Experiment VI

Gamma Ray Spectroscopy, Using NaI(Tl) Detectors*

In Experiment V, we dealt with the operation and characteristics of a solid scintillation detector used strictly as a counter, i.e., to record the number of γ-rays striking the detector. In this experiment, we shall explore the use of a solid scintillation detector as a spectrometer, i.e., to measure the number and energy of the γ-ray striking the detector. Chapter 7 contains a very complete discussion of γ-ray spectrometry and should be consulted prior to performing this experiment.

I. Calibration of Spectrometer

The key feature of most γ-ray spectrometers is a linear relation between the height of the pulse coming from the γ-ray detector and the energy deposited in the detector by a γ-ray. In this section, we will discuss how to determine the exact form of this linear relationship for your spectrometer.

Procedure:

1. Setup (or have your instructor setup) the electronics shown in Figure VI-1. The high voltage applied to the phototube should be that recommended by the manufacturer (or in the case of a range of recommended values, a value

*Although most of the laboratory experiments dealing with radiation detection are designed to be performed in one 3-hour laboratory period, this experiment requires two 3-hour laboratory periods.

near the middle of the range should be selected.) Set the preamp, amplifier and multichannel analyzer controls to the positions indicated by your instructor.*

2. Place a ^{137}Cs source in front of the NaI(Tl) detector (for ^{137}Cs, $E_\gamma \simeq 0.662$ MeV).

3. Adjust the amplifier gain controls so that the 0.662 MeV photopeak for ^{137}Cs falls at ~ 30% of the full scale (in channels) of the analyzer.

4. Accumulate counts in the analyzer until you have a few hundred counts per channel near the ^{137}Cs photopeak. A typical spectrum is shown in Figure VI-2. (See also Fig. 7-5).

5. After obtaining a printed copy of the ^{137}Cs spectrum from the multichannel analyzer, erase the spectrum, and replace the ^{137}Cs source with a ^{60}Co source. Accumulate a ^{60}Co spectrum in the multichannel analyzer (similar to that shown as Figure VI-3; see also Figure 7-7) and obtain a printed copy of this spectrum.

6. Plot number of counts per channel vs. channel number for both the ^{137}Cs and ^{60}Co spectra. From these spectra, fill in the blank entries in Table VI-1.

7. Using the data in Table VI-1, make a plot of γ-ray energy vs. analyzer channel number. It should look like Figure VI-4. Such a linear plot can also be described by an equation such as

$$E_\gamma = m\,(\text{channel number}) + b$$

where E_γ is the γ-ray energy expressed in MeV, m is the slope of the calibration line in MeV/channel and b is the intercept on the energy axis at

* The instructions for this experiment have been written assuming that the student knows how to operate a multichannel analyzer. If this is not the case, we suggest, as done in our laboratories, that the instructor operate the controls of the analyze during the experiment.

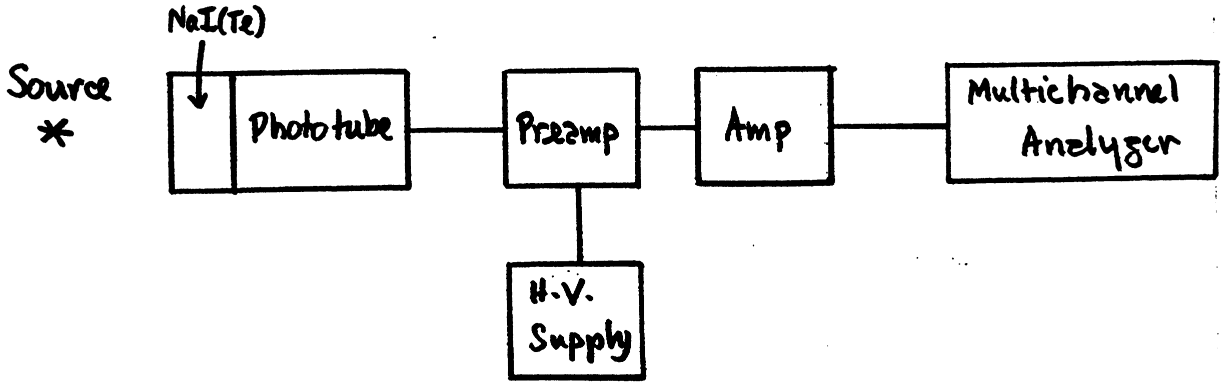


Figure VI-1 Electronic Block Diagram for NaI(Tl) Gamma Ray Spectrometer.

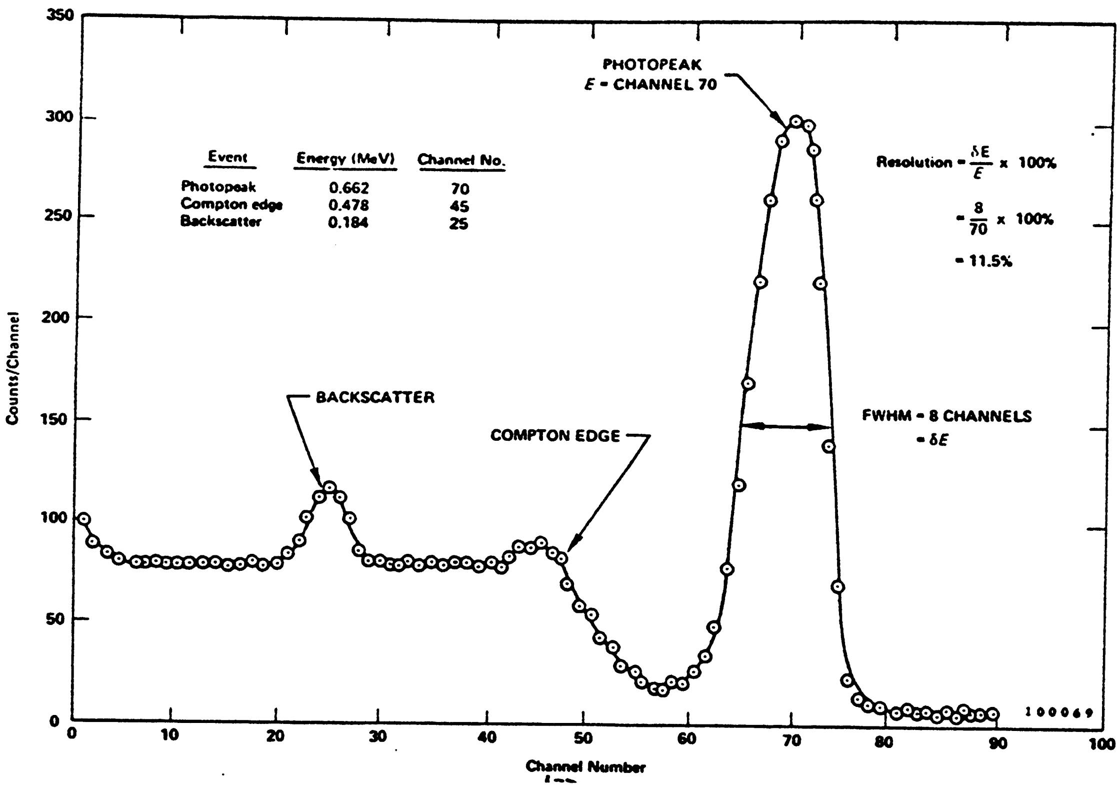


Figure VI-2 A typical ^{137}Cs pulse height spectrum.

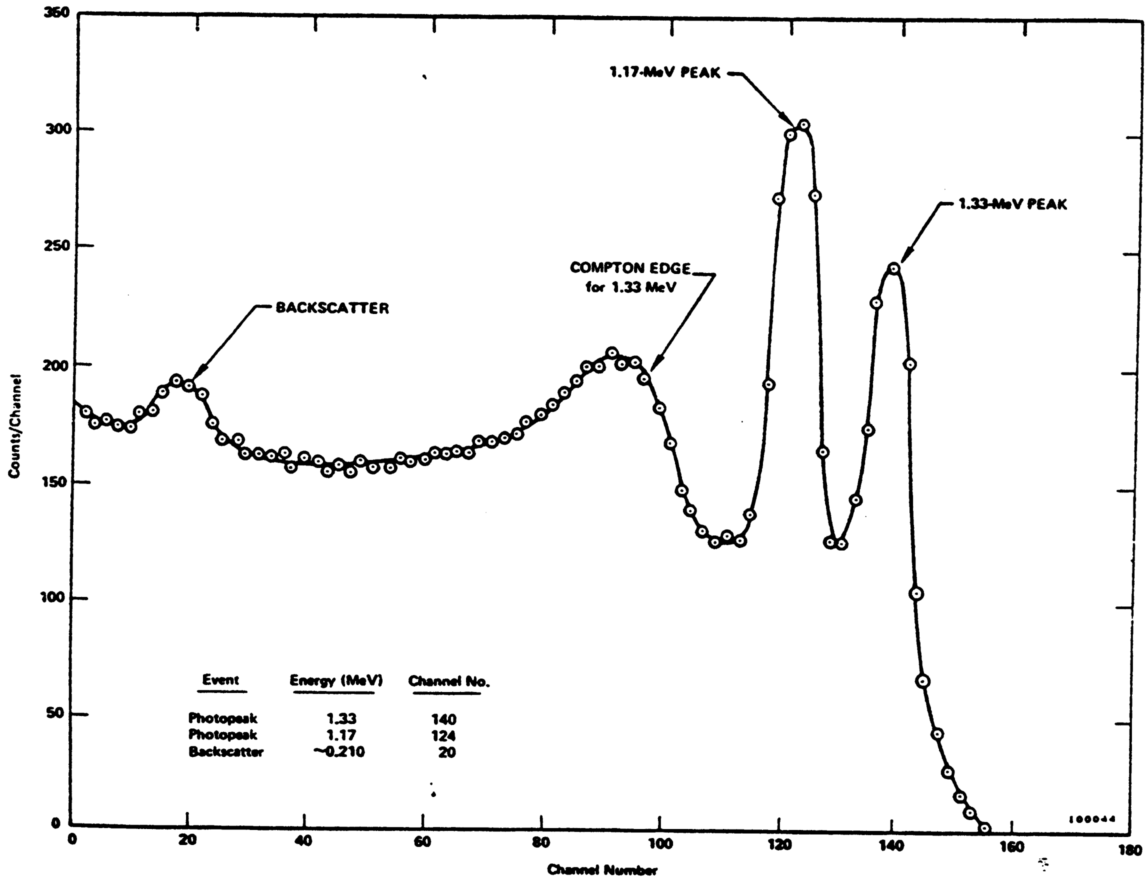


Figure VI-3 ^{60}Co pulse height spectrum.

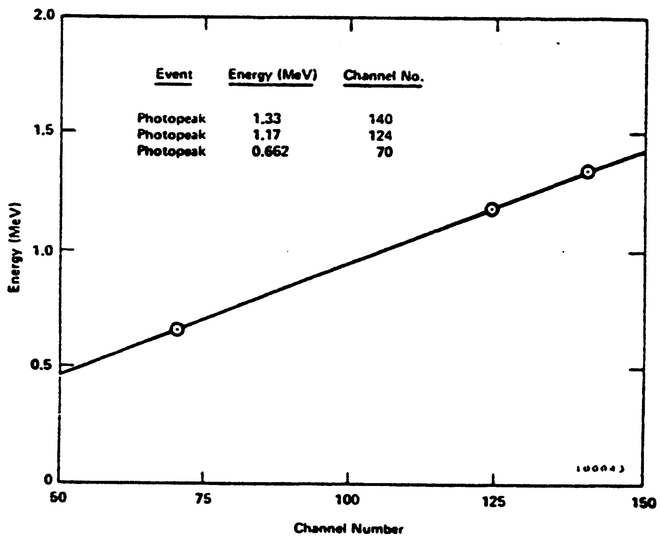


Figure VI-4 Energy calibration curve for γ-ray spectrometer.

Table VI-1

Peak Assignment	Peak Energy (MeV)	Peak Channel Number
0.662 MeV photopeak	0.662	
1.17 MeV photopeak	1.17	
1.33 MeV photopeak	1.13	

channel number 0 expressed in MeV. Determine the constants m and b that describe the energy calibration for your spectrometer. (**See Appendix II for review of slope and intercept finding, if necessary**).

m = ______________MeV/channel

b = ______________MeV.

(Note that b can be positive or negative and is not necessarily zero. A proper determination of the energy calibration of a spectrometer must include a determination of both m and b.)

II. Measurement of the Energy of an Unknown Gamma Ray Emitter

In this section, we shall use the energy calibration determined in Section I, and the spectrometer to measure the energy of an unknown γ-ray emitter.

Procedure:

1. Erase the ^{60}Co spectrum from the analyzer memory but be careful

not to disturb any other settings of the system.

2. Obtain an unknown γ-ray source from your instructor and measure its γ-ray spectrum.

3. Using the energy calibration determined in Section I, measure the energy (s) of the photopeak (s) in the unknown spectrum and report them below in Table VI-2.

Table VI-2

Peak Channel Number	Peak Energy (MeV)	Peak Assignment

4. Using Table 7-3 and Figure 7-7 of the text, make an identification of the unknown radionuclide and the assignment of the various peaks (see Chapter 7 for additional references). Enter your answer in Table VI-2.

III. Analysis of Various Spectral Features

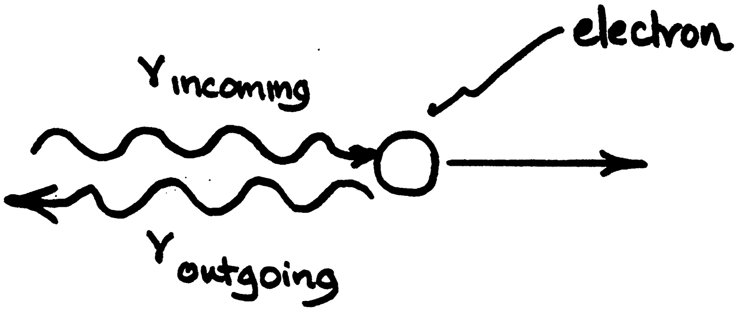
Up to now, we have used the full energy peaks in the spectra (the photopeaks) to establish an energy calibration and to identify unknown γ-ray emitters. Now we wish to try to understand some other features of the spectrum besides the full energy peaks.

As discussed in Chapter 7, one of the primary mechanisms for the interaction of γ-radiation with matter is the Compton effect. Two features of the γ-ray spectrum observed for ^{137}Cs are due to the Compton effect. They are:

(a) The Compton edge which corresponds to the maximum energy an electron can carry away in a Compton scattering event. The distribution of electron energies in a Compton scattering event ranges from 0 MeV up to the Compton edge energy which is given as

$$E_{\text{Compton Edge}} \approx \frac{E\gamma}{1 + \frac{0.511}{2\,E\gamma}} \qquad \text{(VI-1)}$$

where $E\gamma$ is the incident γ-ray energy. (See Figure 3-15). This maximum electron energy corresponds to a Compton event in which the incident photon was scattered through 180°, i.e.



(b) The backscatter peak which corresponds to the γ-ray energy associated with the outgoing photon in a 180° scattering as shown above. Mathematically, we say

$$E_{backscatter} \simeq \frac{E_\gamma}{1 + 4 E_\gamma} \qquad \text{(VI-2)}$$

Procedure:

1. Using your ^{137}Cs and ^{60}Co spectra and equations VI-1 and VI-2, fill in the entries in Table VI-3. (If the backscatter peaks in your spectrum were not prominent enough to identify them, retake the spectra with a Pb sheet behind the source (make sure the Pb sheet doesn't interfere with the passage of γ-rays to the detector).

Table VI-3

Peak Assignment	Peak Energy (MeV)	Peak Channel Number
Compton Edge ^{137}Cs		
Backscatter ^{137}Cs		
Compton Edge ^{60}Co		
Backscatter ^{60}Co		

Compare your answers with those shown in Figures VI-2 and VI-3.

IV. Energy Resolution

The energy resolution of a γ-ray spectrometer is a measure of the ability of the spectrometer to resolve (or separate) adjacent peaks in a γ-ray spectrum. Formally, we can define energy resolution, R, (as in Chapter

7.) as

$$R = \frac{\Delta E}{E} \times 100\% \qquad \text{(VI-3)}$$

where R is energy resolution in %; ΔE is the full width of a given photopeak at half the maximum count rate, measured in number of channels; and E is the peak energy expressed as the channel number of the mid point of the peak. (See Chapter 7 for a sample calculation of peak resolution, Figure 7-11).

The resolution of a scintillation detector depends upon several factors. Among them are:

a. the number of photons per scintillation event.

b. the number of photons that strike the photocathode.

c. the number of photoelectrons released per photon hitting the photocathode.

d. the number of photoelectrons that strike the first dynode.

e. the multiplication factor of the photomultiplier tube.

In general, the greater each one of the above quantities is, the better (i.e., smaller) the resolution. Factors a and b refer to properties of the scintillator while factors c, d, and e refer to the phototube. Mathematically we say that

$$R = \alpha + \frac{\beta}{\sqrt{E_\gamma}} \qquad \text{(VI-4)}$$

where R is the resolution, α and β are constants referring to the scintillator and phototube respectively, and E_γ is the γ-ray energy. Note that R varies inversely as $\sqrt{E_\gamma}$ and thus the higher E_γ is, the smaller R is.

Procedure:

1. Using the same amplifier and analyzer gain settings as before, measure the γ-ray spectra of ^{57}Co and ^{54}Mn. Tabulate these results along with those obtained previously for ^{60}Co and ^{137}Cs in Table VI-4.

2. Using equation VI-3, calculate the resolution for each γ-ray energy and enter it in Table VI-4.

Table VI-4

Peak Assignment	Peak Channel Number	Peak Energy (MeV)	Resolution (%)
^{57}Co Photopeak		0.122	
^{137}Cs Photopeak		0.662	
^{54}Mn Photopeak		0.835	
^{60}Co Photopeak		1.17	
^{60}Co Photopeak		1.33	

3. Plot the resolution R vs. $1/\sqrt{E_\gamma}$ and on a separate graph, R vs. E_γ. Your data should resemble Figure 7-12. Determine the parameters α and β from the plot of R vs $1/\sqrt{E_\gamma}$ and equation VI-4. Comment upon the shape of the plots obtained.

V. Efficiency of the Spectrometer

As discussed in Chapter 7, the efficiency of γ-ray detection with a scintillation spectrometer is a complex function of many quantities. Specifically

$$A_p = D \epsilon_T f_p \Omega f_g \qquad \text{(VI-5)}$$

where A_p is the photopeak area in cps, D is the sample disintegration rate in dps, ϵ_T is the total probability that any γ-ray of a given energy striking the detector will produce a measurable pulse (the total efficiency), f_p is the fraction of the events in the total spectrum that correspond to photopeak events (the photofraction), Ω is the solid angle subtended by the detector with respect to the source and f_g is the fraction of disintegrations giving rise to a γ-ray. The detailed calculation of ϵ_T, f_p, Ω and f_g is discussed in Chapter 6 and 7 of the text. For our purposes here, we shall introduce a simpler version of equation (VI-5), namely by **rewriting it in the following form**

$$A_p = \mathcal{D} \xi \qquad \text{(VI-6)}$$

where **we have collected together various constants as**

$$\mathcal{D} = Df_g$$
$$\xi = \epsilon_T f_p \Omega \qquad \text{(VI-7)}$$

We shall refer to $\mathcal{D}$ as the γ-ray emission rate of the source and ξ as the effective efficiency of the source detector arrangement. In this experiment we shall measure the magnitude of ξ and its dependence on γ-ray energy.

Procedure:

1. Secure three calibrated γ-ray sources (such as ^{57}Co, ^{137}Cs and ^{60}Co) of varying γ-ray energy from your instructor. Place each source in turn ~ 8 cm away from the crystal and measure the γ-ray spectrum for each source. Be sure to accumulate approximately 10,000 counts in each photopeak and carefully note the counting time. Each source should be positioned in exactly the same position relative to the detector.

2. Determine the photopeak area (s) for each spectrum (see Chapter 7) and recor[d] the results in Table VI-5. Calculate the net photopeak counting rates and enter them in Table VI-5. Using equation VI-6 and the known γ-ray emission rate of the sources, calculate ξ, the effective γ-ray efficiency for each energy γ-ray, entering the results in Table VI-5.

3. Plot the log ξ vs. log E_γ on log-log paper. Your results should resemble Figure VI-5.

Table VI-5

Source	Source Strength (γpm)	Net Photo Peak Counts	Counting Time	Net Photopeak Area (cpm)	ξ

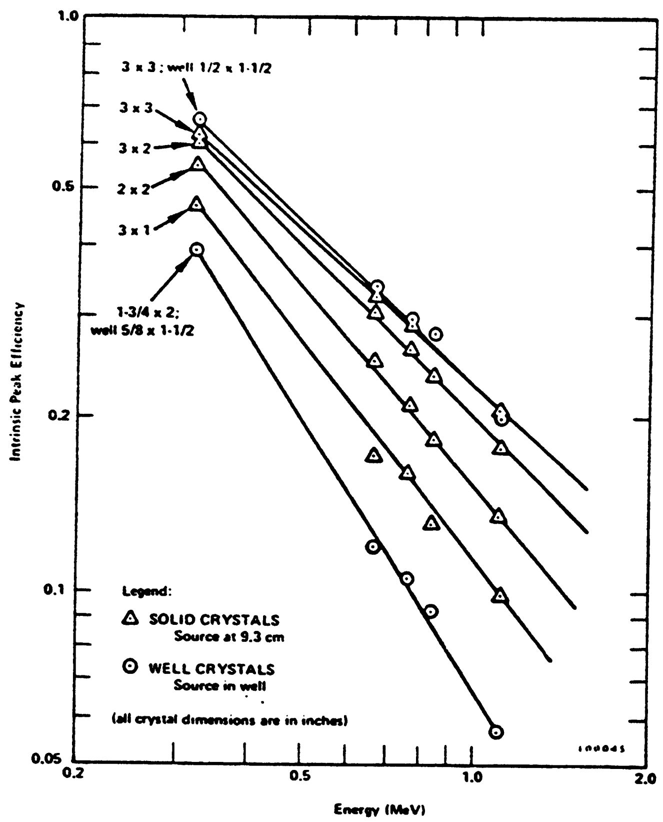


Figure VI-5 Intrinsic Peak Efficiency of Various NaI(Tl) Crystals vs. Gamma Energy.