time constants (i.e., 1 μs). This collection time ensures that 98% of the light will contribute to the analyzed pulse height, thus assuring that the best possible energy resolution can be achieved. If a 0.5-μs shaping time constant is chosen on the linear amplifier, the amplifier output pulse will reach its maximum amplitude in approximately 1.1 μs. Hence this is the minimum shaping time constant that can be employed. If high counting rates are not expected, and the dead time caused by the pulse width is not a problem, a 1-μs shaping time constant can be selected. The latter choice delivers a pulse that reaches peak amplitude in approximately 2.2 μs.

For an MCA having a conversion time <2 μs, the dominant source of dead time is the duration of the amplifier output pulse. The dead time comprises the sum of the time to reach peak amplitude and the width of the pulse at the baseline. For the 0.5 μs shaping time constant, the dead time amounts to about 5 μs, and for the 1 μs time constant, the dead time is approximately 10 μs. Consequently, the NaI(Tl) system will experience a 10% dead time loss in the range of 10,000 to 20,000 counts/second, depending on the choice of amplifier shaping time constant. Above 20,000 counts/second, the gain of the photomultiplier tube can be affected by the counting rate. Consequently, 20,000 counts/second is a reasonable upper limit for normal operation. For more information on pulse shaping and the relevant dead time, see references 1, 11, 12, 13 and 14.

The Multichannel Pulse-Height Analyzer

The other major concept introduced in this experiment is the Multichannel Analyzer (MCA). It is responsible for measuring the height of each pulse delivered by the linear amplifier. Over the period of time the gamma rays are counted, the MCA sorts the pulses, according to pulse height, into a histogram that represents the spectrum of gamma-ray energies intercepted by the NaI(Tl) detector. The MCA is the central analyzer for many of the experiments in this series. Rather than including a complete description of its function in each experiment, the student is referred to the document entitled, The Multichannel Pulse-Height Analyzer which can be found on the Library page at www.ortec-online.com/solutions/educational.aspx.

The MCA listed in the Equipment Required for this experiment uses software in a supporting personal computer to operate the instrument and display the spectrum. The MCA connects to the computer via a USB cable. It is important to become familiar with the controls that are accessible via the MAESTRO software. The most efficient approach may be to have the laboratory instructor provide a quick demonstration. You will need to know how to start/stop data acquisition, clear the contents of the memory, select the digital resolution, adjust the upper and lower discriminator thresholds, set the preset live time, monitor the percent dead time, read the peak positions with the mouse pointer, set regions of interest, and calibrate the horizontal scale to read in keV (energy).

One of the benefits of the MCA is the incorporation of a live time clock. This feature automatically corrects for dead time losses by measuring elapsed time only when the spectrometer is not busy processing a pulse. See references 1, 11, 13 and 14 for more information.

EXPERIMENT 3.1. Energy Calibration

3.1.1. Equipment Setup

Set up the electronics as shown in Fig. 3.2.

1. Turn off power to the NIM Bin and Power Supply and the 556 HV Power Supply.
2. Check that the front-panel controls on the 556 HV Power Supply are set to their minimum values. Confirm that POSitive POLARITY has been selected on the rear panel, and the CONTROL toggle switch has been set to INTernal. The 556 derives its primary power from an AC power outlet. But, for convenience, it can be inserted into a vacant location in the NIM Bin.
3. Ensure that the NaI(Tl) detector assembly is properly mounted in the stand. Connect the MHV High Voltage (Bias) connector on the detector to the SHV High Voltage OUTPUT on the rear of the 556 using the C-34-12 coaxial cable. Note that the connectors are different on each end of this high voltage cable. One connector is specific to the MHV connector used on the detector, and the other is matched to the SHV connector on the rear of the 556 HV Supply.
4. Using the C-24-1 coaxial cable, connect the anode output of the NaI(Tl) detector assembly (BNC connector) to the INPUT of the 113 Preamplifier. Set the 113 INPUT CAPacitance to 200 pF. The polarities of the anode output of the photomultiplier tube and the preamplifier are both negative.
5. Remove the 575A Amplifier from the NIM Bin and check that the slide switches accessible through the side panel are all set to 0.5 μs. That selection ensures that the shaping time constant is set to 0.5 μs. Insert the amplifier back into the NIM Bin.
6. Connect the power cable from the 113 Preamplifier to the PREAMP. POWER connector on the rear of the 575A Amplifier.
7. Using a C-24-12 coaxial cable, connect the OUTPUT of the 113 Preamplifier to the INPUT of the 575A Amplifier.
8. Select the NEGative input polarity on the 575A Amplifier.
9. Using a C-24-4 coaxial cable, connect the UNIpolar OUTput of the 575A Amplifier to the analog INPUT of the EASY-MCA. Using the USB cable, connect the USB port on the rear of the EASY-MCA to the USB port on the supporting computer. Ensure that the MAESTRO software that operates the EASY-MCA has been installed on the computer.
10. Turn on the power to the computer and the NIM Bin and Power Supply.

There are two parameters that ultimately determine the overall gain of the system: the high voltage furnished to the phototube and the gain of the spectroscopy amplifier. The gain of the photomultiplier tube is quite dependent upon its high voltage. A rule of thumb for most phototubes is that, near the desired operating voltage, a 10% change in the high voltage will change the gain by a factor of 2. The desired high voltage value depends on the phototube being used. Consult your instruction manual for the phototube and select a value in the middle of its normal operating range. Sometimes, the detector will have a stick-on label that lists the percent resolution and the voltage at which that resolution was measured. In that case, use the high voltage value on that label. Lacking those sources to specify the operating voltage, check with the laboratory instructor for the recommended value. The operating voltage will likely fall in the range of +800 to +1300 Volts.

11. Set the voltage controls on the 556 High Voltage Power Supply to the operating voltage recommended for the detector. Turn on the POWER switch on the 556.
12. Using the MCB Properties menu in the MAESTRO software, set up the acquisition conditions for the EASY-MCA. Select a conversion gain of 1024 channels for the pulse-height range of 0 to +10 Volts. Turn the GATE to Off. For a starting value, the lower level discriminator threshold can be set to about 100 mV (10 channels). Set the upper level discriminator to full scale, or slightly higher. Initially, the preset time limit can be turned off. Your laboratory instructor may have additional recommendations for the set-up of the EASY-MCA.

3.1.2. Pole Zero Cancellation Adjustment

The NaI(Tl) detector produces a pulse of charge that lasts for about 1 μs at the anode output of the photomultiplier tube. The preamplifier collects that charge on the input capacitance and turns it into a voltage pulse at the preamplifier output. Because the anode pulse has a negative polarity, and the 113 Preamplifier is non-inverting, the voltage pulse at the preamplifier output has a negative polarity. The decay time of the scintillation controls the shape of the leading-edge response of the preamplifier output pulse. For the 250-ns decay time constant of the NaI(Tl) scintillator, the fall time (10% to 90% of the pulse height) on the leading edge of the voltage pulse will be approximately 0.55 μs. Within about 1 μs, the absolute value of the pulse amplitude reaches its maximum excursion. Subsequently, the voltage pulse decays back towards zero Volts with an exponential decay that is characterized by a 50 μs time constant. That decay time constant is nominal, and could lie anywhere in the range of 30 to 80 μs.

In the amplifier, the long exponential decay of the preamplifier must be replaced by the shorter exponential decay selected by the shaping time constant switches on the amplifier. This is the function of the Pole-Zero Cancellation circuit near the input of the amplifier. The adjustment of the Pole-Zero Cancellation to achieve exact replacement will be implemented in the next series of steps. For more information on pole-zero cancellation, consult references 1, 11 and 12.

1. Disconnect the Amplifier UNIpolar OUTput from the EASY-MCA and connect it instead to the Channel 1 (CH1) input of the oscilloscope. Select Auto triggering on CH1 in the oscilloscope, a vertical scale of 5 V per major division and 1 μs per major horizontal division. Adjust the vertical position of the baseline in the display to the centerline of the display. Make sure the input impedance of channel 1 is set to 1 MΩ.
2. Place the ^{137}Cs source from the gamma source kit ($E\gamma$ = 0.662 MeV) in the stand ~2 cm below the front surface of the NaI(Tl) crystal.
3. Observe the signal on the oscilloscope. It should look approximately like the yellow signal in Figure 3.3, except the vertical and horizontal scales will be different. There should be an intense signal at the top of the range of pulse heights, and a distribution of less intense pulses at lower amplitudes. The intense signal at the top of distribution is the full-energy signal from the 662-keV gamma ray. If no signals are observed, try adjusting the oscilloscope triggering and the vertical scale to find the signals.
4. Once you are able to display the signals, adjust the amplifier coarse and fine gain controls to make the amplitude of the full-energy signal from the 662-keV gamma rays approximately 10 Volts. It may be useful to change the oscilloscope triggering mode from Auto to Normal at this point.
5. Change the oscilloscope horizontal scale to 50 μs per major division.
6. Change the vertical scale to 100 mV per major division. Re-adjust the triggering and vertical position so that the baseline before and after the pulses aligns with the main horizontal scale line across the middle of the display.

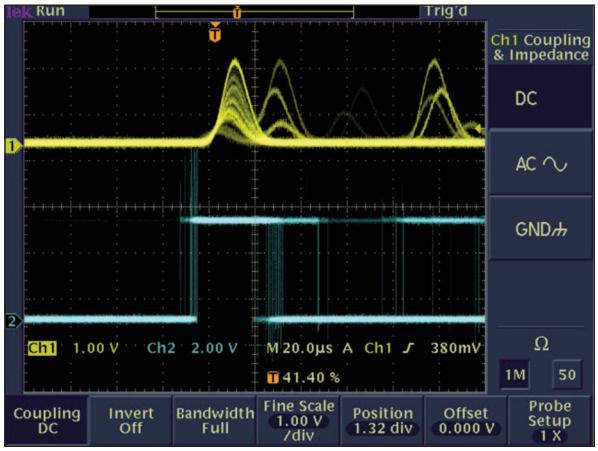

Fig. 3.3. Oscilloscope Signal.

7. Turn the PZ ADJ screwdriver adjustment on the front panel of the 575A Amplifier clockwise and/or counter-clockwise, as needed, to make the observed pulses return to baseline as quickly as possible after each pulse without any undershoot. Consult references 1, 11 and 12 for more guidance.

CAUTION: On some oscilloscopes, the 10-V pulse amplitude may cause an overload of the oscilloscope amplifiers on the more sensitive vertical scales. When this happens the recovery of the trailing edge of the pulse will appear distorted, making it impossible to make a valid PZ adjustment. If this problem is suspected, start with the 5 V per major division scale and increase the vertical scale sensitivity one step at a time. For each increase in vertical sensitivity verify that the shape of the trailing edge differs from the shape on the previous scale setting in proportion to the change in the scale factor. When abrupt distortion is encountered on the more sensitive vertical scale, return to the previous, less sensitive scale to make the PZ adjustment.

It may be useful to try different horizontal scales ranging from 10 μs to 100 μs per major division while making the pole-zero cancellation adjustment.

3.1.3. Adjusting the Gain for Recording Spectra

1. Set the oscilloscope vertical scale to 1 Volt per major division, and the horizontal scale to 1 μs per major division. Adjust the triggering and vertical position if needed to observe the signals.
2. Reduce the amplifier gain to set the 662-keV pulse height to approximately 2.4 Volts.
3. Disconnect the amplifier UNIpolar OUTput from the oscilloscope and re-connect it to the analog INPUT of the EASY-MCA.
4. Acquire a spectrum on the EASY-MCA for at least 30 seconds, and no more than a couple of minutes. The spectrum should look like Figure 3.4.
5. Identify the 662-keV photopeak (full-energy peak). Click on the top of the peak, and note the channel number corresponding to the maximum value.
6. If the 662-keV photopeak position does not correspond to channel 238, adjust the amplifier fine gain and repeat the spectrum acquisition. Repeat this process until the peak position lies at channel 238. This adjustment ensures that the 1.17 + 1.33 MeV =

2.50 MeV sum peak from the ^{60}Co source in Experiment 3.8 will be positioned at channel 900, well within the 1000-channel limit. (Note that the calibration in Fig. 3.4 places the peak at channel 280, which would shift the sum peak in Expt. 3.8 past the top end of the scale.)

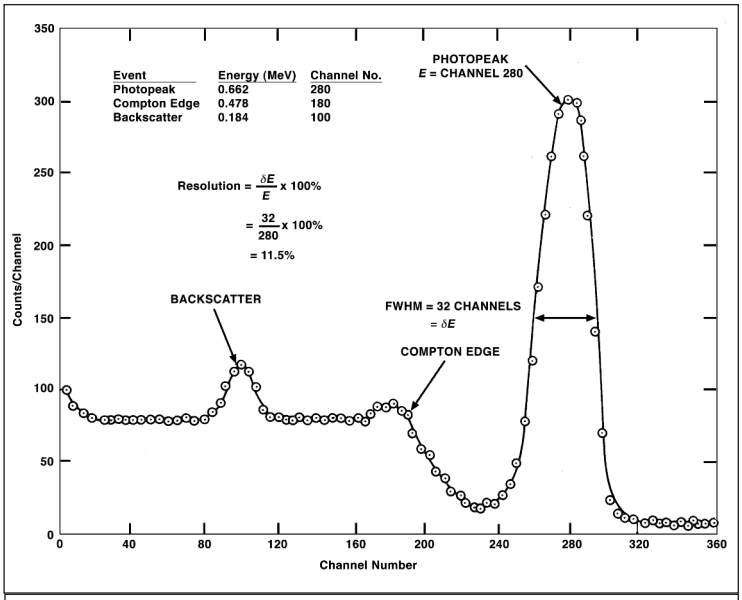

Fig. 3.4. NaI(Tl) Spectrum for ^{137}Cs.

3.1.4. Lower-Level Discriminator Adjustment

The optimum setting of the Lower-Level Discriminator threshold is slightly above the maximum noise amplitude. This prevents the MCA from wasting time analyzing the useless information in the noise surrounding the baseline between valid pulses. Setting the Lower-Level Discriminator threshold reasonably close to the noise improves the quality of the automatic dead time correction by measuring the full duration of the pulses at the noise threshold. To adjust the Lower-Level Discriminator use the following procedure.

1. Remove any radioactive sources from the vicinity of the NaI(Tl) detector, so that no gamma rays are being detected.
2. Start a data acquisition and observe the Percent Dead Time displayed for the MCA. It should be less than 1%. If the dead time is larger than 1% jump to step 5.
3. Using the MCB Properties menu, reduce the Lower-Level Discriminator threshold, start another acquisition and observe the percent dead time.
4. Keep repeating step 3 until the percent dead time abruptly increases.
5. Once the dead time increases significantly above 1%, gradually increase the Lower-Level Discriminator threshold until the percent dead time is less than 1%.
6. Repeat steps 3 through 5 until you are confident the threshold has been set reasonably close to the noise, with little risk of counting random noise excursions.

The absolute amplitude of the noise at the MCA input is dependent on the preamplifier characteristics and the gain setting on the amplifier. Consequently, the MCA Lower-Level Discriminator threshold should be adjusted any time the amplifier gain is changed, or the preamplifier is replaced with a different unit. Adjustment of this threshold is important whenever a detector system is assembled for initial set-up.

3.1.5. Energy Calibration with ^{137}Cs and ^{60}Co

1. Return the ^{137}Cs source to the counting position, and implement an acquisition for a time period long enough to form a well defined spectrum with minimal random scatter in the vertical direction. The amount of scatter is controlled by counting statistics. If the i^{th} channel contains N_i counts, the standard deviation in those counts is expected to be

$$\sigma_{N_i} = \sqrt{N_i} \qquad (2)$$

And the percent standard deviation in the N_i counts is

$$\%\sigma_{N_i} = \frac{\sigma_{N_i}}{N_i} \times 100\% = \frac{100\%}{\sqrt{N_i}} \qquad (3)$$

Note that 100 counts in a channel corresponds to a 10% standard deviation, 10,000 counts yield a 1% standard deviation, and 1 million counts are needed to achieve a 0.1% standard deviation. Consequently, the vertical scatter in the spectrum will begin to appear acceptable when the rather flat continuum at energies below the Compton edge has more than a few hundred counts per channel.

2. Plot the spectrum accumulated in step 1 with a linear vertical scale. Mark the photopeak, the Compton edge and the backscatter peak (if discernable) on the spectrum as indicated in Figure 3.4.

3. Determine the channel number for the 662-keV peak position.
4. After the ^{137}Cs spectrum has been read from the MCA, save it in a file that you designate for possible later recall. Erase the spectrum, and replace the ^{137}Cs source with a ^{60}Co source from the gamma source kit.
5. Accumulate the ^{60}Co spectrum for a period of time long enough for the spectrum to be similar to that in Fig. 3.5.
6. Save the ^{60}Co spectrum for possible later recall and plot the spectrum.

EXERCISES

a. From the ^{137}Cs and ^{60}Co spectra determine the photopeak positions and fill in items 1, 2, and 3 in Table 3.1. These peak positions are most conveniently determined with the mouse pointer in the spectra displayed on the computer screen.

b. From items 1, 2, and 3 in Table 3.1, make a plot of energy of the photopeaks vs. channel number. Fig. 3.6 shows this calibration for the data taken from Figs. 3.4 and 3.5. If other calibration sources are available, additional data points can be added to Fig. 3.6. The other entries in Table 3.1 will be filled out in Experiment 3.3.

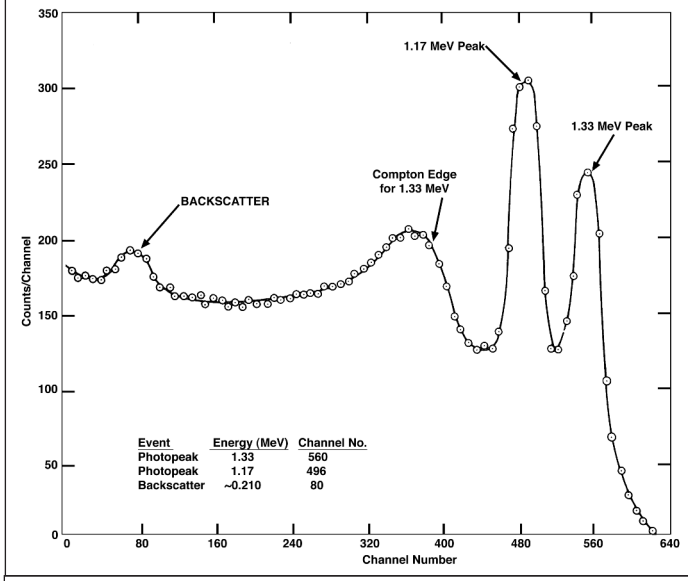

Fig. 3.5. NaI(Tl) Spectrum for ^{60}Co.

c. Use the energy calibration feature of the MCA and compare the results with those found in Exercise b.

d. Does the straight line for the energy calibration intercept channel zero at zero energy? If there is a finite zero intercept, what could cause the offset?

Table 3.1

	Item	Energy (MeV)	Channel No.
1.	0.662-MeV photopeak	0.662	
2.	1.17-MeV photopeak	1.17	
3.	1.33-MeV photopeak	1.33	
4.	Compton Edge ^{137}Cs		
5.	Backscatter ^{137}Cs		
6.	Compton edge for ^{60}Co 1.33-MeV gamma ray		
7.	Backscatter ^{60}Co for 1.33-MeV gamma ray		
8.	Backscatter ^{60}CO for 1.17-MeV gamma ray		

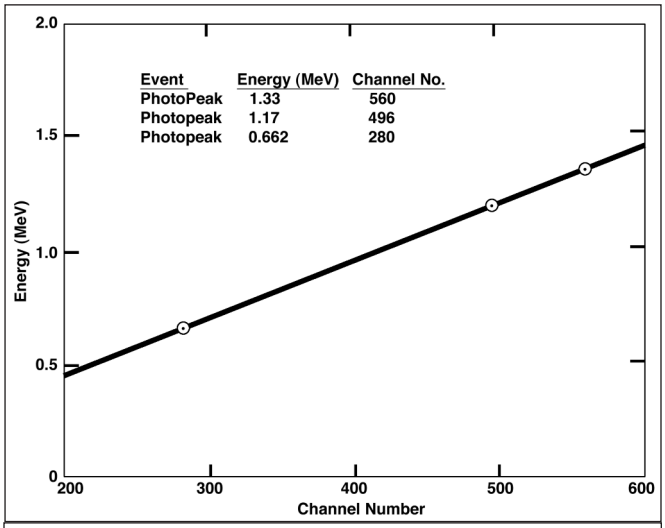

Fig. 3.6. Energy Calibration Curve for NaI(Tl) Detector.

EXPERIMENT 3.2. Energy Analysis of an Unknown Gamma Source

3.2.1 Purpose

This experiment uses the calibrated system of Experiment 3.1 to measure the photopeak energies of an unknown gamma-ray emitter and to identify the unknown isotope.

3.2.2. Procedure

1. Erase the ^{60}Co spectrum from the MCA, but do not change any of the gain calibration settings of the system.
2. Obtain an unknown gamma source from the instructor. Accumulate a spectrum for the unknown source for a period of time long enough to clearly identify its photopeak(s). From the calibration curve, determine the energy for each photopeak.

EXERCISE

Use refs. 7 and 8 to identify the unknown isotope.

EXPERIMENT 3.3. Spectrum Analysis of ^{60}Co and ^{137}Cs

3.3.1. Purpose

The purpose of this experiment is to explain some of the features, other than the photopeaks, usually present in a pulse-height spectrum. These are the Compton edge, the Compton continuum and the backscatter peak.

3.3.2. Relevant Information

The photopeak is created when the gamma-ray photon interacts in the scintillator via the photoelectric effect. The photon encounters an orbital electron that is tightly bound to a nucleus. The entire energy of the photon is transferred to the electron, causing the electron to escape from the atom. The gamma-ray photon disappears in the process. As the photoelectron travels through the scintillator, it loses its energy by causing additional ionization. At the end of the process, the number of ionized atoms is proportional to the original energy of the photon. As the electrons re-fill the vacancies in the ionized atoms, visible light photons are generated. This is the source of the scintillation, wherein the number of visible photons is proportional to the original energy of the gamma-ray. Consequently, the event populates the photopeak in the spectrum. This peak is often called the full-energy peak, because a two-step interaction, a Compton scattering followed by a photoelectric interaction, also contributes a small number of events to the full-energy peak.

The Compton interaction is a pure, kinematic collision between a gamma-ray photon and what might be termed a free electron in the NaI(Tl) crystal. By this process, the incident gamma-ray photon gives up only part of its energy to the electron as it bounces off the free electron. The recoiling electron loses energy by causing ionization as it travels through the crystal. Thus the number of visible photons in the resulting scintillation is proportional to the recoil energy of the Compton electron. The amount of energy transferred from the gamma-ray photon to the recoiling electron depends on whether the collision is head-on or glancing. For a head-on collision, the gamma ray transfers the maximum allowable energy for the Compton interaction. Although it involves a photon and an electron, the interaction is similar to a billiard-ball collision. The reduced energy of the scattered gamma ray can be determined by solving the energy and momentum conservation equations for the collision. The solution for these equations in terms of the scattered gamma-ray energy can be written as

$$E\gamma' = \frac{E\gamma}{1+\frac{E\gamma}{M_o c^2}(1-\cos\theta)} \qquad (4)$$

where

$E\gamma'$ is the reduced energy of the scattered gamma-ray, γ', in MeV,

θ is the scattering angle for the direction of γ' relative to the direction of the incident gamma-ray, γ,

$E\gamma$ is the energy of the incident gamma-ray, γ, in MeV,

$m_0c^2 = 0.511$ MeV is the equivalent energy of the rest mass, m_0, of the electron, and

c is the speed of light.

For a head-on collision, the gamma-ray is scattered backwards along its initial trajectory, and $\theta = 180°$. For this condition, the backscattered gamma-ray energy becomes

$$E\gamma' \cong \frac{E\gamma}{1 + 4E\gamma} \qquad (5)$$

Where the convenient approximation, $(m_0c^2)^{-1} \approx 2$, has been used.

If this backscatter event happens in the detector, the maximum energy transferred to the recoiling electron will be

$$E_e = E\gamma - E\gamma' \qquad (6)$$

Thus the maximum energy that can be recorded in the spectrum for a gamma ray that interacts in the detector by Compton scattering is given by equation (6). This defines the energy of the Compton edge in Figures 3.4 and 3.5. For an initial gamma-ray energy of 1 MeV, equations (5) and (6) predict that the Compton edge will occur at 0.80 MeV, and the energy of the backscattered gamma ray will be 0.20 MeV.

Because the gamma-ray photon can be scattered through any angle from 0 to 180°, and the scattered photon can escape the detector, the energy deposited in the detector can vary from the maximum at the Compton edge through all values down to zero. This is the genesis of the Compton continuum in Figures 3.4 and 3.5.

Note that there is a small, but finite, probability that the Compton scattered photon will be subsequently absorbed in the crystal by the photoelectric process. This two-step interaction will generate a pulse that falls in the full-energy peak.

The backscatter peak in Figures 3.4 and 3.5 is caused by Compton scattering from an entirely different location. Consider a gamma ray emitted by the radioactive source in a direction heading away from the detector. This gamma ray can encounter material in the neighborhood of the radioactive source and undergo Compton scattering. If the scattering angle is 180° the scattered gamma ray travels back towards the detector with an energy defined by equation (5). If this lower-energy gamma ray interacts in the scintillator by the photoelectric effect, it will contribute to a photopeak at the lower energy. Typically this backscatter peak will be of low intensity, if there is minimal material behind the radioactive source. Usually, the backscatter peak is rather broad, because of the range of directions that can contribute to the peak. For an initial gamma-ray energy of 1 MeV, equation (5) predicts that the backscatter peak will occur at 0.20 MeV.

Figure 3.1 illustrates some of the types of interactions that can take place in the NaI(Tl) detector and the surrounding shielding material.

EXERCISES

a. Calculate the energy of the Compton edge for the 0.662-MeV gamma ray from ^{137}Cs. Enter this value in Table 3.1. From your plot and calibration curve, does this calculation agree with your measured value?

b. Calculate the Compton edge energy for the 1.33-MeV gamma ray from ^{60}Co, and enter that result in Table 3.1. Is that value in agreement with your ^{60}Co spectrum?

c. From Eq. (5) calculate the backscatter peak energies for the gamma rays from ^{137}Cs and ^{60}Co. Fill in the rest of Table 3.1. How do your measured energies compare with the theoretical energies from Eq. (5)? If the backscatter peak is not very pronounced in your spectrum, it can be enhanced by accumulating a spectrum with a sheet of lead placed behind the source. Use a sheet from the absorber kit.

EXPERIMENT 3.4. Energy Resolution

3.4.1. Purpose

The purpose of this experiment is to measure the resolution of the NaI(Tl) detector.

3.4.2. Relevant Equations

The resolution of a spectrometer is a measure of its ability to resolve (i.e., separate) two peaks that are fairly close together in energy. Fig. 3.4 shows the gamma spectrum that was plotted for the ^{137}Cs source. The resolution of the photopeak is calculated from the following equation:

$$\% \text{ Resolution} = \frac{\delta E}{E} \times 100\% \qquad (7)$$

Where δE is the Full Width of the peak at Half of the Maximum count level (FWHM) measured in number of channels, and E is the channel number at the centroid of the photopeak.

In Fig. 3.4 the photopeak is in channel 280 and its FWHM = 32 channels. From Eq. (7), the resolution is calculated to be 11.5%. It is standard practice to specify the quality of the NaI(Tl) detector by stating its measured percent resolution on the 662-keV photopeak from a ^{137}Cs radioactive source.

EXERCISE

Calculate the resolution of the system from your ^{137}Cs spectrum. Record this value for later reference.

EXPERIMENT 3.5. Activity of a Gamma Emitter (Relative Method)

3.5.1. Purpose

In Experiments 3.1 and 3.3, procedures were given for determining the energy of an unknown gamma-ray source. Another unknown associated with the gamma-ray source is the activity of the source, which is usually measured in Curies (Ci); 1 Ci = 3.7 x 10^{10} disintegrations/second. Most of the sources used in nuclear experiments have activities of the order of microcuries (μCi). The purpose of this experiment is to outline one procedure, called the relative method, by which the activity of a source can be determined.

In using the relative method, it is assumed that the unknown source has already been identified from its gamma-ray energies. For this example, assume that the source has been found to be ^{137}Cs. Then all that is necessary is to compare the activity of the unknown source to the activity of a standard ^{137}Cs source that will be supplied by the laboratory instructor. For convenience, call the standard source S1 and the unknown source U1.

3.5.2. Procedure

1. Place source S1 ~4 cm from the face of the NaI(Tl) detector (or closer, if necessary to get reasonable statistics). Accumulate a spectrum for a period of live time, selectable on the MCA, long enough to produce a spectrum similar to Fig. 3.4.
2. Use the cursor to determine the sum under the photopeak. In the example shown in Fig. 3.4, this would correspond to adding up all counts in channels 240 through 320. Define this sum to be Σ_{S1}. The easiest and most reliable way to measure this sum is to set a Region of Interest (ROI) across the peak (channels 240 through 320, in the example). Once a Region of Interest is set, the MAESTRO software can display the total number of counts in the region of interest (Gross Area) when the mouse pointer is placed in the ROI. This is the sum over all channels in the ROI. If you are having difficulty learning how to set an ROI or to read the Gross Area of the ROI, consult the instruction manual for the software, or ask for guidance from the laboratory instructor.
3. Clear (erase) the MCA spectrum. Remove source S1 and replace it with source U1, positioned exactly the same distance from the crystal as S1 was. Accumulate a spectrum for the same period of live time that was used in step 1. Sum the peak as in step 2. Call this sum Σ_{U1}.
4. Clear the spectrum from the MCA. Remove source U1 and accumulate background counts for the same period of live time that was used in steps 1 and 3 above.
5. Sum the background counts in the same channels that were used for the photopeaks in steps 2 and 3 above. Call the sum Σ_b.

EXERCISE

a. Solve for the activity of U1 by using the following ratio:

$$A_{U1} = \frac{\Sigma_{U1} - \Sigma_b}{\Sigma_{S1} - \Sigma_b} A_{S1} \qquad (8)$$

Where A_{S1} is the activity of the standard source, S1, and A_{U1} is the calculated activity of the unknown source, U1.

NOTE: Since the efficiency of the detector is only energy dependent, the standard and unknown sources do not have to be the same isotope. It is necessary only that their gamma energies be approximately the same (±10%) in order to get a fairly good estimate of the absolute gamma activity of the unknown. However, this relaxation of the comparison requirements may be invalid if one of the sources has a more complicated decay scheme, or if the gamma-ray decay fraction is different for the two isotopes.

b. Check the nominal activity listed on the label attached to the unknown source. How closely does your calculated value match that number?

c. Increasing the detector-to-source distance results in longer counting times to achieve adequate precision in the counting statistics, as a result of the Inverse Square Law (see Expt. 2.5). What is the other way that the source-to-detector distance significantly affects the accuracy of the relative activity measurement?

EXPERIMENT 3.6. Activity of a Gamma Emitter (Absolute Method)

3.6.1. Purpose

The activity of the radioactive source used in Experiment 3.5 can be determined by the absolute method. The purpose of this experiment is to outline the procedure for this method. Here, the source to be measured will be called U1.

3.6.2. Procedure

1. Place a source U1 (of unknown activity) approximately 10 cm away from the face of the detector.
2. Measure the distance, s, from the middle of the source thickness to the front surface of the NaI(Tl) detector
3. Acquire a spectrum long enough to accumulate at least 10,000 counts in the photopeak, and note the elapsed live time, t_L.
4. Set a region of interest over the photopeak such that all the counts in the peak are included. Record the sum of the counts in the region of interest, Σ_{U1}.
5. Clear the spectrum, remove the source, accumulate background for the same live time, and sum the background, Σ_b, in the same region of interest.
6. Use the following formula to calculate the activity of U1. The units in equation (9) are disintegrations per second.

$$\text{Activity of } U_1 = \left(\frac{\Sigma_{U1} - \Sigma_b}{t_L}\right) \frac{1}{G\varepsilon_p f} \qquad (9)$$

Where

t_L is the live time in seconds,

ε_p is the intrinsic peak efficiency for the gamma-ray energy and detector size used (Fig. 3.7 and ref. 10),

f is the decay fraction of the unknown activity, which is the fraction of the total disintegrations in which the measured gamma ray is emitted (refs. 7 and 8 and Table 3.2)

G = [area of the detector (cm^2)] / [$4\pi s^2$], and

s is the source-to-detector distance in cm.

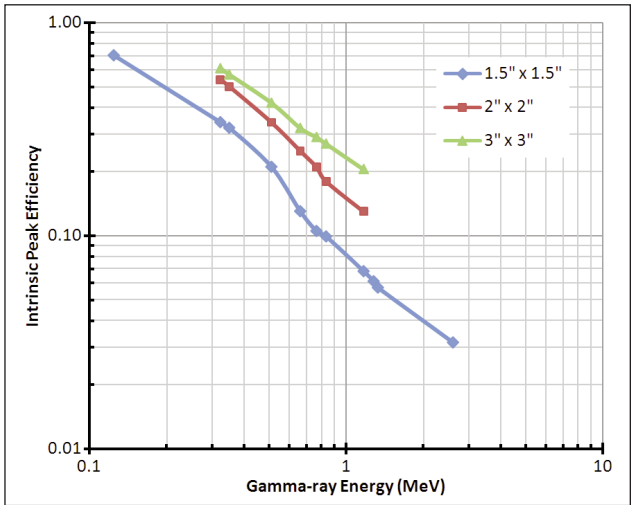

Fig. 3.7. Intrinsic Peak Efficiency of Various NaI(Tl) Crystals vs. Gamma-Ray Energy. Detector to Point-Source Distance is 9.3 cm for the 3-inch x 3-inch and 2-inch x 2-inch crystals and 10 cm for the 1.5-inch x 1.5-inch scintillator.

EXERCISE

a. Convert the activity in disintegrations per second from equation (9) to micro-Curies.

b. Check the nominal activity listed on the label affixed to the source. How closely does your measured activity match the nominal value listed?

c. What is the expected standard deviation in the measured activity due to the number of counts you recorded in the photopeak?

d. Intrinsic photopeak efficiencies are usually documented for a specific source-to-detector distance, and a point source located on the extended center line of the cylindrical scintillator crystal. Why?

e. Placing the source closer to the detector increases the counting rate. How does a smaller source-to-detector distance affect the accuracy of the measurement?

Table 3.2. Gamma Decay Fraction, (f), for some Common Isotopes.

Isotope	Gamma Energy (MeV)	f
^{137}Cs	0.662	0.851
^{51}Cr	0.320	0.0986
^{60}Co	1.173	0.9986
^{60}Co	1.333	0.9986
^{22}Na	1.275	0.9994
^{22}Na	0.511	1.78
^{54}Mn	0.835	0.9998
^{65}Zn	1.116	0.506

EXPERIMENT 3.7. Mass Absorption Coefficient

3.7.1. Purpose

The purpose of this experiment is to measure experimentally the mass absorption coefficient for 662 keV gamma rays in lead.

3.7.2. Relevant Equations

References 2, 3, and 5 point out that gamma rays interact in matter primarily by photoelectric absorption, Compton scattering, or pair-production processes. The total-mass absorption coefficient can be easily measured with a gamma-ray spectrometer. In this experiment we will measure the number of gamma-ray photons that are removed from the photopeak by photoelectric or Compton interactions that occur in a lead absorber placed between the source and the detector.

From the Beer-Lambert law (ref. 1), the decrease in intensity of radiation as it passes through an absorber is given by

$$I = I_0 e^{-\mu x} \qquad (10)$$

where

I is the intensity after the absorber,

I_0 is the intensity before the absorber,

μ is the total mass absorption coefficient in cm^2/g, and

x is the density thickness in g/cm^2.

In this experiment, the intensity will be measured as the net counts in the photopeak divided by the elapsed live time. Net counts means the background contribution has been subtracted from the total counts in the region of interest (ROI) set across the photopeak. The density thickness is the product of the density in g/cm^3 times the thickness in cm.

The half-value layer (HVL) is defined as the density thickness of the absorbing material that will reduce the intensity to one half of its original value. From Eq. (10):

$$\ln\left(\frac{I}{I_0}\right) = -\mu x \qquad (11)$$

If $I/I_0 = 0.5$, and x = HVL, then $\ln(0.5) = -\mu(\text{HVL})$ and hence

$$\text{HVL} = \frac{0.693}{\mu} \qquad (12)$$

In this experiment we will measure μ for lead at 662 keV using the gamma rays from ^{137}Cs. The accepted value for μ at that energy is 0.105 cm^2/g. Values for other materials can be found in references 8 and 15.

Background Subtraction: Two different methods can be used for background subtraction. In Experiments 3.5 and 3.6, the background contribution was determined by measuring the counts when the radioactive source was absent. This is a useful scheme if there is some risk that a natural background is producing a peak that overlaps the photopeak of the radioisotope that is the primary subject of the measurement. There is an alternative method that is productive when it is not feasible to remove the source under investigation, or when other gamma-rays from the source generate a Compton continuum under the peak of interest. In this latter scheme, the counts in background regions on either side of the peak are measured, and an interpolation is employed to estimate the background under the peak. The MAESTRO software can perform this latter calculation of the Net Counts in the region of interest. It generally uses the first three channels and the last three channels of the region of interest to calculate the interpolated background and subtract it. Thus, the ROI should be set up so that the first three and the last three channels are in the flat background regions to either side of the peak. Use the Gross Area readout from the ROI when a separate background spectrum will be acquired for background subtraction. Employ the Net Area when it is desirable to subtract the local background interpolated from both sides of the peak in the spectrum. In Experiment 3.7, use the Net Area to subtract the background.

3.7.3. Procedure

1. Place the ^{137}Cs source about 5.0 cm from the NaI(Tl) detector, and accumulate the spectrum for a preset live time that is long enough for the net counts under the 662 keV peak ($\Sigma_{Cs} - \Sigma_b$) to be at least 6000 counts. Determine ($\Sigma_{Cs} - \Sigma_b$) by employing the Net Area feature of the ROI readout. Record the net counts for zero mg/cm^2 in Table 3.3.
2. Clear the MCA and insert the minimum thickness of lead from the absorber kit between the source and the detector. Accumulate the spectrum for the same period of live time as in step 1 above. Determine ($\Sigma_{Cs} - \Sigma_b$). Record the absorber thickness and the net counts for that thickness in Table 3.3.

3. Repeat the process as the thickness of lead absorber is incremented in steps of no less than 1,000 mg/cm^2 and no more than 1,600 mg/cm^2. It will be necessary to use various combinations of the lead absorbers to achieve an approximately uniform step size. Continue the process until the total thickness of lead exceeds 13,200 mg/cm^2, or the counting rate has dropped below 1/4 of the initial value with no absorber.

Table 3.3. Data for Mass Absorption Coefficient.

Absorber	Absorber Thickness (mg/cm^2)	$\Sigma_{Cs} - \Sigma_b$
1	0	
2		
3		
4		
5		
6		
7		
8		

EXERCISES

a. Using semilog graph paper, plot I vs. absorber thickness in mg/cm^2, where I = $(\Sigma_{Cs} - \Sigma_b)$/(live time). Determine the HVL from this curve, and calculate μ from Eq. (12). How does your value compare with the accepted value of 0.105 cm^2/g?

b. The μ for aluminum at 662 keV is 0.074 cm^2/g, and the density of aluminum is 2.70 g/cm^3. What is the half-thickness of aluminum in mg/cm^2 and in cm? Why is the half-thickness of aluminum so much larger than the half-thickness for lead? How does the mass absorption coefficient depend on atomic number?

EXPERIMENT 3.8. Sum Peak Analysis

3.8.1. Explanation and Relevant Equations

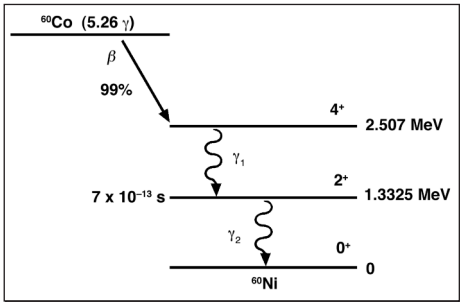

Fig. 3.8. The Decay Scheme of ^{60}Co.

Fig. 3.5 shows the two pronounced peaks from a ^{60}Co radioisotope. Their origin is documented by the ^{60}Co decay scheme illustrated in Fig. 3.8. Most of the time (>99%), the decay occurs by β^- emission to the 2.507 MeV excited state of ^{60}Ni. Subsequent decay to the ground state always occurs by a 1.174 MeV gamma-ray emission to the 1.3325 MeV level, followed almost simultaneously by the 1.3325 MeV gamma emission to the ground state. Experiment 19 will demonstrate that these two events are in coincidence, and have an angular correlation that deviates from an isotopic distribution by only 16%. For the purposes of this experiment we can assume that each of these gamma rays are isotropically distributed. In other words, if γ_1 departs in a particular direction, γ_2 can go in any direction that it wishes. The range of available angles (directions) for each of the two gamma-rays covers the 4π steradians of a sphere centered on the point source. There is a certain probability that γ_2 will go in the same direction as γ_1. If this occurs within the resolving time of the detector, the energies of γ_1 and γ_2 will be summed in the scintillator. Hence a sum peak will show up in the spectrum. Adopting the definitions in Experiment 3.6, the number of counts, Σ_1, under the γ_1 peak is given by:

$$\Sigma_1 = \varepsilon_1 G f_1 t_L A \qquad (13)$$

where A is the activity of the sample, t_L is the live time for the measurement, ε_1 is the intrinsic photopeak efficiency at the γ_1 energy, and f_1 is the fraction of the total decays in which γ_1 is emitted. Similarly, the sum Σ_2 for γ_2 is given by:

$$\Sigma_2 = \varepsilon_2 G f_2 t_L A \qquad (14)$$

Using the basic concepts behind equations (13) and (14), the number of counts in the sum peak, Σ_s, can be expressed as:

$$\Sigma_3 = \varepsilon_1 \varepsilon_2 f_1 f_2 G^2 A t_L [W(0°)] \qquad (15)$$

where W(0°) is a term that accounts for the angular correlation function (ref. 16 & 17). For the case of ^{60}Co, W(0°) ≈ 1.0, $f_1 \approx f_2 \approx 1.0$, and Eq. (15) can be approximately expressed as:

$$\Sigma_3(^{60}_{27}\text{Co}) \approx \varepsilon_1 \varepsilon_2 G^2 A t_L \qquad (16)$$

3.8.2. Purpose

This experiment, will confirm that the sum peak for ^{60}Co has an energy of 2.507 MeV, and that the number of counts in the sum peak is given by Eq. (16).

3.8.3. Procedure

1. Set up the electronics as shown in Fig. 3.2.
2. Use the gamma sources from the gamma source kit to calibrate the MCA so that full scale is ~3.0 MeV. For 1000 channels this would put the ^{137}Cs (0.662 MeV) peak at approximately channel 221.
3. Construct a calibration curve as in Experiment 3.1.
4. From Fig. 3.7, identify the intrinsic peak efficiency curve that is appropriate for your NaI(Tl) detector. Note the source to detector distance specified for that curve. Place the ^{60}Co source from the source kit at exactly that distance from the face of the detector, and center the source on the cylindrical center line of the scintillator crystal.
5. Count for a live time that is long enough to accumulate an area under the sum peak of approximately1000 counts. This procedure was outlined in Experiment 3.6.

EXERCISES

a. Verify that the energy of the sum peak is 2.507 MeV. Subtract the background from the sum peak and verify that its sum agrees with the prediction from Eq. (16). Note that either equation (13) or (14) will have to be used to measure the activity of the source according to the procedure in Experiment 3.6.

b. Repeat this sum peak analysis for the ^{22}Na source. Fig. 3.9 shows the decay scheme for ^{22}Na and a typical spectrum with the sum peak. How does the competition among β^+ and electron-capture decay to the 1.274-MeV excited state and β^+ decay to the ground state affect the calculation?

Equations (13), (14), (15) and (16) provide an alternate way to determine the absolute activity of the ^{60}Co source. Divide equation (15) by equations (13) and (14) to yield:

$$\frac{\Sigma_3}{\Sigma_1\Sigma_2} = \frac{W(0°)}{At_L} \qquad (17)$$

EXERCISES

c. Measure the net counts in the 1.17-MeV, 1.33-MeV and 2.50-MeV peaks from ^{60}Co, and use equation (17) to calculate the source activity. Use the approximation, $W(0°) \approx 1.0$. How does the measured activity compare to the nominal activity on the source label? Note that you may need to account for the decay time constant and the elapsed time since the original activity certification.

d. Measure the activity of the ^{22}Na source by that same method. How does the competition among electron-capture and β^+ decay to the 1.274-MeV excited state and β^+ decay to the ground state affect the calculation? How does the measured activity compare to the nominal activity on the source label?

e. What are the benefits and drawbacks of employing equation (17) to measure the source activity?

EXPERIMENT 3.9. Photoelectric Absorption

3.9.1. Purpose

The purpose of this experiment is to study the photoelectric absorption of photons and verify the strong dependence of this process on the atomic number of the absorbing material.

3.9.2. Explanation and Relevant Equations

When a gamma of energy <150 keV interacts with matter, the process has a high probability of being a photoelectric interaction. In that situation, the gamma-ray photon interacts with one of the tightly bound electrons in the material. Normally, the photon is completely absorbed by the electron, transferring its total energy to the electron. The electron has too much energy to remain bound to the atom. Subsequently, it escapes from the atom with an energy given by:

$$E_e = E\gamma - E_B = hv - E_B \qquad (18)$$

where $E\gamma = hv$ is the original energy of the gamma-ray photon, h is Planck's constant, v is the oscillatory frequency of the photon, and E_B is the binding energy of the electron in its host atom. The probability of a photoelectric interaction occurring is dependent on the atomic number of the absorbing material and the energy of the gamma-ray or x-ray photon. Although it is difficult to write an exact

analytical expression for this probability, it can be shown that, for low-energy photons

$$\mu \approx \frac{kZ^n}{E_\gamma^3} \qquad (19)$$

where k is a proportionality constant, Z is the atomic number, and n is usually a number between 4 and 5.

Taking the logarithm of both sides of the equations yields

$$\ln(\mu) \approx [\ln(k) - 3\ln(E_\gamma)] + n\ln(Z) \qquad (20)$$

For this experiment, the gamma-ray energy will be held constant at E_γ = 122 keV, while the atomic number of the absorber is varied. Consequently, the terms within the square brackets in equation (20) will be constant. Thus, plotting the mass absorption coefficient versus the atomic number on log-log graph paper should produce a straight line with a slope equal to n.

3.9.3. Procedure

The setup for this experiment is the same as for Experiment 3.7.

1. Place the 20 μCi ^{57}Co source between 4 and 10 cm from the front surface of the NaI(Tl) detector on the cylindrical center line of the scintillator crystal. Accumulate a spectrum on the MCA for a 100-second live-time. Determine the number of counts in the entire spectrum divided by the live time. If this number is not between the limits of 2000 counts/second and 8,000 counts/second, adjust the source position to bring the counting rate within that range. Obviously, a higher counting rate will shorten the time taken to complete the experiment. But, too high a counting rate will distort the gain of the photomultiplier tube. If you notice a shift in the photopeak position at the higher counting rates, reduce the counting rate to eliminate the peak shift. In no case should the source-to-detector distance be less than 4 cm.
2. Once the optimum source position is determined, accumulate a spectrum for a live time period long enough to get reasonable statistics in the 122 keV peak. As in Experiment 3.7, the net counts above background in the peak area should be at least 10,000 counts.
3. Table 3.4 shows the half-value layer thicknesses for the various pure-element foils, along with typical foil thicknesses. Use Table 3.4 to determine the number of foils to insert between the ^{57}Co source and the NaI(Tl) detector to reduce the counting rate by a factor of 2. For some elements, it will not be possible to achieve a thin enough absorber, or a thick enough absorber to approximate the half-value layer. In those cases choose a thickness that comes as close as feasible to the half-value layer.

Table 3.4. Elemental Foil Parameters

Foil Element	Individual Foil Thickness			Density (g/cm^3)	μ @ 122 keV in cm^2/g	Half Value Layer in g/cm^2
	Inches	cm	g/cm^2			
Al	0.030	0.0762	0.206	2.70	0.154	4.51
Fe	0.005	0.0127	0.099	7.80	0.272	2.55
Cu	0.010	0.0254	0.226	8.89	0.321	2.16
Mo	0.003	0.0076	0.069	9.00	0.685	1.01
Sn	0.004	0.0102	0.074	7.30	1.020	0.68
Ta	0.005	0.0127	0.211	16.60	2.592	0.27
Pb	0.039	0.0986	1.119	11.35	3.376	0.21

4. Clear the MCA memory contents. Insert enough aluminum foils between the ^{57}Co source and the detector to get as close as possible to the half-value layer thickness. Accumulate a spectrum for the same live time as employed in step 1. From the change in the net counts in the 122-keV peak and the known absorber thickness, calculate the mass absorption coefficient of aluminum.
5. Repeat steps 2 through 4 for the other thin absorbers, Fe, Cu, Mo, Sn, Ta, and Pb from the absorber kits. NOTE: the counting time might have to be increased as the atomic number of the absorber is increased.

EXERCISES

a. On log-log graph paper, make a plot of μ vs. Z from your experimental data. (Alternatively, plot the ln(μ) versus the ln(Z) in an Excel spreadsheet). Draw a straight line through the data points and calculate the value of "n" in equations (19) and (20) from the slope of that straight line. How do your results compare to the theory?

b. How does the inability to match the half-value layer thickness affect the accuracy of the measurement?

EXPERIMENT 3.10. The Linear Gate in Gamma-Ray Spectroscopy

3.10.1. Purpose

The purpose of this experiment is to learn how to set up the analog and logic signal alignment when employing a linear gate to restrict the categories of nuclear events that are analyzed. The demonstration will involve limiting the analyzed events to only those appearing in the photopeak.

3.10.2. System Set-up

1. Begin with the setup and energy calibration used in any of the prior experiments from 3.1 through 3.9. The system will be altered according to Figure 3.9.

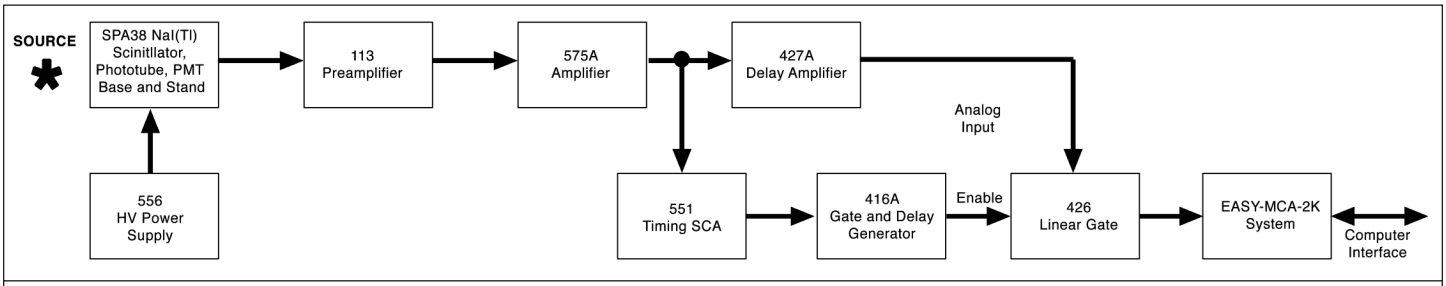

Fig. 3.9. Block Diagram of the Electronics for Gamma-Ray Spectrometry with a Linear Gate Interposed.

2. Turn off the NIM Bin Power Supply, and insert the 427A Delay Amplifier, the 551 Timing SCA, the 426 Linear Gate, and the 416A Gate and Delay Generator in the NIM Bin. Turn the NIM Bin Power on again.
3. Place a BNC Tee on the INPUT to the 427A Delay Amplifier. Connect one arm of the Tee to the 575A Amplifier UNIpolar OUTput using a short 93-Ω coaxial cable. Connect the other arm of the Tee to the DC INPUT of the 551 Timing SCA via a short 93-Ω cable.
4. Using a short 93-Ω cable, connect the OUTPUT of the 427A to the 426 analog INPUT.
5. Connect the POSitive OUTput of the 551 to the POSitive INPUT of the 416A with a short 93-Ω cable.
6. Using a short 93-Ω cable, connect the POSitive DELAYED OUTPUT of the 416A to the ENABLE input of the 426 Linear Gate.
7. Connect the analog OUTPUT of the 426 Linear Gate to the analog INPUT of the EASY-MCA.
8. Ensure that the rear-panel switches on the 551 are both set to the INTernal position.
9. On the front panel of the 551, set the μsec switch to the 0.1 – 1.1 μsec range, and turn the DELAY dial to its minimum value.
10. On the 551, set the INT/NOR/WIN switch to the NORmal mode.
11. On the 551, set the LOWER LEVEL dial to 50 mV (5/1000). Set the UPPER LEVEL dial to 10 V (1000/1000).
12. On the 416A, set the DELAY dial to its minimum value, and the delay range switch below it to 1.1 μsec.

3.10.3. Initial Adjustments

1. Disconnect the BNC Tee from the 427A INPUT. Apply the 100-Ω terminator to the 427A INPUT. Measure the DC voltage at the OUTPUT of the 427A. Using the DC ADJ screwdriver control on the 427A, adjust the dc level as close to zero as possible (typically within ±10 mV of zero). NOTE: The DC offset from zero mV at the 575A output, the 427A output and the 426 Linear Gate output will affect the zero intercept of the energy calibration for the MCA.
2. Remove the 100-Ω terminator and re-connect the BNC Tee to the 427A INPUT. Check that the coaxial cables attached to the Tee still provide their connections to the 575A UNIpolar OUTput and the 551 DC INPUT.
3. Place a 1-μCi ^{137}Cs source in the counting position a few cm from the front surface of the scintillation crystal.
4. Observe the 416A POSitive DELAYED OUTPUT on channel 1 of the oscilloscope. Trigger the oscilloscope from the channel 1 input. If the logic signal is not present, raise the LOWER LEVEL setting on the 551 slightly, until the logic pulse appears. If that does not work, check for improper connections or settings, and correct any errors.
5. Using the AMPLITUDE control on the 416A, adjust the POSitive DELAYED OUTPUT to a pulse height of approximately +5 V.

6. Note the width of the 416A output. It will be adjusted in a later step in the experiment.

3.10.4. Analog and Logic Signal Alignment

1. With the 416A output still triggering the oscilloscope on channel 1, connect the 427A OUTPUT to channel 2 of the oscilloscope.
2. Using the DELAY switches on the 427A, increase the DELAY until the analog signal from the 427A OUTPUT begins after the start of the logic signal from the 416A. This condition should require 1.5 to 2.0 μs of DELAY. EXPLANATION: The logic output pulse from the 551 SCA is generated on the trailing edge of the analog pulse when the amplifier pulse falls through 50% of its maximum amplitude. Thus the required DELAY should equal the time from the start of the analog pulse to the point at 50% of its maximum amplitude on the trailing edge.
3. Make fine adjustments to the 427A DELAY so that the analog pulse starts to rise from the baseline 0.25 to 0.5 μs after the rising edge of the logic pulse from the 416A.
4. Re-connect the 427A OUTPUT to the analog INPUT of the 426 Linear Gate. Re-connect the 416A POSitive DELAYED OUTput to the ENABLE input of the 426.
5. Set the PULSE INHIBIT / NORM / DC INHIBIT mode switch on the 426 to NORM.
6. Observe the OUTPUT of the 426 Linear Gate on the oscilloscope. Depending on the 426 GATE WIDTH adjustment, either all, or a portion of the analog pulse should be observed.
7. Confirm that the GATE WIDTH on the 426 controls the portion of the analog pulse that is transmitted through the Linear Gate by turning the screwdriver adjustment through its entire range.
8. Confirm that the DELAY dial on the 416A controls how much of the leading edge of the analog pulse is allowed through the Linear Gate.
9. Verify that the DELAY dial on the 551 SCA duplicates the function of the DELAY dial on the 416A.
10. Adjust the GATE WIDTH control on the 426 so that all of the analog signal passes through the Linear Gate, and nothing before or after the analog pulse is transmitted. To position the gating on the leading edge of the analog pulse, it may be necessary to make adjustments to the 427A DELAY switches and the 416A DELAY dial or the 551 DELAY dial.
11. Record the final settings of the 427A DELAY switches, the 551 DELAY and the 416A DELAY.

3.10.5. Restricting Pulse Heights Passing Through the Linear Gate.

1. Connect the linear OUTPUT of the 426 Linear Gate to the analog INPUT of the EASY-MCA.
2. Via the MAESTRO software, make sure that the MCA linear gate function is turned off.
3. Collect a spectrum on the MCA long enough to qualitatively identify the composition of the spectrum. Both the Compton continuum and the Photopeak from the ^{137}Cs source should be observed. NOTE: If the dc offset of the baseline between pulses has changed significantly at the MCA INPUT, it may be necessary to optimize the lower level threshold accordingly on the MCA. If the Percent Dead Time is abnormally high, even when the radioactive source is removed, raise the lower level threshold until the dead time is less than 1%. Otherwise, do not worry about this threshold for the purposes of the remainder of this experiment.
4. Save a record of the full spectrum for your report. Record the UPPER and LOWER LEVEL dial settings for this spectrum
5. Erase the spectrum, and start a new spectral acquisition while raising the LOWER LEVEL threshold on the 551 SCA. Increase the LOWER LEVEL setting until all energies below the photopeak are eliminated from the spectrum. This may require repeated erasing and restarting of the acquisitions as the threshold is adjusted.
6. Reduce the UPPER LEVEL threshold on the 551 SCA until all pulse heights above the photopeak are eliminated.
7. Save a record of the spectrum limited to the photopeak for your report. Record the UPPER and LOWER LEVEL dial settings for this spectrum.

EXERCISE

a. With the additional modules inserted, there are at least two factors that may have changed the energy calibration of the spectrum in this experiment compared to the previous experiments. What are those factors?

   It will not be necessary to re-calibrate the horizontal (energy) scale, as long as the features of the spectrum are readily identifiable for the purposes of Experiment 3.10.

3.10.6. Replacing the 426 Linear Gate with the MCA Linear Gate

Currently, external linear gates are rarely used in nuclear measurements, because virtually all commercially-available MCAs incorporate a linear gate. It turns out that it is much easier, and more convenient, to design a high-quality linear gate into the MCA. The previous set of measurements demonstrated what is happening in the linear gate. The next set of measurements shows how to meet the needs of the linear gate imbedded in the MCA.

Because the goal of the MCA is to measure the maximum height of the analog pulse, it automatically closes its linear gate after the peak amplitude of the pulse has been captured. Consequently, the linear gate logic pulse does not need to last more than a few tenths of a microsecond past the peak amplitude of the analog pulse. Different MCAs have diverse requirements for when the linear gate logic pulse must begin relative to start of the analog pulse. Some designs require that the logic pulse arrive slightly before the start of the analog pulse. Others simply require that the logic pulse be present at the time the peak amplitude of the analog pulse is captured.

In the following set of measurements, the alignment requirements of the EASY-MCA gating function will be investigated.

3.10.7 Procedure

1. Starting with the set-up in experiment 3.10.5, remove the 426 Linear Gate from the system.
2. Connect the 427A Delay Amplifier OUTPUT directly to the EASY-MCA analog INPUT.
3. Connect the 416A POSitive DELAYED OUTput to the GATE input of the EASY-MCA.
4. Turn the 416A gate WIDTH screwdriver adjustment to its maximum clockwise limit (4 μs).
5. Via the MAESTRO software, check the ADC properties, and ensure that the Gate function is turned off.
6. Acquire a spectrum and confirm that the full spectrum, including the Compton continuum and the photopeak are being acquired. Save a copy of this spectrum for your report. NOTE: If the dc offset of the baseline between pulses has changed significantly at the MCA INPUT, it may be necessary to optimize the lower level threshold accordingly on the MCA. If the Percent Dead Time is abnormally high, even when the radioactive source is removed, raise the lower level threshold until the dead time is less than 1%. Otherwise, do not worry about this threshold for the purposes of the remainder of this experiment.
7. Using the MAESTRO software, select the Coincidence Gate function. This allows acquisition of a spectrum for only those analog pulses that are accompanied by a logic pulse at the GATE input of the EASY-MCA.
8. Acquire a spectrum. If the settings on the 551 have not been changed from the prior experiment, only the ^{137}Cs photopeak should be acquired, with all events eliminated above and below that peak. Save a copy of that spectrum for your report.
9. Increase the DELAY dial setting on either the 551 or the 416A until the MCA no longer acquires a spectrum. Reduce the DELAY dial setting until the MCA just reliably acquires a spectrum. Record the new DELAY dial settings.
10. Reduce the WIDTH screwdriver adjustment (counterclockwise) on the 416A until the MCA will no longer acquire a spectrum. Turn the WIDTH adjustment until the MCA reliably acquires a spectrum.
11. Reduce the LOWER LEVEL setting on the 551 to 100 mV (10/1000) and increase the UPPER LEVEL setting to 10 V (1000/1000).
12. Repeat steps 9 and 10.
13. Display the analog signal from the 427A on channel 1 of the oscilloscope. Trigger the oscilloscope on the positive pulses with the triggering threshold set just above the noise on the baseline.
14. Observe the POSitive DELAYED OUTput pulse from the 416A on channel 2 of the oscilloscope.

EXERCISE

b. Make a sketch of the analog and logic pulses showing their time relationship.

If the timing requirements of the MCA linear gate are not well known, the above procedure can be employed to determine those requirements. Alternatively, it is usually safe to adjust the gating logic pulse to span the entire analog pulse.

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