

AN34 Experiments in Nuclear Science Laboratory Manual Fourth Edition



Experiment IV-3 Gamma-Ray Spectroscopy Using NaI(Tl)

Gamma-Ray Spectroscopy Using NaI(Tl)

Introduction

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.

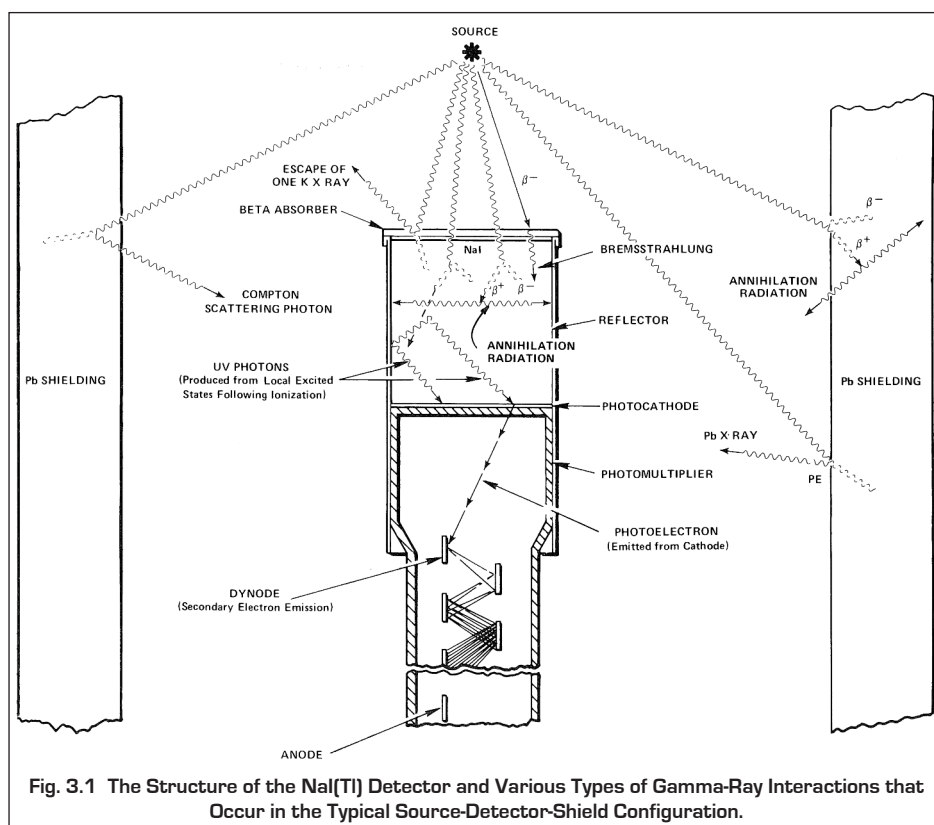
Decay Schemes and Gamma Emission

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, to enable identification of the source. The other is counting the number of gamma-ray photons that leave the source per unit of time. This number is proportional to the activity of the source. In this experiment the student will become familiar with some of the basic NaI(Tl) measurements associated with identifying a gamma emitting radioisotope and determining its activity.

Introduction to 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.



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.

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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. Figure 3.2 shows the modular electronics configuration used with the NaI(Tl) detector. The digiBASE is an all-in-one device which includes all of the required functions.

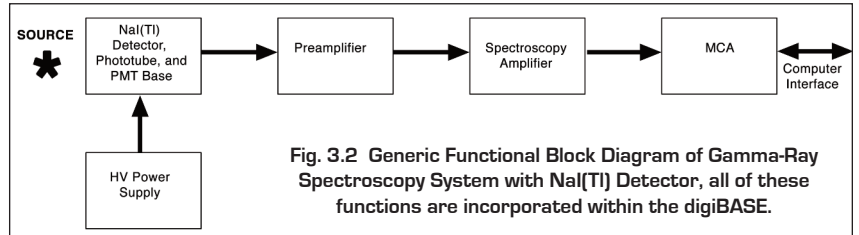


Fig. 3.2 Generic Functional Block Diagram of Gamma-Ray Spectroscopy System with NaI(Tl) Detector, all of these functions are incorporated within the digiBASE.

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



Fig. 3.3 digiBASE All-in-One PMT Base, HV, Preamplifier, Amplifier, and Digital MCA.

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

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 $< 2 \mu\text{s}$, 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.

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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 www.ortec-online.com/Products-Solutions/Multichannel-Analyzers-Overview.aspx.

The MCA in the digiBASE, which is 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 in a "plug and play" manner.

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). Another approach is to refer to the MAESTRO operating manual which may be downloaded from www.ortec-online.com.

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 IV-3 Equipment Required

- | | |
|---|--|
| <ul style="list-style-type: none">• DETECTOR-STAND-AX NaI Detector Downlooking Stand with source and foil holder.• 905-3 NaI Scintillation Detector, 2x2-in. crystal, 2-in. PMT/• DIGIBASE PMT Base with integrated bias supply, preamplifier and digital multichannel analyzer.• Personal Computer with a USB port and a recent, supportable version of the Windows operating system.• 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 IV-3.2 can be selected from the remaining sources. | <ul style="list-style-type: none">• GF-137-M-5 * 5 μCi $\pm 5\%$ ^{137}Cs Gamma Source (used as a reference standard for activity in Experiment IV-3.5).• GF-057-M-20 * 20 μCi ^{57}Co Source (for Experiment IV-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 (FoilElementThickness).• 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. |
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* Sources are available direct from supplier. See the ORTEC website at www.ortec-online.com/Service-Support/Library/Experiments-Radioactive-Source-Suppliers.aspx

EXPERIMENT IV-3.1. Energy Calibration

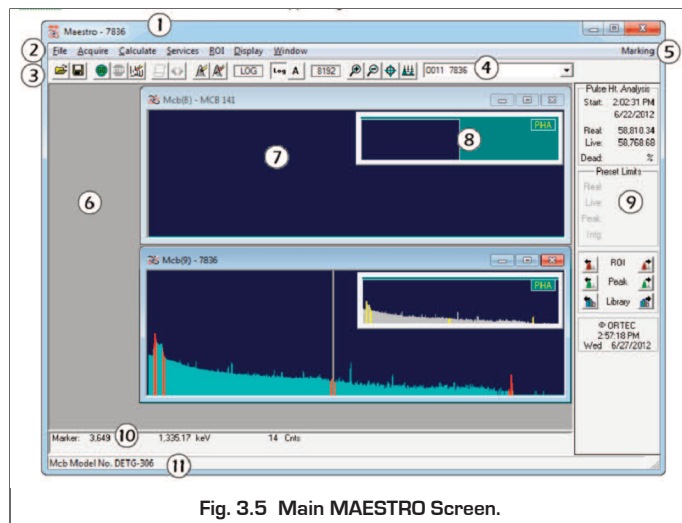
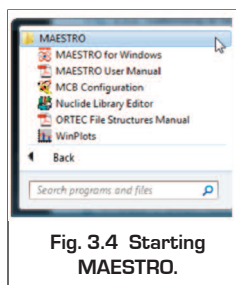
The system should already be cabled correctly. A single USB cable between the digiBASE and the PC is all that is required.

If the software is installed correctly, then starting the MAESTRO program "MAESTRO for Windows" should result in the main MAESTRO screen appearing (Fig. 3.4).

If the screen shows "Buffer" in block 4 (Fig. 3.5), then the software has been unable to "find" the digiBASE and assistance should be sought, or the MAESTRO manual referred to.

Assuming that the legend in the box reads "digiBASE", communication is established.

1. Under the MAESTRO menu item "Acquire" select "MCB Properties".



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The MCB properties for the digiBASE will look similar to Fig. 3.6 The tabs provide access to the controlling functions of the digiBASE.

2. Ensure that the NaI(Tl) detector assembly is properly mounted in the stand.
3. There are two parameters that ultimately determine the overall gain of the system: the high voltage furnished to the PMT and the gain of the spectroscopy amplifier. The gain of the PMT is quite dependent upon its high voltage. A rule of thumb for most PMTs is that, near the desired operating voltage, a 10% change in the high voltage will change the gain by a factor of 2.
4. The correct high voltage value depends on the PMT being used. Consult your instruction manual for the PMT 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.
5. Select the High Voltage tab
6. Enter the detector high voltage in the Target field, click On, and monitor the voltage in the Actual field.
7. On the Amplifier tab, choose a shaping time of 0.75 μ s and a starting fine gain setting of 0.5 and 0.5 respectively. (The coarse gain on the digiBASE is set by Jumper, and should not need to be changed).
8. Using the ADC tab 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 (1023).
9. On the Presets tab set both real and live presets to Zero ("off").

IV-3.1.2. A Note on Bipolar Filtering

Unlike many "Gaussian" spectroscopy amplifier filters which require so called "Pole-Zero" cancellation, the Bipolar filter in the digiBASE requires no such adjustment. For further discussion on amplifier filters see www.ortec-online.com/download/Amplifier-Introduction.pdf

A representation of the digital bipolar waveform may be displayed through the use of the "InSight" display mode selectable via the "Amplifier 2" tab. Remember to click the "STOP" control on returning to the Amplifier 2 tab or you will not be able to display the gamma-ray spectrum!

IV-3.1.3. Adjusting the Gain for Recording Spectra

1. Place the ^{137}Cs source from the gamma source kit ($E_\gamma = 0.662 \text{ MeV}$) in the stand $\sim 2 \text{ cm}$ below the front surface of the NaI(Tl) crystal.
2. Set the HV to the designated value. Adjust the amplifier coarse and fine gain until the spectrum looks as in Fig. 3.10 Accelerator keys allow this adjustment to be made while observing the spectrum:
 - ALT+ increases the gain one increment
 - ALT- decreases the gain one increment
 - SHIFT ALT + increases the gain several increments
 - SHIFT ALT - decreases the gain several increments
 - ALT 1 starts an acquisition
 - ALT 2 stops an acquisition
 - ALT 3 clears acquired or acquiring data
3. Acquire a spectrum with the digiBASE for at least 30 seconds, and no more than a couple of minutes. The spectrum should look like Figure 3.10

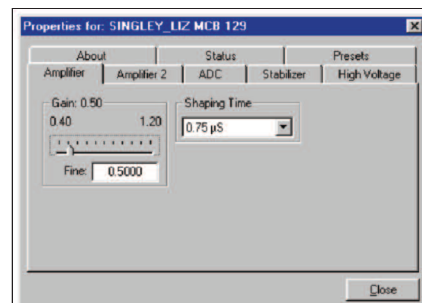


Fig. 3.6 MCB Properties.

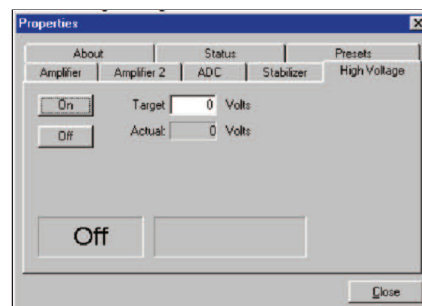


Fig. 3.7 High Voltage Tab.

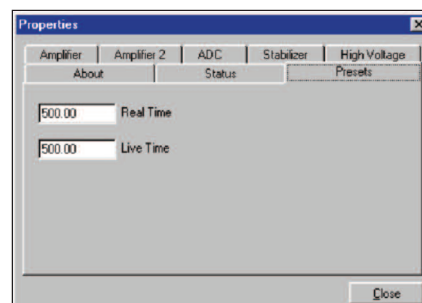


Fig. 3.8 Presets Tab.

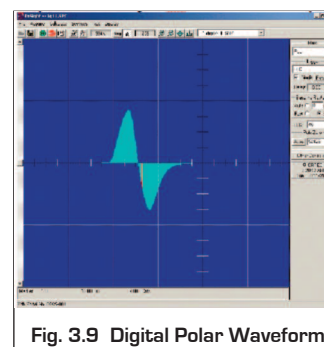


Fig. 3.9 Digital Polar Waveform.

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- 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.
- By adjustment of the fine gain, set the 662-keV photopeak position in 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 $1.17 + 1.33 \text{ MeV} = 2.50 \text{ MeV}$ sum peak from the ^{60}Co source in Experiment IV-3.8 will be positioned at channel 900, well within the 1000-channel limit. [Note that the calibration in Fig. 3.10 places the peak at channel 280, which would shift the sum peak in Expt. IV-3.8 past the top end of the scale.]

IV-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.

- Remove any radioactive sources from the vicinity of the NaI(Tl) detector, so that no gamma rays are being detected.
- 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.
- Using the MCB Properties menu, reduce the Lower-Level Discriminator threshold, start another acquisition and observe the percent dead time.
- Keep repeating step 3 until the percent dead time abruptly increases.
- Once the dead time increases significantly above 1%, gradually increase the Lower-Level Discriminator threshold until the percent dead time is less than 1%.
- 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.

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

- 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

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

And the percent standard deviation in the N_i counts is

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

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.

- 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 3.10

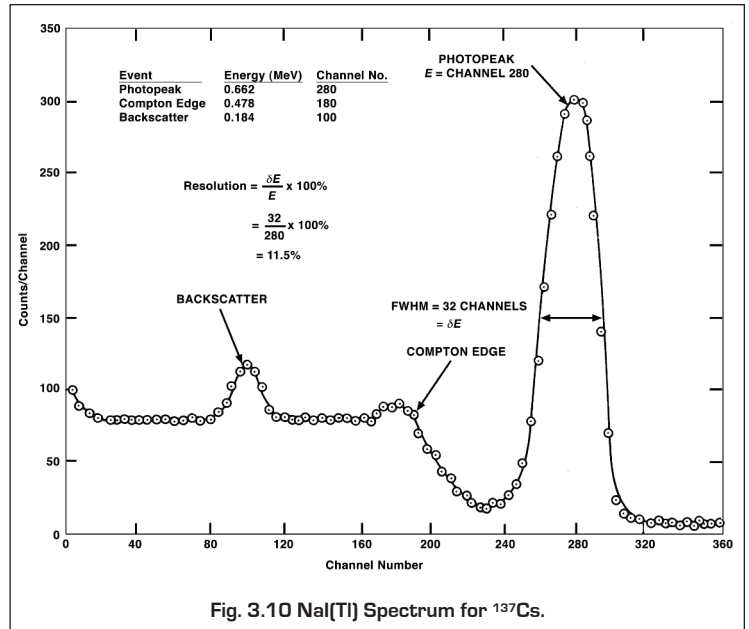


Fig. 3.10 NaI(Tl) Spectrum for ^{137}Cs .

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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. 3.11
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 1, make a plot of energy of the photopeaks vs. channel number. Fig. 3.12 shows this calibration for the data taken from Figs. 3.10 and 3.11. If other calibration sources are available, additional data points can be added to Fig. 3.12. The other entries in Table 1 will be filled out in Experiment IV-3.3.
- c. Use the energy calibration feature of the MAESTRO MCA software 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?

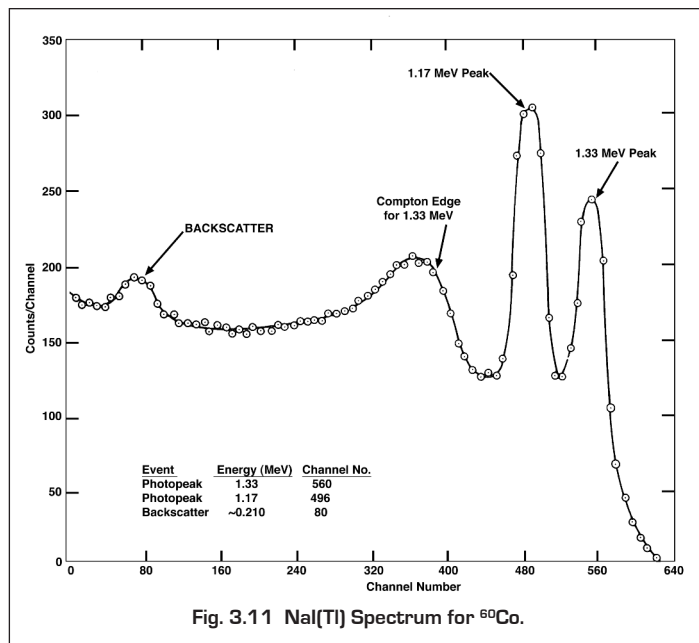


Fig. 3.11 NaI(Tl) Spectrum for ^{60}Co .

	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		

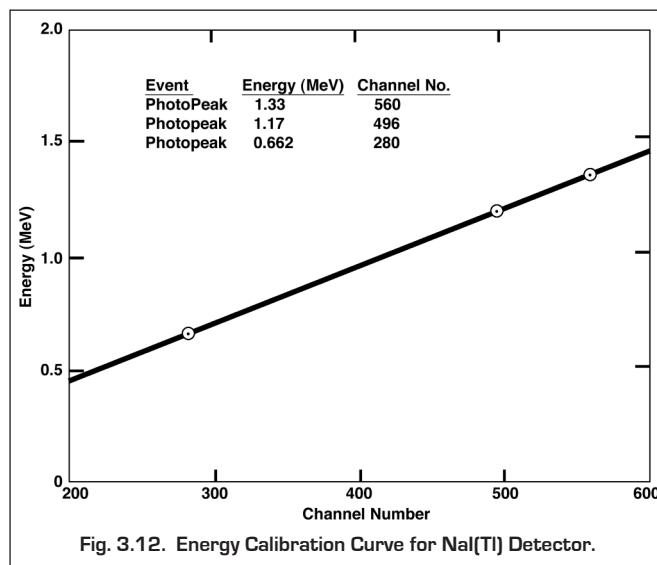


Fig. 3.12. Energy Calibration Curve for NaI(Tl) Detector.

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EXPERIMENT IV-3.2. Energy Analysis of an Unknown Gamma Source

IV-3.2.1 Purpose

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

IV-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. Alternatively if the instructor has loaded an appropriate library of nuclides into the MAESTRO software, you can use the identify feature in the software: place the cursor on the peak, select "Calculate, Peak Info". The identification is made on the basis of the nearest peak energy in the table to the peak energy in the spectrum.

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

IV-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.

IV-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

$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0c^2} [1 - \cos\theta]} \quad (4)$$

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_{γ} 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.

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

$$E_{\gamma'} \cong \frac{E_{\gamma}}{1 + 4E_{\gamma}} \quad (5)$$

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

$$E_e = E_{\gamma} - E_{\gamma'} \quad (6)$$

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 3.10 and 3.11. 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 3.10 and 3.11.

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 3.10 and 3.11 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

- 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?
- 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?
- 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 IV-3.4. Energy Resolution

IV-3.4.1. Purpose

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

IV-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. 3.10 shows the gamma spectrum that was plotted for the ^{137}Cs source. The resolution of the photopeak is calculated from the following equation:

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

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.

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In Fig. 3.10 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 IV-3.5. Activity of a Gamma Emitter (Relative Method)

IV-3.5.1. Purpose

In Experiments IV-3.1 and IV-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); $1 \text{ Ci} = 3.7 \times 10^{10}$ 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.

IV-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. 3.10
 2. Use the cursor to determine the sum under the photopeak. In the example shown in Fig. 3.10, 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:

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

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 ($\pm 10\%$) 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. What is the other way that the source-to-detector distance significantly affects the accuracy of the relative activity measurement?
-

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

IV-3.6.1. Purpose

The activity of the radioactive source used in Experiment IV-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.

IV-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.

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

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. 3.13 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 2)

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

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

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?

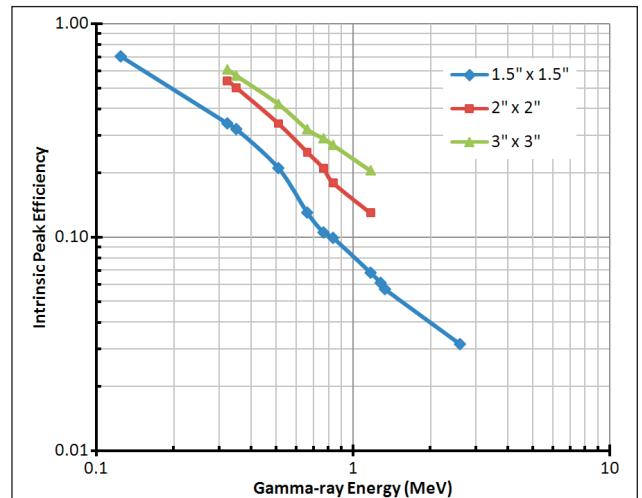


Fig. 3.13. Intrinsic Peak Efficiency of Various NaI(Tl) Crystals vs. Gamma-Ray Energy. Detector to Point-Source Distance is 9.3 cm for the 3-inch x 3-inch and 2-inch x 2-inch crystals and 10 cm for the 1.5-inch x 1.5-inch scintillator.

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

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EXPERIMENT IV-3.7. Mass Absorption Coefficient

IV-3.7.1. Purpose

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

IV-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

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

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):

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

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

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

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 $0.105 \text{ cm}^2/\text{g}$. 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 IV-3.5 and IV-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 IV-3.7, use the Net Area to subtract the background.

IV-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 ($\Sigma_{\text{Cs}} - \Sigma_{\text{b}}$) to be at least 6000 counts. Determine ($\Sigma_{\text{Cs}} - \Sigma_{\text{b}}$) 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 ($\Sigma_{\text{Cs}} - \Sigma_{\text{b}}$). Record the absorber thickness and the net counts for that thickness in Table 3.3.

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3. Repeat the process as the thickness of lead absorber is incremented in steps of no less than 1,000 mg/cm² and no more than 1,600 mg/cm². 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/cm², or the counting rate has dropped below 1/4 of the initial value with no absorber.

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/cm², where $I = (\Sigma_{Cs} - \Sigma_b)/[\text{live time}]$. Determine the HVL from this curve, and calculate μ from Eq. (12). How does your value compare with the accepted value of 0.105 cm²/g?
- b. The μ for aluminum at 662 keV is 0.074 cm²/g, and the density of aluminum is 2.70 g/cm³. What is the half-thickness of aluminum in mg/cm² 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 IV-3.8. Sum Peak Analysis

IV-3.8.1. Explanation and Relevant Equations

Fig. 3.11 shows the two pronounced peaks from a ⁶⁰Co radioisotope. Their origin is documented by the ⁶⁰Co decay scheme illustrated in Fig. 3.14. Most of the time (>99%), the decay occurs by β^- emission to the 2.507 MeV excited state of ⁶⁰Ni. 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 IV-19 will demonstrate that these two events are in coincidence, and have an angular correlation that deviates from an isotropic 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 4 π 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 IV-3.6, the number of counts, Σ_1 , under the γ_1 peak is given by:

$$\Sigma_1 = \epsilon_1 G f_1 t_L A \quad (13)$$

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:

$$\Sigma_2 = \epsilon_2 G f_2 t_L A \quad (14)$$

Using the basic concepts behind equations (13) and (14), the number of counts in the sum peak, Σ_3 , can be expressed as:

$$\Sigma_3 = \epsilon_1 \epsilon_2 f_1 f_2 G^2 A t_L [W(0^\circ)] \quad (15)$$

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

$$\Sigma_3[{}^{60}\text{Co}] \approx \epsilon_1 \epsilon_2 G^2 A t_L \quad (16)$$

IV-3.8.2. Purpose

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

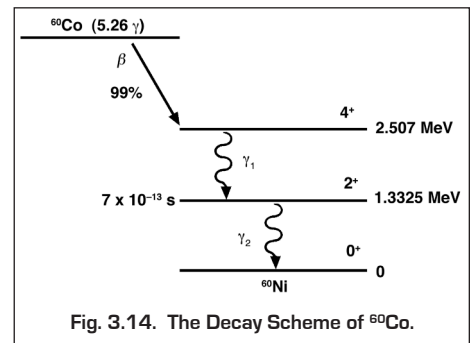


Fig. 3.14. The Decay Scheme of ⁶⁰Co.

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IV-3.8.3. Procedure

1. 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.
2. Construct a calibration curve as in Experiment IV-3.1.
3. From Fig. 3.13, 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.
4. Count for a live time that is long enough to accumulate an area under the sum peak of approximately 1000 counts. This procedure was outlined in Experiment IV-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 IV-3.6.
- b. Repeat this sum peak analysis for the ^{22}Na source. Fig. 3.15 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:

$$\frac{\Sigma_3}{\Sigma_1 \Sigma_2} = \frac{W(0^\circ)}{At_L} \quad (17)$$

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, $W(0^\circ) \approx 1.0$. 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 IV-3.9. Photoelectric Absorption

IV-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.

IV-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:

$$E_e = E_\gamma - E_B = h\nu - E_B \quad (18)$$

where $E_\gamma = h\nu$ is the original energy of the gamma-ray photon, h is Planck's constant, ν 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

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

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

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

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

For this experiment, the gamma-ray energy will be held constant at $E_\gamma = 122$ 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 .

IV-3.9.3. Procedure

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

- 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.
- 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 IV-3.7, the net counts above background in the peak area should be at least 10,000 counts.
- Table 4 shows the half-value layer thicknesses for the various pure-element foils, along with typical foil thicknesses. Use Table.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.
- 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.
- 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.

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

EXERCISES

- On log-log graph paper, make a plot of μ vs. Z from your experimental data. [Alternatively, plot the $\ln(\mu)$ 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?
- How does the inability to match the half-value layer thickness affect the accuracy of the measurement?

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