ORTEC®

AN34 Experiment 7

High-Resolution Gamma-Ray Spectroscopy

Equipment Needed from ORTEC

- GEM10P4/CFG-PV4/DWR-30 Coaxial Detector System (Includes detector, cryostat, dewar, preamplifier, and 12-ft. cable pack); typical specifications: 10% relative efficiency, 1.75 keV resolution at 1.332 MeV, 41:1 peak-to-Compton ratio.
- 659 0–5 keV Detector Bias Supply
- 672 Spectroscopy Amplifier
- 480 Pulser
- C-24-12 Cables (2 ea.)
- C-24-1 Cable
- C-29 BNC Tee Connector
- 4001A/4002D NIM Bin and Power Supply
- TRUMP-PCI-8K Plug-In MCA Card (other ORTEC MCAs may be used)

Other Equipment Needed

- PC operating Windows 98/2000/XP
- Sealed Solid Disk Gamma-Ray Sources ~1 µCi, ^{137}Cs, ^{60}Co, ^{22}Na, ^{65}Zn, ^{54}Mn (substitute alternate sources with similar energies)
- Other Sources: 5 µCi ^{137}Cs; 10 µCi ^{60}Co; 10 µCi ^{228}Th
- Oscilloscope

Optional for Experiment 7.4

1- to 3-Ci americium-beryllium isotopic neutron source. If the source is not in a paraffin howitzer, place a 6-inch thickness of paraffin between the source and the HPGe detector to thermalize the source neutrons.

Purpose

Gamma-ray energies will be measured with a High-Purity Germanium (HPGe) detector and research-grade electronics. The theory of response characteristics is explained, and the high-resolution measurement results are contrasted with those from a sodium iodide (NaI) scintillation detector performed in Experiment 3.

Introduction

Most of the experiments in this manual are written for use with ORTEC educational modules. However, in this experiment, which illustrates the superior resolution capabilities of HPGe detector systems, research-grade signal processing modules have been listed in order to fully utilize the detector's capabilities.

Many colleges have Nuclear Spectroscopy Centers in which research efforts in the area of high-resolution gamma spectroscopy are normally directed. It is possible to do a great amount of publishable research in areas such as decay scheme analysis, etc. with these high-resolution systems. In many cases additional lines can be found in spectra, or the improved resolution can reveal a doublet whereas earlier measurements with NaI(Tl) detectors indicated only a single energy line.

Decay schemes for isotopes are included in refs. 10 and 12. More recent information on certain nuclei can be found in ORTEC's Nuclide Navigator Master Library software package (Model C53-B32).

In Experiment 3, gamma-ray spectroscopy with NaI(Tl) detectors was studied. The typical energy resolution that can be obtained with NaI(Tl) is ~7% for the 0.662 MeV ^{137}Cs gamma line. For NaI(Tl) detectors, the resolution is a strong function of energy. Variations in resolution result primarily from the statistical fluctuation of the number of photoelectrons produced at the photocathode surface in the photomultiplier tube. Table 7.1 illustrates some typical resolutions for NaI(Tl) spectroscopy as functions of the gamma energies.

Table 7.1. Typical Resolutions of NaI(Tl) for Different Gamma Energies

Isotope	Gamma Energy (keV)	Resolution (%)
^{166}HO	81	16.19
^{177}Lu	113	13.5
^{133}Te	159	11.5
^{177}Lu	208	10.9
^{203}Hg	279	10.14
^{51}Cr	320	9.89
^{198}Au	411	9.21
^{7}Be	478	8.62
^{137}Cs	661	7.7
^{54}Mn	835	7.26
^{207}Bi	1067	6.56
^{65}Zn	1114	6.29
^{22}Na	1277	6.07
^{88}Y	1850	5.45

The information for this table was taken from IRE Trans. Nucl. Sci. NS-3(4), 57 (Nov. 1956). "Intrinsic Scintillator Resolution," by G.G. Kelley et al., quoting results from F.K. McGowan,et.al.

The use of germanium detectors has completely revolutionized gamma spectroscopy. Fig. 7.1 illustrates the striking contrast in results obtained with these two types of detectors. There is a factor of 30 improvement in the data at the full-width-half-maximum (FWHM) levels. As the result of this improved resolution, many nuclear energy levels that could not be seen with NaI(Tl) detectors are easily identified with HPGe detectors.

In a parallel fashion, the development of Silicon Lithium-

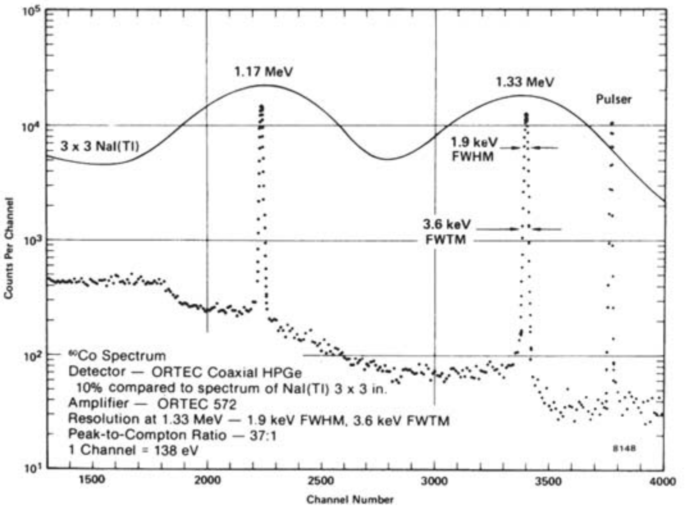

Fig. 7.1. ^{60}Co Spectrum Showing Resolutions and Peak-to-Compton Ratios for an HPGe Coaxial Detector and an NaI(Tl) Detector.

drifted [S(iLi)] detectors has revolutionized x-ray spectroscopy. These Si(li) devices will be studied in Experiment 8.

The purpose of this experiment is to study some of the properties of HPGe detector systems. This experiment deals only with the practical aspects of making measurements with these detectors. To understand the properties of these detector systems, the following brief review of gamma-ray interactions and pair-production processes is included.

In Experiment 3, it was pointed out that the pair-production process at gamma energies >3 MeV is a very important gamma interaction. Fig. 7.2 shows graphs for the three important gamma interactions for both germanium and silicon. The information for germanium is of interest in this experiment; that for silicon will be used in Experiment 8.

When a gamma enters a detector, it must produce a recoil electron by one of three processes before it is recorded as an event: (1) the photoelectric effect, (2) the Compton effect, or (3) pair production.

In the photoelectric process, the gamma or x-ray gives all of its energy to the recoil electron. It is the recoil electron that produces the electron-hole pairs in the detector that yield the output pulse. For the photoelectric process, the output pulse from the detector is proportional to the energy of the gamma or x-ray that produced the interaction. These events will show up as full-energy photopeaks in the spectrum.

In the Compton process, there is a distribution of pulse

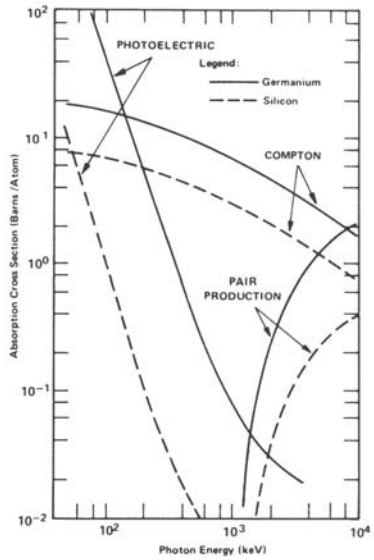

Fig. 7.2. Relative Probability of Each of the Three Types of Interactions as a Function of Energy.

amplitudes up to some maximum pulse height. This maximum pulse height produces the Compton edge, as explained in Experiment 3, and there is a statistical probability that each event has an approximately equal chance to produce a pulse with any height up to this maximum. Thus, Compton events will provide a well-distributed low-energy area in the spectrum.

In large detectors with high peak-to-Compton ratios, some Compton events also contribute to the full energy peak when the scattered photons undergo one or more additional interactions, thus resulting in complete absorption.

The pair-production process can also provide a total absorption of the gamma-ray energy. The gamma enters the detector and creates an electron-positron pair. From the law of conservation of mass and energy, it follows that the initial gamma must have an energy of at least 1.02 MeV because it takes that much energy to create both the negative and positive electrons. The net mass that is produced is two electron masses, and this satisfies the law of conservation of energy, $E = mc^2$.

Note that 1.02 MeV is about twice the annihilation energy that was measured from ^{22}Na (0.511 MeV). Fig. 7.3 illustrates what happens in the detector in the pair-production process. In Fig. 7.3 the e (ordinary electron) will produce a pulse whose magnitude is proportional to the energy of e^- (E_{e^-}). The positron will produce a pulse proportional to E_{e^+}. Since these two pulses are produced simultaneously, the output pulse from the detector would

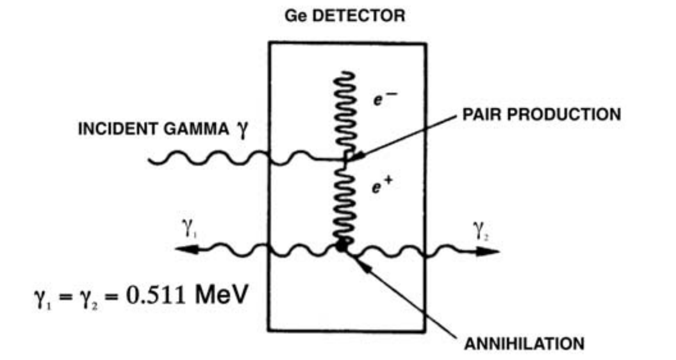

Fig. 7.3. Process of Pair Production in Germanium.

be the sum of the two pulses. When the positron annihilates in the detector, the annihilation radiation γ_1 and γ_2, will be produced. In Fig. 7.3, both γ_1 and γ_2 are shown escaping from the boundaries of the detector without making any further interactions. (Note: $\gamma_1 = \gamma_2 = 0.511$ MeV). Thus, in this example, an energy of exactly 1.02 MeV escapes from the detector and is subtracted from the total energy that entered the detector. It is possible for only one, either γ_1 or γ_2, to make a photoelectric interaction in the detector while the other escapes. In such cases, the total energy absorbed is 0.511 MeV less than the original incident gamma energy. It is also possible for both gammas to make photoelectric interactions without escaping, with all the original energy being left in the detector. Therefore, in the spectrum being measured, there will be three peaks for each gamma energy. These peaks, labeled Full-Energy Peak, Single-Escape Peak, and Double-Escape Peak, will be separated by 0.511 MeV increments. Fig. 7.4 shows a typical spectrum that would be obtained for an incident gamma energy of 2.511 MeV. The lower end of the spectrum that shows the Compton distribution has not been included. This effect is obtained by adjusting the

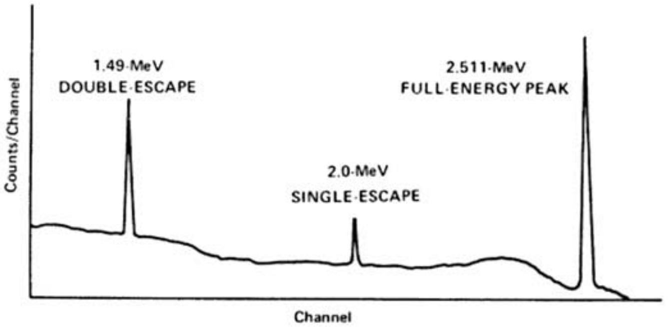

Fig. 7.4. Typical Spectrum for an Incident Gamma Energy of 2.511 MeV.

Lower-Level Discriminator control on the MCA to eliminate the lower energies and adjusting the conversion gain on the MCA to expand the distribution of the higher energy pulses across the range that is measured. The Single-Escape Peak occurs at 2.00 MeV (E_γ – 0.511MeV), and the Double-Escape Peak occurs at 1.49 MeV (E_γ – 1.02 MeV). Of course, the full-energy peak represents those events for which there was a combination of pair production and photoelectric effect in which all the energy was absorbed in the detector.

Now refer again to Fig. 7.2 and specifically to the curves for the interaction in germanium. The absorption cross section, plotted in the y direction, is a measure of the relative probability that an interaction will occur in a germanium detector. These probabilities of relative interactions, for the most part, determine the shape of the observed spectrum. For example, a photon (or gamma) with an energy of 100 keV has an absorption cross section of ~55 barns/atom for the photoelectric process. The corresponding Compton cross section is ~18 barns/atom. There is no pair production. This indicates that, since the approximate ratio of the cross section is 3:1, at 100 keV there are 3 times as many photoelectric interactions as Compton interactions. Fig. 7.5 shows the shape of a spectrum that could be expected for measurement of the 100 keV energy events.

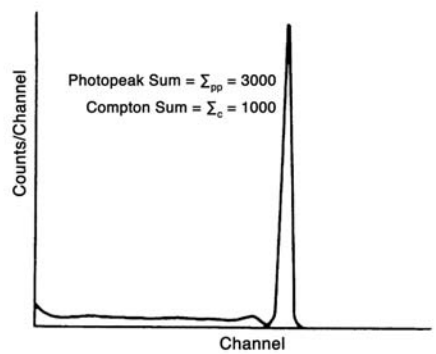

Fig. 7.5. Typical Spectrum Expected for 100-keV Energy in HPGe.

The shape of the spectrum changes drastically from 100 keV to 1 MeV. Fig. 7.6 shows the gamma spectrum that could be expected for the 1 MeV gammas incident on a HPGe detector. From Fig. 7.2 the ratio of Compton cross section to photoelectric cross section is ~90; so, in Fig. 7.6, Σ_c is 90,000 and Σ_{pp} is 1000. The variations of cross sections for HPGe and Si(Li) detectors can also be approximated from Fig. 7.2. For example, at E_γ = 400 keV the photoelectric cross section for germanium is 6 barns/atom and that for silicon is ~0.1 barn/atom. This is a ratio of 60:1 and indicates that there will be 60 times as many counts under the photopeak for a germanium detector as for a silicon detector at 400 keV, assuming that the detectors are the same size. The reason for this is that the photoelectric cross section varies as Z^5, where Z is the atomic number of the absorbing material. The atomic number of Ge is 32 and 14 for Si. The ratio of these two numbers raised to the 5th power is 62.22, which is within remarkable agreement with the above cross-section ratios.

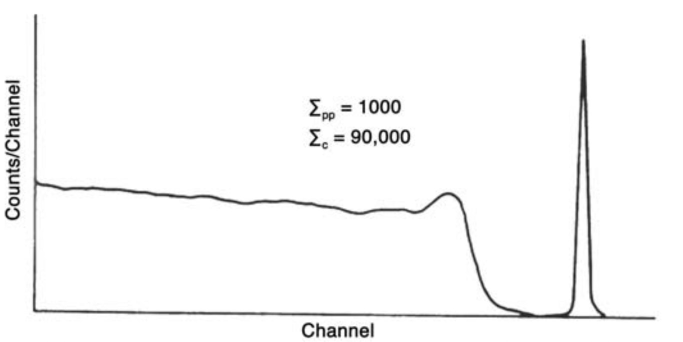

Fig. 7.6. Typical Spectrum Expected for 1-MeV Energy in HPGe.

EXPERIMENT 7.1
Energy Resolution with a HPGe Detector

The instructor will provide the HPGe detector and instructions for its use. Before attempting to use the detector, carefully read the the instruction manual.

This is a very expensive detector system and must be handled very carefully.

Procedure

1. Install the 659, 480 and 672 in the 4001A/4002D NIM bin and power supply and interconnect the modules as shown in Fig. 7.7. The preamplifier is mounted as an integral part of the HPGe detector and the interconnect for the signal connections to the detector is made through the preamplifier. Connect the 659 to the Detector Bias Input, the Auto HV shutdown cable to the HV shutown output , and the 480 to the Test input on the preamplifier. Connect the preamplifier power cable to the Preamplifier Power connector on the rear of the 672 amplifier. Connect a signal output from the detector to the Positive Input of the 672 amplifier. Connect the Unipolar Output from the 672 to the ADC input of the TRUMP MCA.

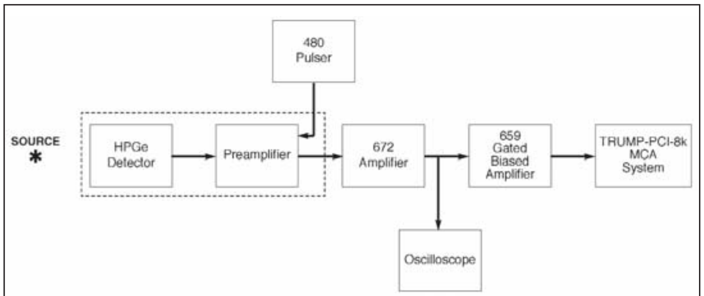

Fig. 7.7. Electronic Interconnections for Experiment 7.1

Set the module controls as follows:

672 Amplifier: Unipolar output; Shaping Time 6 µs; Delay Out.

480 Pulser: Attenuated Output

659 0–5 kV Detector Bias Supply: Leave at zero until all other connections have been made; consult the instructions for the HPGe detector to determine both the bias polarity and amplitude required for the detector; apply the correct bias in the correct polarity when ready to operate the detector.

2. Place the ^{60}Co source from the gamma source kit ~1 cm from the face of the detector. Adjust the gain of the 672 Amplifier so that the 1.332 MeV gamma has an amplitude of 6 V at the amplifier unipolar output. The two lines for 1.172 and 1.332 MeV should be quite easily seen on the oscilloscope.

3. Start acquisition on the MCA and observe the spectrum. Adjust the 672 gain until the two sharp photopeaks are positioned as shown in Fig. 7.8. In this measurement the two photopeaks should be separated by at least 200 channels, based on a MCA conversion gain of 1024 channels total.

4. From the positions of the two photopeaks, make a calibration curve of energy (y direction) vs. channel number (x direction) and determine the keV per channel.

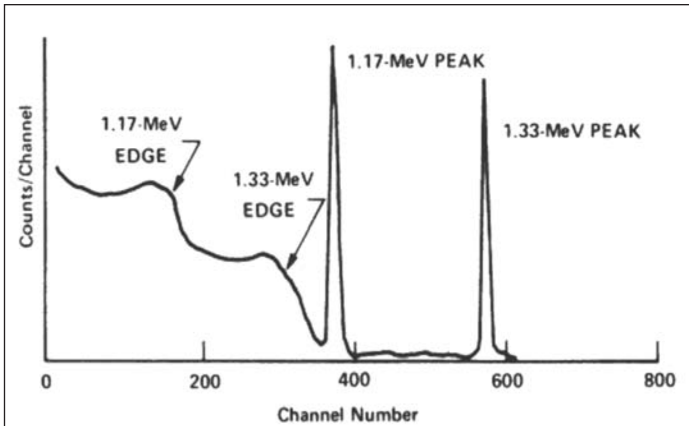

Fig. 7.8. Locating the Two Photopeaks for ^{60}Co in the HPGe Spectrum.

EXERCISES

a. What is the resolution in keV for the two photopeaks? How does this compare in value with the detector's resolution specifications?

b. From the data, determine the energies of the Compton edges for the two gammas. How do these compare with the values that were calculated from the formula used in Experiment 3?

5. Turn on the 480 Pulser and adjust the output so that the pulser peak falls about half-way between the 1.17 and 1.33 MeV peaks. After the pulser has produced 1000 counts in its peak channel, read that portion of the analyzer memory and determine resolution, R(E). The contribution by the detector to the overall resolution can be calculated from the formula

$$\text{system resolution} = \sqrt{[R(d)]^2 + [R(E)]^2} \qquad (1)$$

where R(d) is the detector resolution and R(E) is the electronic resolution. These resolutions are said to add in quadrature. There is a lower limit to R(d) which is energy-dependent. The recoil electron produced in the gamma interaction loses energy in the HPGe detector by dE/dx. The average energy required to produce an ionization in germanium is 2.95 eV/electron-hole pair. Thus for a 1.5 MeV recoil electron there would be 5.08×10^5 electron-hole pairs produced. The production of electron-hole pairs is a statistical process; hence there are fluctuations in the actual number produced. When the proper statistics are used, the theoretical lower limit to R(d) is given by

$$R(d) = K\sqrt{F \bullet E} \qquad (2)$$

where K is a constant, E is the energy of the photon in MeV, and F is the statistical Fano factor. To a very good approximation this equation reduces to

$$R(d)\ (\text{in keV}) = 1.35\sqrt{E\ (\text{in MeV})} \qquad (3)$$

Solving Eq. (3), the theoretical lower limit of detector resolution is 1.44 keV for a 1 MeV gamma and 4.5 keV for a 10 MeV gamma.

EXERCISES

c. Calculate the values of R(d) from Eq. (3) for the values of E in Table 7.2

d. Make a plot of the values from Table 7.2 on linear graph paper. From Eq. (1), calculate the experimental R(d) for the 1.33 MeV peak of ^{60}Co. How does this compare with the theoretical limit? Remember that the

Table 7.2

Energy (MeV)	Theoretical *R(d)* (keV)
0.1	
0.3	
0.5	
1.0	
3.0	
6.0	
8.0	
10.0	

R(d) theory is the absolute lower limit of the resolution value.

EXPERIMENT 7.2
Photopeak Efficiency for HPGe Detectors

Resolution with HPGe detectors is better by a factor of 30 or more than that obtained with conventional NaI(Tl) detectors. This dramatic increase in resolution is sometimes coupled with a compromise of the photopeak efficiency because the pricing of HPGe detectors is related to their photopeak efficiency. The standard method for comparing the efficiencies of HPGe detectors with NaI(Tl) detectors is to compare their counting rates at the 1.332 MeV line of ^{60}Co, using a standard distance of 25 cm from the source to the detector face and placing the source on the detector axis.

The resolution of HPGe detectors is so many times better than that of the NaI(Tl) that the ability to see a photopeak above the Compton distribution is remarkably enhanced. Consider a simple example in which the efficiencies of the HPGe and NaI(Tl) are assumed to be the same. In a particular experiment, we observe 10,000 counts under the photopeak for each detector. If the resolution of the HPGe detector is only 10 times that of the NaI(Tl) detector, the HPGe detector will have 10 times the maximum number of counts that the NaI(Tl) detector has, because the area under the photopeak (10,000 in this example) is approximately proportional to the width times the height of the peak. Since the width of the HPGe peak is only 1/10 the width of the NaI(Tl) peak, its height must be 10 times as great.

This example can easily be extrapolated to real situations where the advantages of superior resolution are very important. For example, Fig. 7.9 shows the striking differences for a spectrum obtained on a mixed sample of ^{76}As, ^{122}Sb, and ^{124}Sb with each of the two types of detectors. Each of the closely spaced energy lines is shown separately in the HPGe spectrum while they are all included in a single broad photopeak in the NaI(Tl) spectrum.

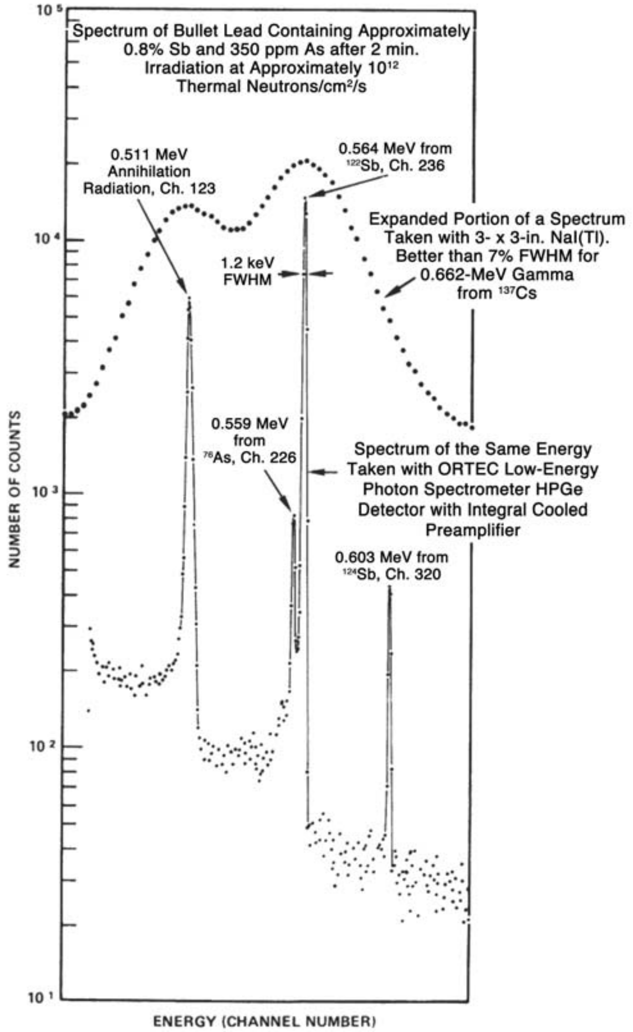

Fig. 7.9. Comparative Spectra Taken with HPGe and NaI(Tl) Detectors.

In this experiment, we will measure some of these photopeak efficiencies and also determine the peak-to-Compton ratio for a HPGe detector.

Procedure

1. Use the same equipment setup that was used for Experiment 7.1. Adjust the 672 gain and the MCA conversion gain for a ^{60}Co spectrum similar to that of Fig. 7.10.

2. Accumulate the spectrum in the MCA for a time period long enough to determine heights h_1 and h_2 to a fair degree of accuracy. In Fig. 7.10, h_1 is the 1.332 MeV photopeak and h_2 is the maximum for the comparable Compton distribution, normally located just below the Compton edge. Read the data from the MCA.

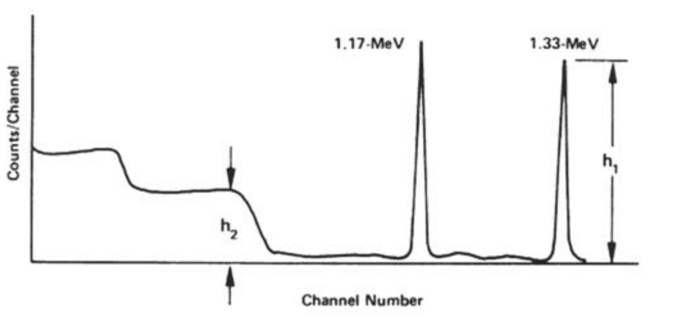

Fig. 7.10. Typical Distribution of ^{60}Co Spectrum for Experiment 7.2.

EXERCISE

a. Calculate the peak-to-Compton ratio in Fig. 7.10, which is h_1 divided by h_2. Compare your value with the value for this detector. Check with your laboratory instructor for the record of the ratio.

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3. Clear the spectrum from the MCA. Place a 10-µCi ^{60}Co source at a distance of exactly 25 cm from the face of the detector.

4. Accumulate a spectrum for this source of ~3000 counts under the 1.332 MeV photopeak. Read the data from the MCA; be sure to record the live time for the measurement.

EXERCISES

b. Calculate the number of counts per second for the events that were recorded in the 1.332 MeV photopeak; call this R_1:

$$R_1 = \frac{\Sigma_{pp}}{\text{time in seconds}} \qquad (4)$$

c. The rate, R_1 from Eq. (4) is to be compared with the rate, R_2, that is expected for the same source when it is located 25 cm from the face of a 3-in. x 3-in. NaI(Tl) detector. The efficiency of this size NaI(Tl) detector for a source-to-detector distance of 25 cm is given as 1.2×10^{-3}, (from "Gamma Ray Spectrum Catalog" by R. L. Heath, Idaho Falls Report IDO-16880). Using ε1 for this number, the number of counts, (N), that you would observe under the photopeakfor a 3-in. x 3-in. NaI(Tl) detector at 25 cm source distance is given by

$$N = \varepsilon_1 A t \qquad (5)$$

where A is the gamma activity of the source in counts per second and t is the live time in seconds. The rate R_2 will then be

$$R_2 = \frac{N}{t} = \varepsilon_1 A \qquad (6)$$

Since ^{60}Co has a 1.332 MeV gamma ray for each decay, A is given by

$$A = 3.7 \times 10^4 \ (x) \quad (7)$$

Calculate R_2 from Eq. (6). The relative photopeak efficiency is obtained for the detector by

$$\text{relative photopeak efficiency} = \frac{R_1}{R_2} \times 100 \quad (8)$$

Calculate this value for your measurement and compare it with the value that is recorded for the detector. Check with your laboratory instructor for the record of the detector's efficiency.

EXPERIMENT 7.3
Escape Peaks and Efficiency for HPGe Detectors

As discussed earlier, when an incident gamma with sufficient energy enters the crystal it can create an electron-positron pair. When the positron annihilates, two gammas with equal energy at 0.511 MeV are produced which leave with an angular separation of 180°. In Fig. 7.3, these two gammas are shown as γ_1 and γ_2. For small detectors, it is very probable that both γ_1 and γ_2 will escape from the detector before they make any further interactions in the crystal. The energy thus absorbed would be $E\gamma$ – 1.02 MeV, and is shown as the Double-Escape Peak in Fig. 7.4. As the detector size increases, the probability is greater that either γ_1 or γ_2 will make a photoelectric interaction within the crystal. If one of these gammas does make a photoelectric interaction, the energy of the event that is recorded in the detector is the Single-Escape Peak in Fig. 7.4. For even larger detectors, the probability of photoelectric interactions is even greater when both γ_1 and γ_2 interact and the total energy of the gamma is absorbed in the crystal.

Fig. 7.11 shows some measurements that have been made for coaxial and planar HPGe detectors. From this figure, the ratios of Full-Energy, Double-Escape Peak, and Single-Escape Peak efficiencies can be determined by inspection for the size of detector that is identified in the figure.

To see how the measurements were made for Fig. 7.11, consider the $E\gamma$ of 2.511 MeV shown in Fig. 7.4. Assume that the Compton distribution has been subtracted for each peak in Fig. 7.4, and that the following sums have been measured:

Σ at Full Energy, 2.511 MeV = 6000,
Σ at Single-Escape, 2.00 MeV = 1000
Σ at Double-Escape, 1.489 MeV =3000.

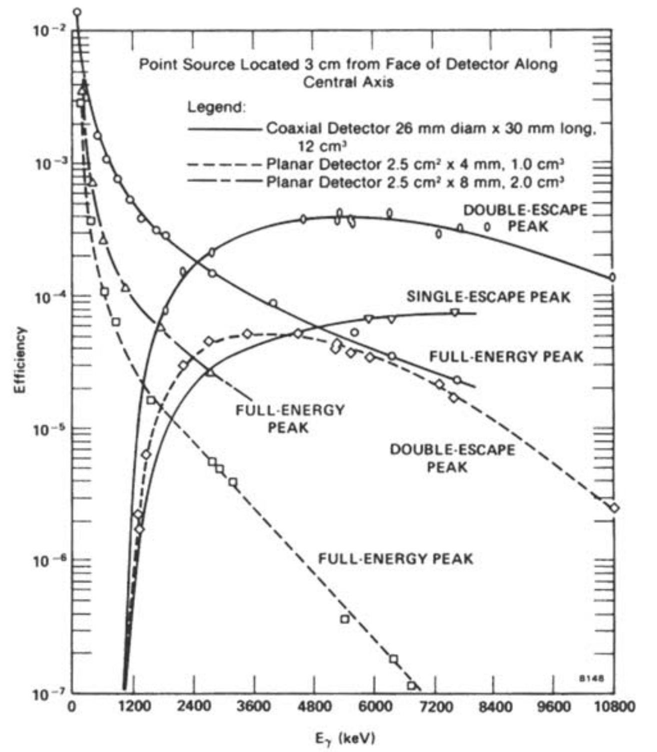

Fig. 7.11. Measured Efficiencies for HPGe Detector.

From these numbers the simple ratios can be obtained.

Procedure

1. Use the same equipment setup that was used for Experiment 7.1. Use the ^{60}Co and ^{137}Cs sources from the gamma source kit. Adjust the gain on the 672 and the conversion gain on the MCA to calibrate the analyzer to roughly 1 to 3 MeV.

2. Remove the energy calibration sources and use a ^{228}Th (or other high-energy source) to accumulate a spectrum. Accumulate for a period of time long enough to see all the pronounced peaks in the spectrum. Read the data from the MCA.

EXERCISES

a. Plot the spectrum on semilog graph paper. On the plot, identify all the major peaks and the corresponding escape peaks. Compare the energies at these peaks with those that are identified with the source.

b. Calculate the escape peak ratios. Define Σ_f as the sum of counts under the full-energy peak, Σ_1 as the sum under the single-escape peak, and Σ_2 as the sum under the double-escape peak. Be sure to subtract the Compton distribution from these sums; then determine the ratios Σ_f/Σ_1, Σ_f/Σ_2, and Σ_2/Σ_1. How do these ratios compare with those the laboratory instructor has for the ^{228}Th source and the detector you are using?

EXPERIMENT 7.4
The Response of HPGe Detectors to High-Energy Gammas

(Optional. Recommended if Experiments 16, 17, or 18 are to be done.)

If an isotopic neutron source of the Am-Be type is available, it is possible to obtain high-energy gammas from this source. The neutrons from the source are produced by

$$^{9}Be + \alpha \rightarrow {}^{12}C + n \qquad (9)$$

The Q value for the reaction is ~5 MeV. Since the alpha energies from most sources are also ~5 MeV, it is possible to produce neutrons with these sources up to 10 MeV. The neutron spectrum from these sources shows a distribution of neutron energies up to this maximum energy. More importantly, in the reaction it is also possible for ^{12}C to be left in an excited state. The de-excitation of ^{12}C is by gamma emission. Gammas from the second excited state of ^{12}C have an energy of 7.656 MeV and make an excellent source of high-energy gammas.

Procedure

1. Use the same equipment setup that was used for Experiment 7.1. Use the ^{60}Co source and the pulse generator to adjust the gain of the system so that the MCA range is ~3 to 8 MeV.

2. Use a block of paraffin ~6-in. thick between the detector and the neutron source, and place the source ~12-in. from the detector. The paraffin will thermalize the neutrons from the source without attenuating the high-energy gammas. In some cases the neutron source is in a paraffin howitzer. If this is the case, place the source close to the outside of the howitzer.

3. Accumulate a spectrum. This will require several hours and sometimes overnight runs are necessary. Read the data from the MCA.

EXERCISE

a. Plot the spectrum on semilog graph paper and identify all the peaks. As in Experiment 7.3, calculate the ratios Σ_f/Σ_1, Σ_f/Σ_2, and Σ_2/Σ_1.

For your reference. Fig. 7.12 is a plot on linear graph paper of a typical neutron source with an iron scatterer. The reaction is ^{56}Fe(n,γ)^{57}Fe, which yields two high-energy gammas from the ^{56}Fe scatterer. The main photopeak energies are 7.639 and 7.625 MeV.

The resolution of a gamma line is dependent on the gamma energy of the peak. The student can easily verify this by measuring the resolution of the detector for the sources available in the laboratory. Fig. 7.13 shows the spectral response and resolution of several common sources for an HPGe detector.

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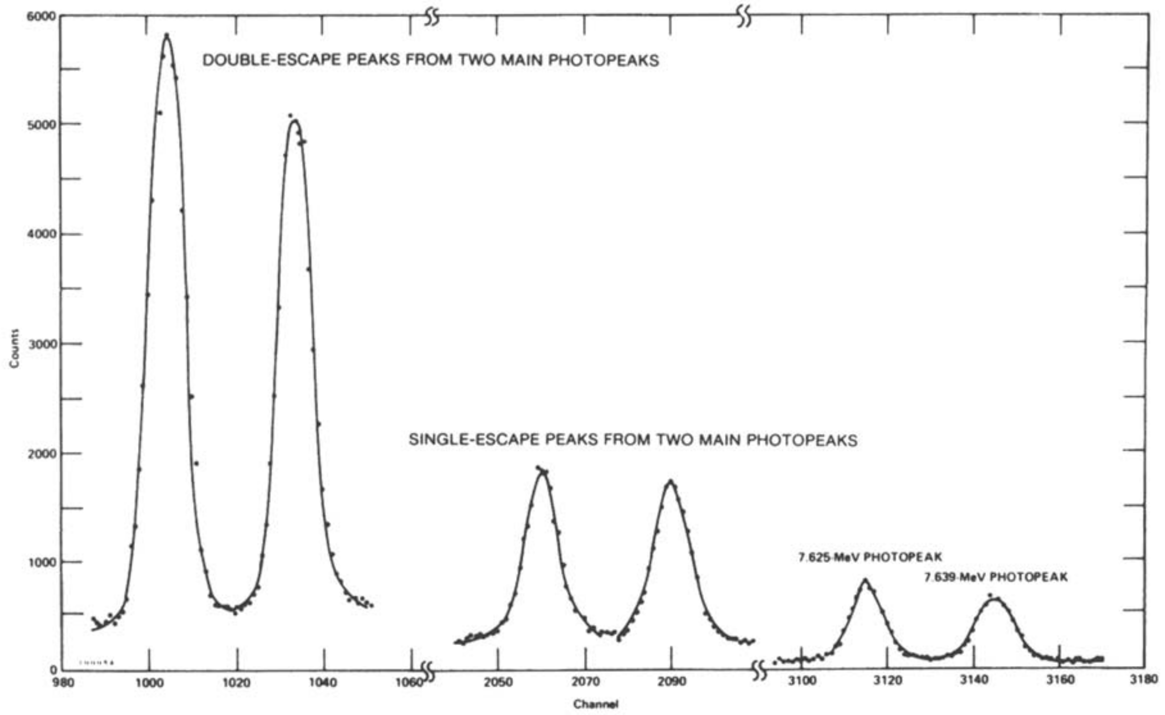

Fig. 7.12. Typical High-Energy Gamma Spectrum from a Neutron Source with Iron Scatter.

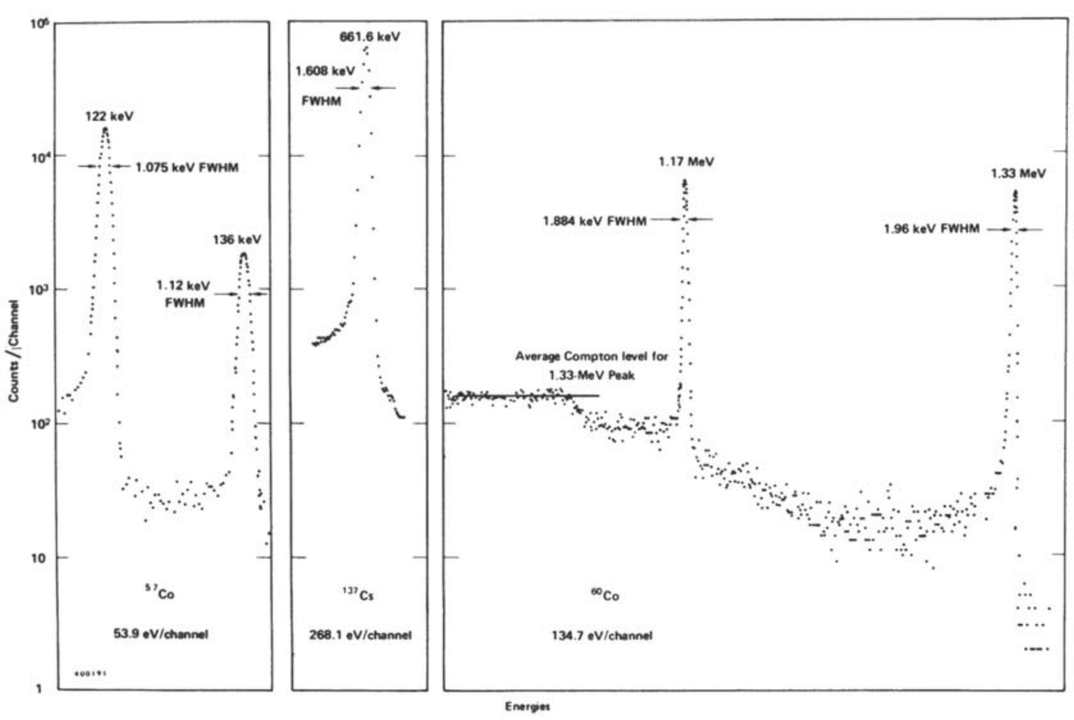

Fig. 7.13. Typical Spectral Response of an ORTEC HPGe Detector to Various Gamma-Ray Energies.