Laboratory Manual:
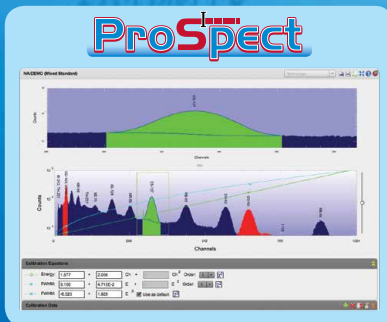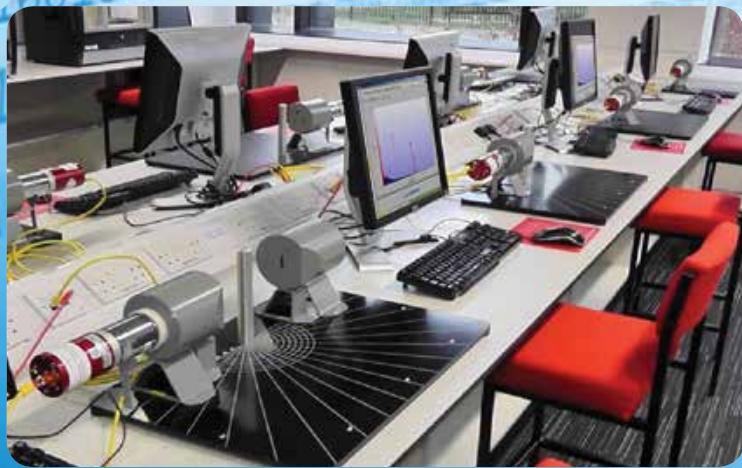
Nuclear Science Experiments with Digital Electronics

NUCLEAR MEASUREMENT SOLUTIONS FOR SAFETY, SECURITY & THE ENVIRONMENT

α β γ n

CANBERRA

WWW.CANBERRA.COM

Table of Contents

List of Contributors:

James Cocks, Ph. D. in Nuclear Physics, University of Liverpool, 1996.
Gabriela Ilie, Ph.D. in Nuclear Physics, University of Köln, 2008.
Henrik Jäderström, Ph.D. in Nuclear Physics, Uppsala Universitet, 2008.
Wilhelm Mueller, Ph.D. in Nuclear Physics, University of Tennessee, 1997.
Babatunde Oginni, Ph.D. in Nuclear Physics, Ohio University, 2009.
Amol Patil, Ph.D. in Nuclear Engineering, Missouri University of Science and Technology, 2010.
Ramkumar Venkataraman, Ph.D. in Nuclear Engineering, University of Michigan, 1995.
Professor Paul Nolan, University of Liverpool
Dr Andrew Boston, University of Liverpool

www.canberra.com

→ Foreword

The purpose of this laboratory manual is to describe nuclear physics experiments utilizing the latest counting electronics that are in broad use in today's industry.

The goal is to deliver highly productive training in the fundamentals of nuclear physics while providing the student with hands-on experience that is of vocational relevance.

The experiments are built around the Osprey™ and Lynx® Digital Signal Analyzers. The versatility of these instruments enables the performance of fundamental experiments in high-and low-medium resolution gamma spectroscopy and neutron counting. Their advanced features allow for higher-level experiments, such as coincidence and anti-coincidence, with both hardware gating and event-by-event data.

The Osprey and Lynx are easy to use and feature highly-stable digital electronics, thereby providing the optimum solution for laboratory instruction. The devices are controlled with ProSpect™ Gamma Spectroscopy Software which includes a flexible security feature to ensure that the student is only presented with the functions required for the class. This increases the productivity of the training.

The format of each experiment is consistent across the manual, beginning with the goal and the equipment required. Each description includes the required steps together with the format of the data entry and the results. It is envisaged that, in some cases, the instructor may wish to produce his or her own laboratory script with this as a starting point.

A relatively modest investment yields a flexible equipment package that can serve undergraduate and post-graduate university training in addition to in-house training for industrial users.

The experiments described in this manual are performed using two packages available for purchase:

1 **LABKIT-Basic:** for Experiments 1-5

2 **LABKIT-Advanced:** for Experiments 6-12 (also requires LABKIT-Basic)

Contact CANBERRA for more information.

CANBERRA

→ Precautions with Radioactive Sources

Several types of radioactive sources are required to perform the experiments described in this Laboratory Manual. These include both sealed and unsealed sources with a range of activity. When working with radioactive sources, utilize the three basic principles of ALARA, either individually or in combination:

ALARA – As Low As Reasonably Achievable

Time: The simplest way to reduce exposure is to keep the time spent around a radioactive source to a minimum. If time is cut in half, so is the exposure, with all the other factors remaining constant.

Distance: Distance is another effective means to reduce radiation exposure. A formula known as the "inverse square law" relates the exposure rate to distance. Doubling the distance from a radioactive source reduces the exposure to one-fourth its original value. If the distance is tripled, the exposure is reduced by a factor of nine.

Shielding: Shielding is any material used to reduce the radiation reaching the user from a radioactive source. While a single sheet of paper may stop some types of radiation such as alpha particles, other radiation such as neutrons and photons require much more shielding. Dense materials, such as lead or steel, are used to shield photons. Materials containing large amounts of hydrogen, such as polyethylene, are used to shield neutrons.

Generally speaking, radioactive sources prepared for educational use are of two types:

1 Solid sources in which the radioactive material is deposited in a plastic disk and sealed inside with a durable epoxy.

2 Unsealed sources packaged in small vials, supplied in solution form.

For each, the immediate container for the radioactive material will bear a label identifying the radioisotope, the quantity of activity, and the warning "radioactive material".

Solid sealed sources are typically easier to use and account for than sealed sources. Because they usually contain radioactive isotopes with long half-lives, they can be reused year after year. Additionally, one is not faced with possible spills and decontamination when using solid sealed sources. Sealed sources of low activity, such as a gamma source of 1 µCi (or 37 kBq) or less, can be handled directly without significant risk, although it is good practice to utilize tongs. More active sealed gamma sources, such as 10 µCi (or 370 kBq) or more, should only be handled with tongs.

Liquid sources or unsealed sources are required for certain experiments and pose a greater risk for contamination and ingestion. Thin rubber or disposable gloves should always be worn when handling liquid sources, and it is also a good practice to work over a tray lined with absorbent paper when using these solutions.

Storage

Because of the low levels of activity used in student sources, storing these radioactive materials is a relatively simple matter. Solid sealed sources can be safely stored in the original plastic containers in which they are received. Liquid sources are normally received in plastic vials surrounded by packing material. These containers are sufficient for the safe storage of radioisotopes. It is recommended that all radioactive materials be kept in one specific and secured place, such as in the instructor's preparation room and in a locked cabinet. This cabinet can be lined with lead sheets or bricks if additional shielding is necessary. Any storage cabinet, locked drawer, or lead isotope container should be properly labeled with approved radioactive material warning labels. Conducting a frequent inventory of sources is also a good procedure to follow.

Disposal

The very fact that radioactive materials decay with time can be a most effective method of disposal. Dilution and burial are two other often-used methods. Solid radioactive waste which may accumulate in the laboratory includes materials such as empty radioisotope vials, disposable gloves, syringes, and absorbent paper. These often result in exempt quantities of radioisotopes, which can generally be safely disposed of with the routine laboratory trash. It is normal practice in radioisotope laboratories to pour all liquid waste into a single wide-mouth bottle labeled "radioactive liquid waste". This waste can be held by the teacher for as long as possible in order to allow for normal decay. For both solid and liquid radioactive waste, consult with your local regulatory authority regarding proper and safe disposal in the development of your protocols.

A word of CAUTION!

Never wear the same rubber gloves while operating your counting instrument, as any contamination on the glove could be transferred to the instrument. No food or drink is ever to be permitted in a radioactive laboratory. Another good habit to acquire is never allowing the hands to touch any other part of the body, or another individual, while working with liquid sources.

→ Equipment Matrix

Model	Description	Experiment 1	2	3	4	5	6	7	8	9	10	11	12
Osprey-ProSpect	ProSpect Gamma Spectroscopy Software	B	B	B	B	B	B	B	B	B	B	B	B
	Osprey Digital Tube Base	B	B	B	B	B				B	B		
802-2x2	NaI Detector 2" x 2"	B	B	B	B	B	B			B	B		
LABKIT-Table	Teaching Laboratory Scattering Table Assembly (Includes Table, NaI Detector Shielding, Source Collimation, and Scattering Pillar)	B	B	B	B	B	B		B	B	B		
LABKIT-ABS	Teaching Laboratory Absorber Set			B								B	B
LABKIT-SR-Cs137	^{137}Cs source compatible with Scattering Table Assembly				B								
Radioisotopes (provided separately)	^{137}Cs button source 1 microcurie, ±20% unc	S	S	S			S	S	S	S			
	^{22}Na button source 1 microcurie, ±20% unc			S						S	S		S
	^{60}Co button source 1 microcurie, ±20% unc	S						S	S				S
	^{57}Co button source 1 microcurie, ±20% unc			S				S					
	^{88}Y button source 1 microcurie, ±20% unc	S											
	^{152}Eu reference standard ±5% unc								S			S	S
	Irradiated Vanadium Foils (requires Neutron source) or ^{137m}Ba Isogenerator					S							
	Unknown volumetric sample (such as Marinelli Beaker)											S	
2007P	Photomultiplier Tube Base/Preamplifier						A			A	A		
RCP-CABLE-10	CP Preamp 10 FT. Cable Set						A	A	A	A	A	A	A
Lynx-MCA	Lynx-Digital Signal Analyzer						A	A	A	A	A	A	A
BE2825	BE2825 Broad Energy Germanium Detector System with ISOCS Characterization and RCP-Cable-10									A			
LABKIT-SRCEHLD	Set of Two HPGe Source Holders							A	A	A		A	A
802-2x2	Extra 802 2x2 NaI Detector 2" x 2"									A	A		
LABKIT-NAICOLL	Extra 802 2x2 NaI Detector Shielding									A	A		
S574	LabSOCS Mathematical Efficiency Calibration Software											A	A

→ **B** Base experiment package

Model LABKIT-Basic
- > Osprey-ProSpect
- > 802-2x2 NaI Detector
- > LABKIT-Table
- > LABKIT-Abs

Model LABKIT-SR-Cs137
- > LABKIT-SR-Cs137

→ **S** Sources purchased separately
- > ^{137}Cs (Experiment 1, 2, 3, 6, 7, 8, 9)
- > ^{22}Na (Experiment 3, 9, 10, 12)
- > ^{60}Co (Experiment 1, 7, 8, 12)
- > ^{57}Co (Experiment 3, 7)
- > ^{88}Y (Experiment 1)
- > ^{152}Eu (Experiment 8, 11, 12)
- > Neutron Source + Vanadium Foils OR ^{137m}Ba Isogenerator (Experiment 5)

→ **A** Additional advanced package

Model LABKIT-Advanced
- > BE2825 HPGe Detector System
- > Lynx-MCA
- > 802-2x2 NaI Detector
- > LABKIT-SRCEHLD
- > LABKIT-NAICOLL
- > S574 LabSOCS Software
- > 2007P Preamplifier
- > RCP-10-CABLE

Experiment ①

Gamma-Ray Detection with Scintillator Detectors

→ Purpose:

① To demonstrate the use of a NaI scintillator detector and its response to gamma rays.

② To demonstrate the three dominant gamma-ray interactions with matter.

③ To demonstrate energy calibration.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base MCA with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc
Radioisotope:	^{60}Co button source 1 microcurie, ± 20% unc
Radioisotope:	^{88}Y button source 1 microcurie, ± 20% unc
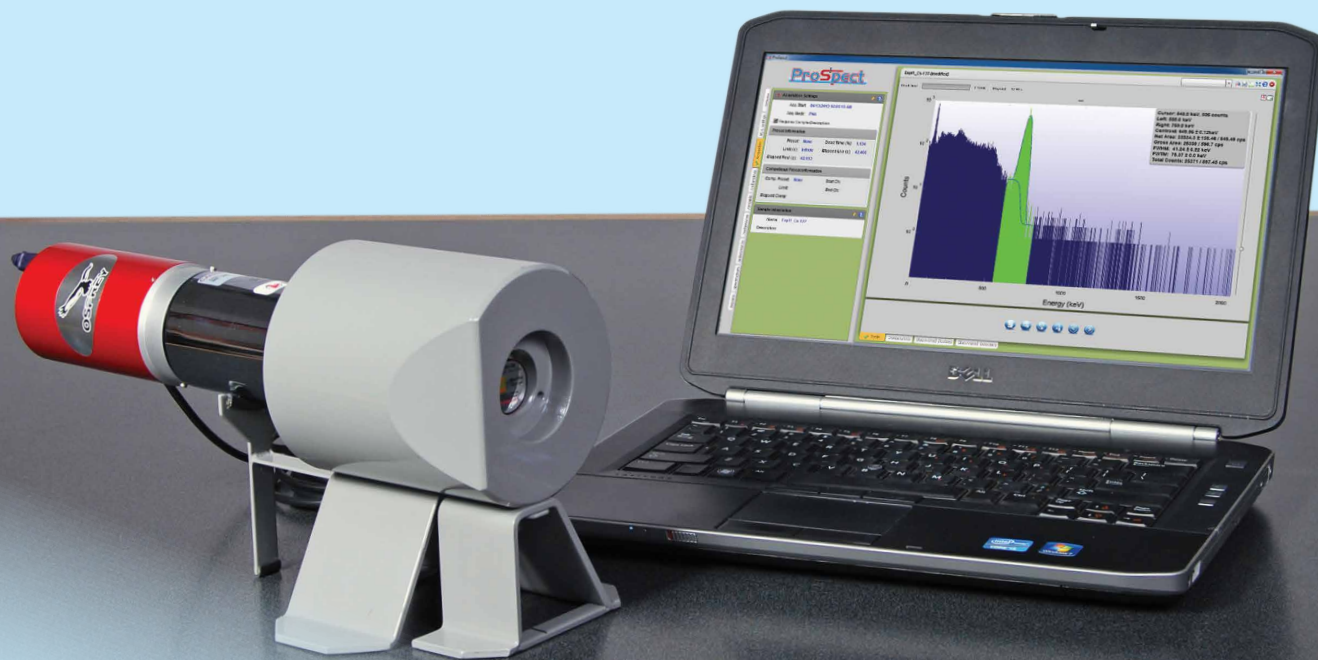
→ Theoretical Overview:

How gamma rays are produced

Radioactive nuclei decay by emitting beta or alpha particles. Often the decay is to an excited state in the daughter nucleus, which usually decays by emission of a gamma ray. The energy level sequence and therefore the gamma-ray energy spectrum for every nucleus is unique and can be used to identify the nucleus. The energy levels and decay process of ^{22}Na, ^{60}Co and ^{137}Cs are given in Figure 1-1. The term beta decay means β- (electron), β+ (positron) emission or electron capture by the nucleus.
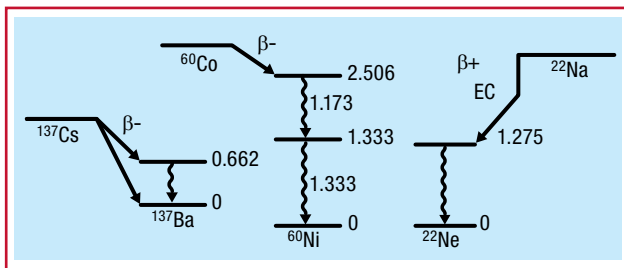
Figure 1-1:
Energy level sequences for ^{137}Cs, ^{60}Co and ^{22}Na (energy levels in MeV)

NaI(Tl) detectors

The thallium-activated sodium iodide detector, or NaI(Tl) detector, responds to the gamma ray by producing a small flash of light, or a scintillation. The scintillation occurs when scintillator electrons, excited by the energy of the photon, return to their ground state. The detector crystal is mounted on a photomultiplier tube which converts the scintillation into an electrical pulse. The first pulse from the photocathode is very small and is amplified in 10 stages by a series of dynodes to get a large pulse. This is taken from the anode of the photomultiplier, and is a negative pulse.

The NaI(Tl) crystal is protected from the moisture in the air by encasing it in aluminum, which also serves as a convenient mounting for the entire crystal/photomultiplier unit. A schematic is shown in Figure 1-2.
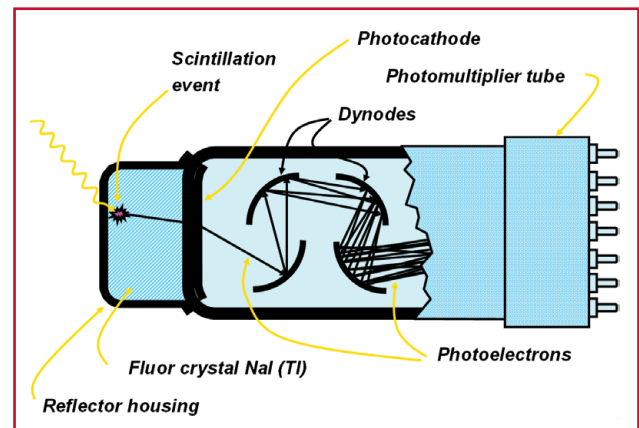
Figure 1-2:
Illustration of a scintillation event in a photomultiplier tube

Gamma-ray interactions with matter

There are three dominant gamma-ray interactions with matter:

1. **Photoelectric effect**
2. **Compton effect**
3. **Pair production**

The photoelectric effect is a common interaction between a low-energy gamma ray and a material. In this process the photon interacts with an electron in the material losing all of its energy. The electron is ejected with an energy equal to the initial photon energy minus the binding energy of the electron. This is a useful process for spectroscopy since an output pulse in a detector is produced that is proportional to the gamma-ray energy, as all of the energy of the gamma ray is transferred to the detector. This produces a characteristic full-energy peak in the spectrum that can be used for the purpose of identifying the radioactive material.

The photon can scatter by a free electron and transfer an amount of energy that depends on the scattering angle. This process is called Compton scattering. The energy of the scattered photon E' is:

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}(1 - \cos\theta)}$$ *Equation 1-1*

where E is the incident gamma-ray energy and θ is the angle of scatter. The term $m_0 c^2$ is the rest mass of the electron, equal to 511 keV. The energy given to the electron is:

$$E_e = E - E'$$ *Equation 1-2*

The maximum energy given to an electron in Compton scattering occurs for a scattering angle of 180°, and the energy distribution is continuous up to that point (since all scattering angles up to 180° are possible). This energy, known as the Compton edge, can be calculated from the incident gamma ray energy.

For θ = 180°:

$$E' = \frac{E}{1 + \frac{2E}{m_0 c^2}}$$ *Equation 1-3*

and:

$$E_e = E - E' = E - \left[\frac{E}{1 + \frac{2E}{m_0 c^2}}\right]$$ *Equation 1-4*

The spectrum for ^{137}Cs shows that if the gamma ray scatters and escapes the crystal then the energy deposited will be less than the full-energy peak (see Figure 1-3).

Theoretical Overview

Continued

The actual energy deposited depends upon the angle of scatter as described in the equations above. The spectrum shows that many pulses have energies in a range below the Compton edge – called the Compton Continuum.

If the gamma ray does not escape the crystal and scatters again giving up its remaining energy through the photoelectric effect, then its full energy will be deposited in the full-energy peak (at 662 keV for ^{137}Cs). This is more likely for larger crystals.

Pair production can occur when the gamma-ray energy is greater than 1.022 MeV and is a significant process at energies above 2.5 MeV. The process produces a positron and electron pair that slow down through scattering interactions in the material. When the positron comes to rest, it annihilates with an electron producing a pair of 511 keV gamma rays that are produced back-to-back. These can be absorbed through the photoelectric effect to produce full-energy peaks at 511 keV. A component due to Compton scattering can also be observed. When a photon interacts with the crystal through pair production, one or both of the annihilation photons can escape undetected from the crystal. If one of the photons escapes undetected, then this will result in a peak in the spectrum at an energy of 511 keV less than the full-energy peak. This is called the single escape peak. Similarly, if both photons escape undetected, a peak will appear 1022 keV below the full-energy peak, called the double escape peak.
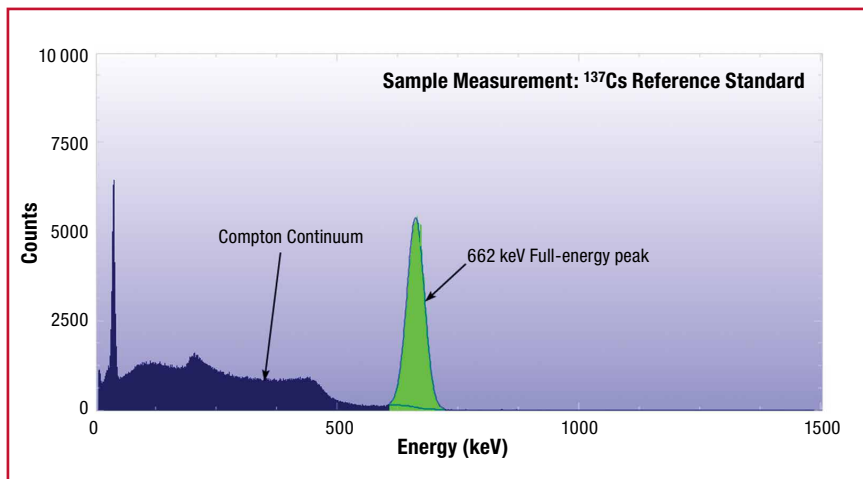
Figure 1-3:
Example spectrum of a ^{137}Cs source

→ **Experiment** **1** **Guide:**

Photoelectric effect and Compton scattering

1. Ensure that the Osprey (with the NaI(Tl) detector connected) is connected to the measurement PC either directly or via your local network.

2. Place the ^{137}Cs source in front of the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Osprey.

4. Adjust the MCA settings to correspond with those listed in Table 1-1. It is recommended to use these settings throughout this manual unless otherwise specified.

5. Use the software to apply the recommended detector bias to the NaI(Tl) detector.

6. Set the amplifier gain such that the photopeak is close to 40% of the full range of the spectrum.

7. Acquire a spectrum (use a count time such that there are at least 10 000 counts in the photopeak).

8. Use annotations (using the right click menu) to identify the Photopeak, the Compton Continuum and the Compton Edge.

9. Copy the spectrum to clipboard and paste into a Word document (provide an appropriate caption for the spectrum).

10. Save the spectrum.

Table 1-1:
Standard Gain and Filter Settings for NaI 2x2 with Osprey or Lynx MCA

Parameter	Setting
Acquisition Mode	PHA
LLD Mode	Automatic
LLD %	0.1
Polarity	Positive
ULD %	100.0
BLR Mode	Automatic
Fast Disc Shape	Normal
Fast Disc Mode	Automatic
Manual Fast Disc	1.0
Rise Time	1.0
Flat Top	1.0
PUR Guard	1.1
Conversion Gain	2048

Pair production

11. Clear the spectrum.

12. Replace the ^{137}Cs source with a ^{88}Y source.

13. Acquire a spectrum (use a count time such that there is at least 10 000 counts in each photopeak).

14. Use annotations (using the right click menu) to identify the 898 keV and 1836 keV full-energy peaks. Also Identify the single escape peak from 1836 keV, which should have an energy of 1836 – 511 = 1325 keV.

15. Copy the spectrum to clipboard and paste into a Word document (provide an appropriate caption for the spectrum).

16. Save the spectrum.

Energy calibration

17. Load the ^{137}Cs and ^{88}Y spectra.

18. By left-click dragging a region of interest across each peak, determine the centroid channel for the 662 keV, 836 keV and 1836 keV full-energy peak. Note down the centroid channel and uncertainty for each peak as presented by the tooltip in ProSpect.

19. Using Microsoft Excel or another spreadsheet or graphing application, enter the energy, channel and the uncertainty in channel. Plot the energy vs. channel (with channel uncertainties displayed as error bars).

20. Use the spreadsheet to calculate the energy calibration coefficients. Enter these into ProSpect using the Calibration tab for the detector.

21. Collect a ^{60}Co spectrum and identify the energies of the two full-energy peaks.

→ NOTES:

Experiment ❷

Counting Statistics and Error Prediction

→ Purpose:

① To understand the statistical nature of radiation.

② To calculate statistical quantities.

③ To perform uncertainty analysis on a set of acquired data.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base MCA with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc

→ Theoretical Overview:

Radioactive decay is a random process. In an experiment, the number of counts obtained will fluctuate due to the statistical nature of the data. One can predict the distribution function that describes the results of many such repeated measurements.

Three common statistical models that are used in radiation counting are:

1. **Binomial distribution**
2. **Poisson distribution**
3. **Gaussian distribution**

Statistical analysis

The basis of any statistical distribution is the variation of a given measurement from the true value. The true value is often determined experimentally from a set of measurements, and includes both the experimental mean as well as the standard deviation. The experimental mean $\overline{x_e}$ for a set of N independent measurements can be expressed as:

$$\overline{x_e} \; = \; \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \textit{Equation 2-1}$$

where:

N is the total number of measurements and x_i is the value of a given measurement.

Meanwhile, the sample variance is expressed as:

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(\overline{x_e} - x_i\right)^2 \qquad \textit{Equation 2-2}$$

The square root of the sample variance is the standard deviation of the sample, which is often used to quantify the level of uncertainty of a value being measured.

Uncertainty propagation

Let us assume that three independent variables x, y, z are directly measured with uncertainties $\sigma_x, \sigma_y, \sigma_z$.

The difference in the measured number of counts, u, between x and y can be expressed as:

$$u = x - y \qquad \textit{Equation 2-3}$$

The propagated measurement uncertainty becomes:

$$\sigma_u \; = \sqrt{\sigma_x{}^2 + \sigma_y{}^2} \qquad \textit{Equation 2-4}$$

The same applies to the sum of the counts. The sum of the counts x and z can be expressed as:

$$v = x + z \qquad \textit{Equation 2-5}$$

The propagated measurement uncertainty for the sum of x and z is:

$$\sigma_v \; = \sqrt{\sigma_x{}^2 + \sigma_z{}^2} \qquad \textit{Equation 2-6}$$

Poisson distribution

The Poisson distribution is "characterized by a constant and small probability of success for each individual trial" (refer to Reference 3 on Page 77). Consider the probability of a nuclear decay occurring in a certain time interval. Does the probability go up or down if the half-life of the material is small?

The expected standard deviation for one measurement subject to Poisson fluctuations is:

$$\sigma_i = \sqrt{x_i} = \sqrt{\overline{x_e}} \qquad \text{\textit{Equation 2-7}}$$

(Since the mean value is approximately the same as any typical value). If the data fits the Poisson model, then your experimentally-measured variance should be approximately the same as the calculated variance.

Chi-square analysis

An experimenter should always ask the question: is obtained data true, or is it affected by some extraneous disturbances? One of the more frequently used tests to check the goodness of the data is the χ^2 (chi-squared) test:

$$\chi^2 = \frac{\sum_{i=1}^{N} (\overline{x_e} - x_i)^2}{\overline{x_e}} \qquad \text{\textit{Equation 2-8}}$$

where:

x_i and $\overline{x_e}$ represent the N individual measurements and average of the N measurements.

To evaluate the chi-squared test, the expected result for data fitting a Poisson distribution is equivalent to $N-1$. The greater the deviation from $N-1$, the greater the variation of the data from the expected behavior. If the deviation is large, this may lead the experimenter to investigate further into the experiment, whether this is reviewing the expected result or reviewing the experimental data.

2

→ **Experiment** **2** **Guide:**

1. Connect the Osprey and NaI detector and configure as recommended in Experiment 1. Adjust the gain such that the a ^{137}Cs photopeak is in the center of the spectrum.

2. Record a set of 20 background readings from a NaI detector. Set the PHA acquisition preset live time in ProSpect to be 30 seconds for each measurement.

3. Once this data has been taken, place a ^{137}Cs source near the detector. Repeat the measurements with the source present.

   Warning: do not change the geometry of the detector and source once you start.

4. For each set of data in steps 2 and 3, calculate the experimental mean ($\overline{x_e}$) and the sample variance (σ^2) using Equations 2-1 and 2-2, using the total counts in the spectrum.

5. Calculate the uncertainty of a single measurement in each case which in this case is given by: $\sigma_i = \sqrt{x_i}$

6. From the results in Steps 4 and 5, comment on whether the data fits with the Poisson model of data.

7. Apply the χ^2 test to the sets of data obtained in steps 2 and 3. Comment on the results.

8. Calculate the standard deviation on the net counts (the average source count minus the average background count) using Equation 2-4.

→ **NOTES:**

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

Experiment 3

Gamma-Ray Absorption in Matter (Basic)

→ Purpose:

1 To demonstrate attenuation of gamma rays in matter.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base MCA with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding; Scattering Table
LABKIT-ABS:	Teaching Laboratory Absorber Set
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc
Radioisotope:	^{22}Na button source 1 microcurie, ± 20% unc
Radioisotope:	^{57}Co button source 1 microcurie, ± 20% unc
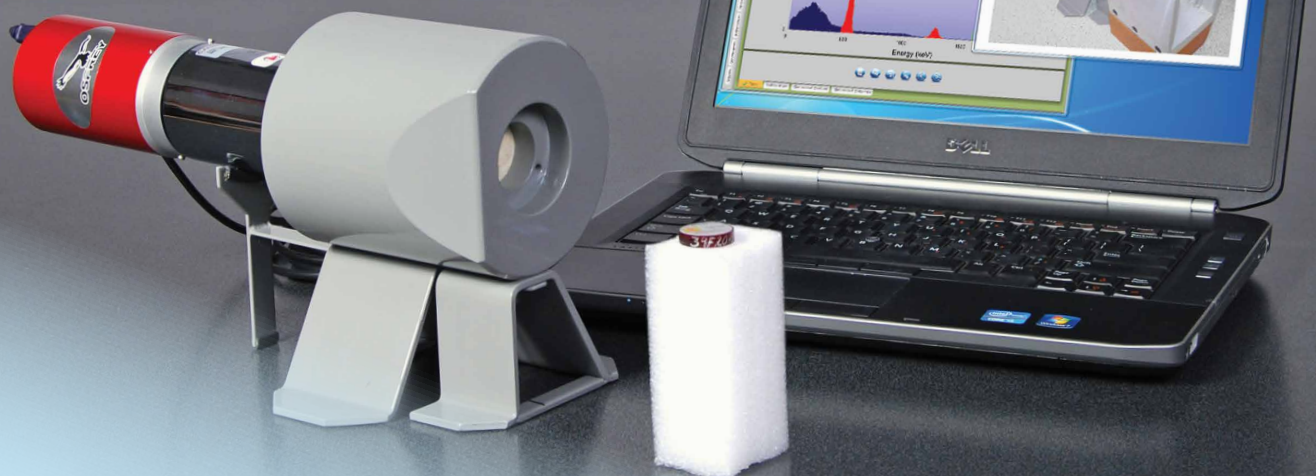
→ Theoretical Overview:

Gamma-ray interactions with matter

There are three dominant gamma-ray interactions with matter:

1. **Photoelectric effect**
2. **Compton effect**
3. **Pair production**

Photoelectric effect

The photoelectric effect is a common interaction between a low-energy photon and a material. In this process the photon interacts with an electron in the material losing all of its energy. The electron is ejected with an energy equal to the initial photon energy minus the binding energy of the electron. This is a useful process for spectroscopy since an output pulse in a detector is produced that is proportional to the gamma-ray energy, as all of the energy of the gamma ray is transferred to the detector. This produces a characteristic full-energy peak in the spectrum that can be used for the purpose of identifying the radioactive material.

The probability of the photoelectric effect is strongly dependent on the Z of the atoms in the matter and the photon energy; it is the dominant process at low photon energy. The probability has discontinuities at the binding energies of the electrons in the constituent atoms in the matter because the probability of transferring the energy to an electron with higher binding energy than the incoming photon energy is zero. The probability of the photoelectric effect therefore rapidly decreases when transitioning from a photon energy just above the binding energy of the electrons to an energy just below it.

Compton scattering

In the Compton effect, the gamma ray scatters from an electron, transferring an amount of energy that depends upon the angle of scatter.

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}(1 - \cos\theta)}$$

Equation 3-1

where:

E' is the scattered energy of the gamma ray.

E is the incident gamma-ray energy.

θ is the angle of scatter.

The term $m_0 c^2$ is the rest mass of the electron, equal to 511 keV. The energy given to the electron is:

$$E_e = E - E'$$

Equation 3-2

The maximum energy given to an electron in Compton scattering occurs for a scattering angle of 180°, and the energy distribution is continuous up to that point (since all scattering angles up to 180° are possible).

If the photon is on a trajectory towards the detector it can Compton scatter at a small angle and still result in hitting the detector. However, since all Compton scattering transfers some energy to the electron, the scattered photon will not deposit its full initial energy in the detector and it will not contribute to the full-energy peak. In the vast majority of measurements performed with spectroscopic detectors the quantity that is measured is the number of counts in the full-energy peak so a Compton-scattered photon is considered to be an unwanted photon even if it ends up depositing energy in the detector.

Pair production

Pair production can occur when the gamma-ray energy is greater than 1.022 MeV and is a significant process at energies above 2.5 MeV. The process produces a positron and electron pair that slows down through scattering interactions in the matter. When the positron comes to rest it annihilates with an electron producing a pair of 511 keV gamma rays that are emitted back-to-back.

The probability of pair production is 0 up to the energy threshold of twice the electron mass (1.022 MeV/c^2) and it increases with energy up to 100 MeV where it becomes constant.

The total photon interaction probability in matter

Figure 3-1 shows the probability of the three dominant interaction processes in matter as a function of photon energy. The figure displays the discontinuity at the binding energy of the electrons in the atom, the decrease of the probability of photoelectric effect when the energy increases, the dominance of Compton scattering at medium energies and the dominance of pair production at higher photon energies.
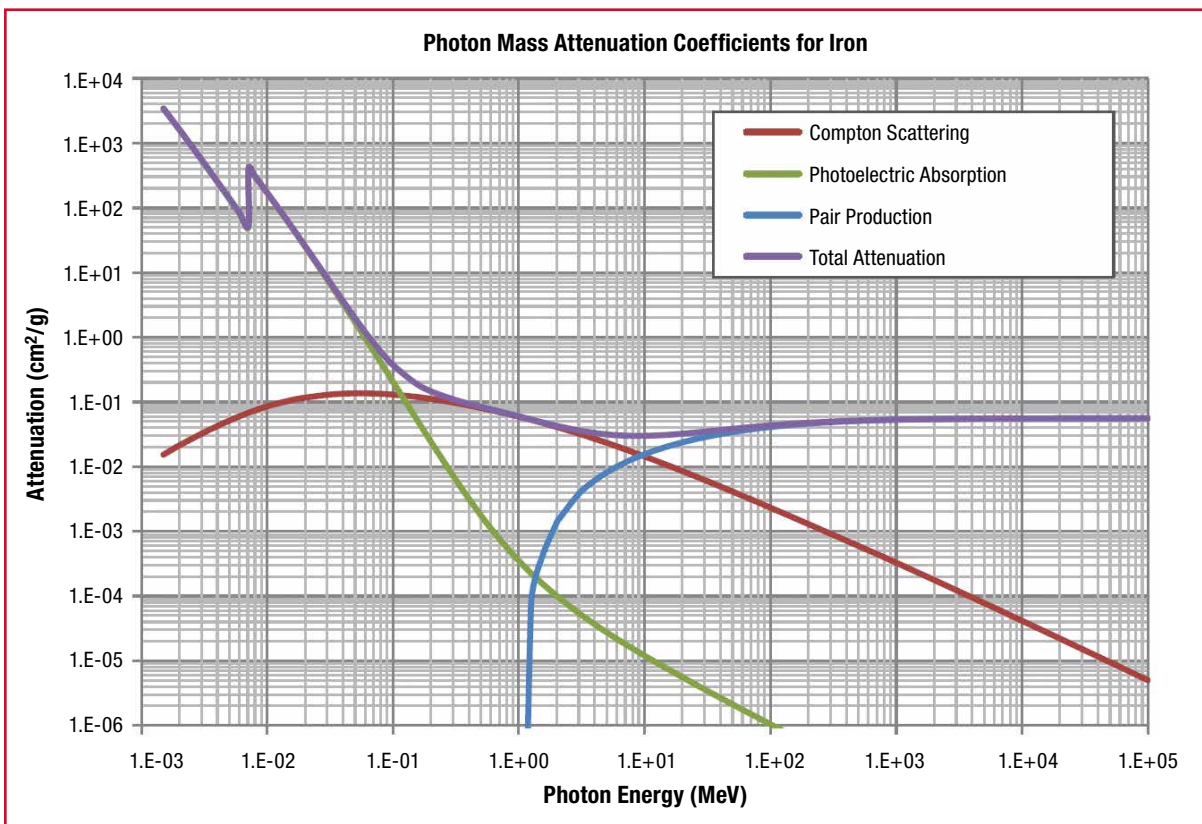
Figure 3-1:
The probability of photon interaction as a function of energy

» Theoretical Overview

Continued

Attenuation in matter

The rate of change per unit length *(dI/dx)* of photons of intensity I traversing matter is given by:

$$-\frac{dI}{dx} = \mu I \qquad \text{\textit{Equation 3-3}}$$

where μ is the linear attenuation coefficient and this is dependent upon the proton *(Z)* number of the attenuating material, the material density and the photon energy.

By solving this differential equation, the intensity as a function of the length traversed *I(x)* can be obtained:

$$I(x) = I_0 e^{-\mu x} \qquad \text{\textit{Equation 3-4}}$$

where I_0 is the initial intensity at *x=0*.

Half-length

The half-length $x_{1/2}$ is defined as the length at which the photon intensity is reduced to one-half. It can be expressed as:

$$I\left(x_{1/2}\right) = I_0 e^{-\mu x_{1/2}} = \frac{I_0}{2} \qquad \text{\textit{Equation 3-5}}$$

And solving for $x_{1/2}$ gives:

$$x_{1/2} = \frac{\ln 2}{\mu} \qquad \text{\textit{Equation 3-6}}$$

This means that as the attenuation of a material increases, the half-length gets shorter.

→ Experiment **3** Guide:

1. Ensure that the Osprey (with the NaI(Tl) detector connected) is connected to the measurement PC either directly or via your local network.

2. Place the ^{137}Cs source in front of the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Osprey.

4. Configure your detector settings as recommended in Experiment 1.

5. Use the software to apply the recommended detector bias to the NaI(Tl) detector.

6. Set the amplifier gain such that the full-energy peak is close to one third of the spectrum.

7. Acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

8. Make a record of the number of counts in the full-energy peak and the count time.

9. Place one piece of the aluminum attenuator between the source and the detector.

10. Acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak or acquire for 5 minutes, whichever is shortest).

11. Make a record of the number of counts in the full-energy peak, the count time and the thickness of the absorber.

12. Add another piece of aluminum attenuation and repeat steps 10 and 11.

13. Repeat step 12 until there are 5 absorbers between the source and the detector.

14. Repeat step 9-13 for lead and polyethylene.

15. Repeat step 9-13 for one of the attenuator materials for a ^{22}Na source and a ^{57}Co source.

16. Using Microsoft Excel or another graphing application, plot the count rate (number of counts in the full-energy peak divided by the count time) for ^{137}Cs for the three absorbers. Do the graphs have the expected shapes? Which material attenuates photons most?

17. Plot the count rate as a function of attenuator thickness for the three sources. Which source has the highest penetration through matter?

18. Using one of the plots, read out the half-length thickness for that material and energy and calculate the linear attenuation coefficient.

→ **NOTES:**

Experiment ④

Compton Scattering

→ Purpose:

1 Demonstrate how the gamma-ray energy varies following Compton scattering.

2 Demonstrate the possible range of scattered gamma-ray energies.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base MCA with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: Base Plate; NaI Detector Shielding; Source Collimation; Scattering Pillar
Radioisotope: **LABKIT-SR-Cs137**	^{137}Cs source compatible with Scattering Table Assembly

4
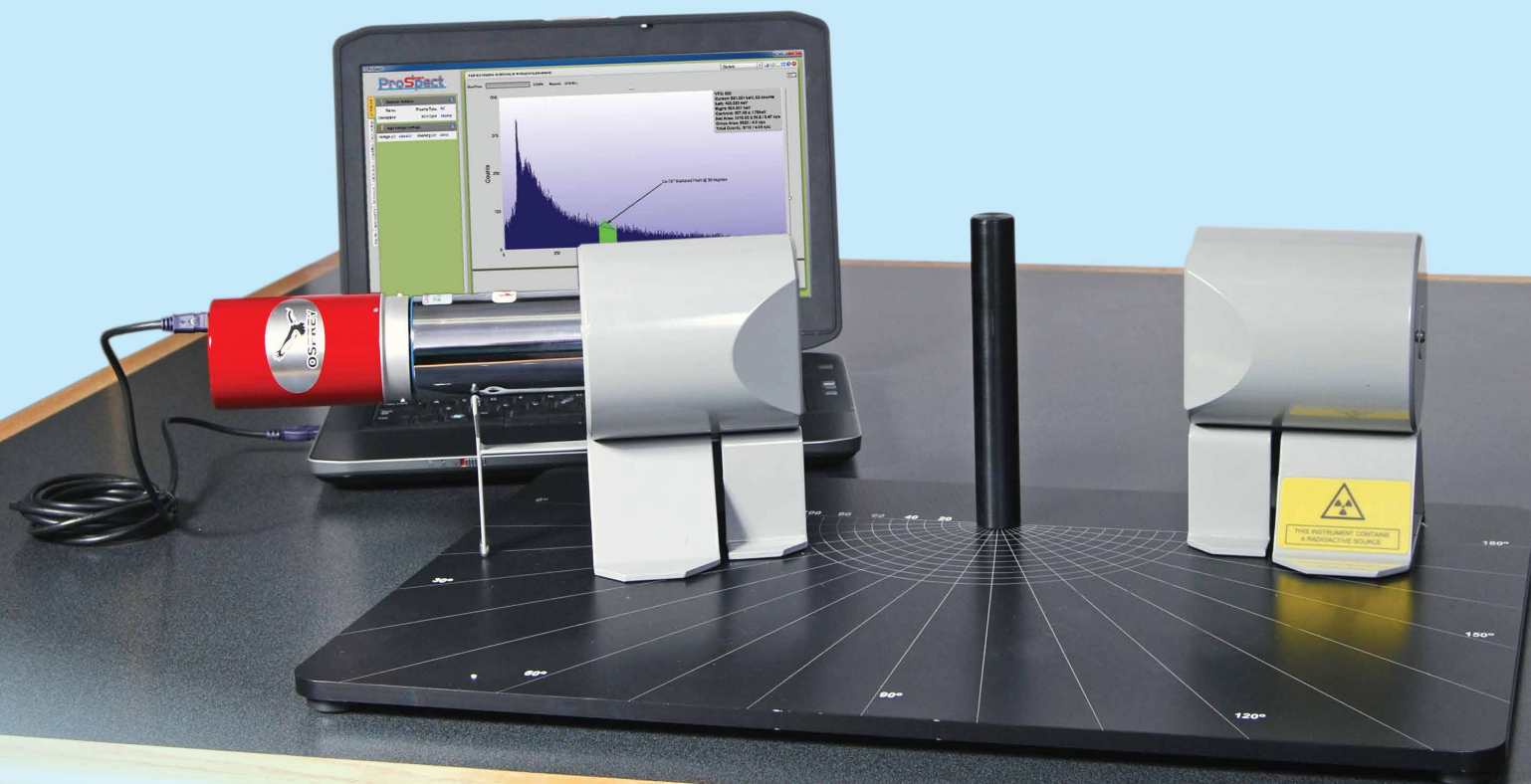
→ Theoretical Overview:

Scattered energy as a function of angle

As previously discussed in Experiment 1, in Compton scattering a photon of energy $E\gamma$ and momentum $E\gamma/c$ scatters inelastically from an electron of mass m_0c^2. Some of the energy of the photon is transferred to the electron, and the photon is scattered through an angle θ with reduced energy $E\gamma'$.

The Compton scattering formula can be written as:

$$\frac{1}{E_\gamma{'}} - \frac{1}{E_\gamma} = \frac{1}{m_0 c^2}\left(1 - \cos\theta\right)$$ *Equation 4-1*

This may be rearranged as the equation for a straight line:

$$\frac{1}{E_\gamma{'}} = -\left(\frac{\cos\theta}{m_0 c^2}\right) + \left(\frac{1}{E_\gamma} + \frac{1}{m_0 c^2}\right)$$ *Equation 4-2*

In this experiment $E\gamma$ is measured as a function of θ for incident gamma rays of 662 keV from a ^{137}Cs source. Figure 4-1 illustrates the experimental setup, where the detector is positioned at about $\theta = 40°$.

Figure 4-1:
Collimated ^{137}Cs source and NaI detector positioned on the scattering table.

Note: During this experiment you should work in keV, where the mass of the electron is 511 keV/c^2.

The expected energies are shown in Figure 4-2:
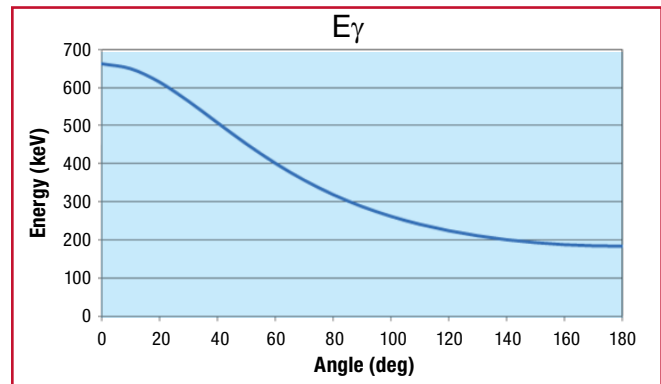
Figure 4-2:
The energy of the Compton-scattered photon as a function of scattering angle for an initial photon energy of 662 keV.

Angular distribution

The scattering probability as a function of angle is called the *differential cross section*, and for Compton scattering it is given theoretically by the Klein-Nishina formula (the units are square meters per steradian, m²/sr):

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{r_0^2}{2}\left\{\frac{1 + cos^2\theta}{[1 + \alpha(1 - cos\theta)]^2}\right\}\left\{1 + \frac{\alpha^2(1 - cos\theta)^2}{[1 + cos^2\theta][1 + \alpha(1 - cos\theta)]}\right\}$$

Equation 4-3

where:

r_0 = 2.82 x 10⁻¹⁵ m, the classical electron radius, and for ¹³⁷Cs

$$\alpha = \frac{E_\gamma}{m_0 c^2} = \frac{662 keV}{511 keV} = 1.29$$

Equation 4-4

A plot of the differential cross section, dσ/dΩ, is shown in Figure 4-3. The units are barns per steradian, b/sr, where 1 barn = 10⁻²⁸ m².

Compton Scattering Differential Cross Section
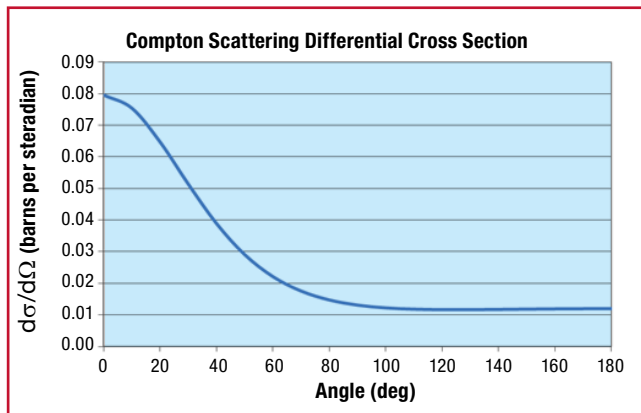
Figure 4-3:
The differential cross section of Compton scattering for a photon energy of 662 keV

→ Experiment **4** Guide:

1. Use the ProSpect software to connect to the detector. Configure the MCA settings and bias voltage as recommended in Experiment 1. Make sure that the detector is correctly calibrated for energy.

2. Ensure the collimated ^{137}Cs source fixture is aligned at the 180° mark and is pointing toward the aluminum scattering pillar. During this experiment, keep the source fixture fixed at this location.

   Caution: Be sure to be aware of your surroundings. Do not have the source pointed at yourself or any other people working in the laboratory.

3. Place the detector with the collimated detector shielding on the scattering table. Starting with the 0° marking, orientate the detector assembly toward the aluminum scattering pillar. Acquire a spectrum until a noticeable peak is visible.

   Note: To increase the count rate, you can complete this experiment without the add-on detector collimator slit. For better angular resolution, use the detector collimator slit in the vertical orientation and extend the counting time until good statistics are achieved.

4. Repeat **Step 3**, moving the detector assembly to different angles up to 160° degrees.

5. For each measurement determine the centroid energy of the scattered peak.

6. In a spreadsheet, plot the energy of the scattered peak as a function of angle and compare the results with Figure 4-1.

7. Plot the reciprocal of the scattered gamma-ray energy ($1/E'$) as a function of ($1 - \cos \theta$). Use the graph and Equation 4-1 to determine the original gamma-ray energy and the rest mass of the electron. Check that these match the values provided above.

→ NOTES:

_____

_____

_____

_____

_____

_____

_____

Experiment (5)

Half-Life Measurement

→ Purpose:

(1) To demonstrate how to determine a half-life from decay data.

(2) To demonstrate the importance of background subtraction.

(3) To provide the theory on production of short-lived isotopes by neutron activation.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base MCA with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
	One of the following:
Radioisotope:	Irradiated Vanadium Foils (requires Neutron Source)
Radioisotope:	^{137m}Ba Isogenerator
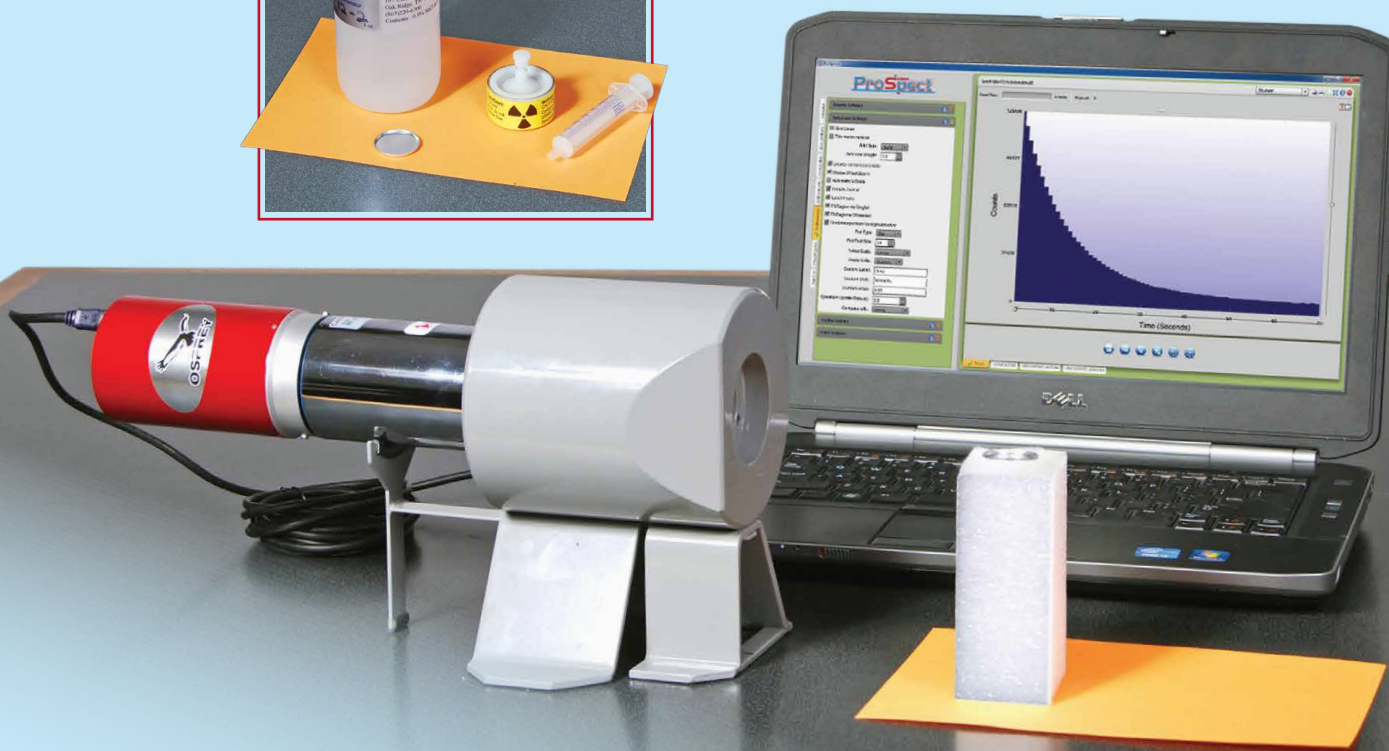
→ Theoretical Overview:

Nuclear half-life

The activity of a radioactive substance is the number of nuclei that decay (through the emission of particles) per unit time. The activity of radioactive material depends upon the amount of material present and decreases with time as the nuclei decay to another state. The change in the number of un-decayed nuclei, ΔN, is proportional to the number of un-decayed nuclei, N, and the time over which the change takes place, Δt:

$$\Delta N = N \lambda \, \Delta t \qquad \text{Equation 5-1}$$

where λ is the nuclear decay constant that depends on the particular isotope and the type of particle that is being emitted.

For infinitesimally small times this equation may be written as:

$$dN = N \lambda \, dt \qquad \text{Equation 5-2}$$

This can be solved using calculus to provide the following:

$$N = N_0 e^{-\lambda t} \qquad \text{Equation 5-3}$$

where:

N is the number of un-decayed nuclei at time t.

N_0 is the number of un-decayed nuclide at time $t = 0$.

e is the natural exponential number (approximately equal to 2.7138).

Since the activity of a sample, A, is proportional to the number of nuclides, N, this can be expressed as:

$$A = A_0 e^{-\lambda t} \qquad \text{Equation 5-4}$$

where A_o is the initial activity of the sample at time $t = 0$. The activity of a sample can be measured as a function of time and the rate constant can be determined experimentally.

A useful parameter in nuclear measurement is the nuclear half-life. This is defined as the time that it takes the activity to decrease by half of the original activity. Measurement of the nuclear half-life for an unknown sample can help with sample identification through comparison of the measured value with published values.

The nuclear half-life τ is defined such that if the initial activity is A_o at time $t = 0$, then the activity at time $t = \tau$ will be $A = \frac{1}{2}A_o$ and:

$$\frac{1}{2}A_0 = A_0 e^{-\lambda \tau} \qquad \text{Equation 5-5}$$

This equation is solved for the half-life by simplifying and taking the natural logarithm of both sides of the equation:

$$\frac{1}{2} = e^{-\lambda \tau} \qquad \text{Equation 5-6}$$

or:

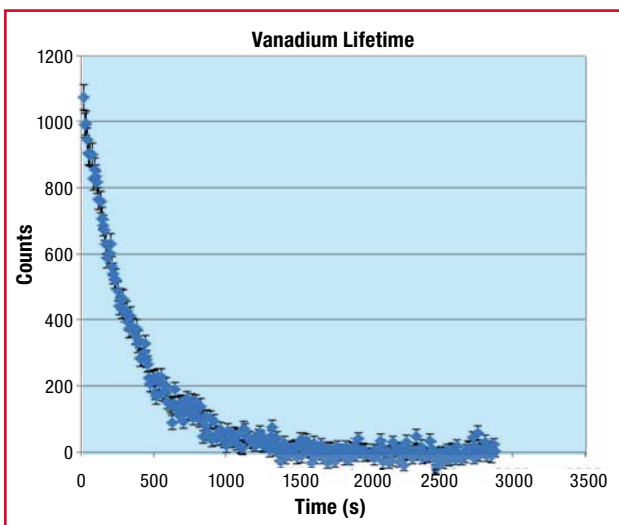$$2 = e^{\lambda \tau} \qquad \text{Equation 5-7}$$

Taking the natural logarithm of each side gives:

$$\ln(2) = \lambda \tau \qquad \text{Equation 5-8}$$

or:

$$\tau = \frac{0.693}{\lambda} \qquad \text{Equation 5-9}$$

The figure below shows an example of ^{52}V decay by measuring the counts observed as a function of time (following a subtraction of the background). The figure shows the exponential nature of the radioactive decay.

Figure 5-1:
*The observed counts of ^{52}V with background subtraction as a function of time*

Neutron Activation

Equation 5-1 shows that the amount of decay (or emitted radiation) is proportional to the decay constant. Equation 5-9 demonstrates that this is inversely proportional to the half-life. This experiment therefore requires a nuclide with a short enough half-life to provide enough decay data in the relatively short duration of this teaching class.

A popular method of producing short-lived activity is to activate a natural metal (such as Vanadium) with a neutron source such as ^{252}Cf or an Americium/Beryllium combined source.

To activate the sample, the Vanadium foil is placed in a water tank close to the neutron source (several centimeters away). The neutrons emitted by the source lose energy in the water. By the time they reach the sample the neutrons are known as "thermal neutrons" as their energy has reduced to the same energy as their surroundings, which is room temperature water. The energy of the neutrons is ~0.025 eV and the cross section for Vanadium to absorb these neutrons is 4.9 barns, which indicates a high probability for the reaction to occur.

Vanadium essentially consists on one isotope ^{51}V (99.75% of natural vanadium). The foil absorbs the neutrons to produce ^{52}V which decays by beta decay to ^{52}Cr with a half-life of 3.75 minutes:

$$V^{51} + n \rightarrow V^{52}$$
$$V^{52} \rightarrow Cr^{52} + e^- + \gamma$$
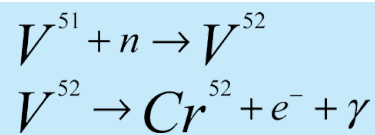
In this experiment, we will measure the gamma rays associated with the ^{52}V decay in order to determine the half-life of ^{52}V.

If a large neutron source and Vanadium foil are unavailable, an option is to purchase a ^{137m}Ba mini-generator. The generator utilizes the beta decay of ^{137}Cs:

$$Cs^{137} \rightarrow Ba^{137m} + e^-$$
$$Ba^{137m} \rightarrow Ba^{137} + \gamma$$
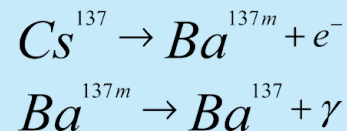
The parent isotope ^{137}Cs beta decays with a half-life of 30.1 years to the metastable state of ^{137m}Ba. This further decays by gamma emission (662 keV) with a half-life of 2.6 min. to the stable ^{137}Ba isotope. ^{137m}Ba is selectively "milked" from the generator, leaving behind the ^{137}Cs parent. The generator can be used to measure the half-life of the ^{137m}Ba sample through measurement of the emitted 662 keV gamma rays.

→ **Experiment** **5** **Guide:**

1. Position the sample (irradiated vanadium foil or ^{137m}Ba sample) a few centimeters from the face of the NaI(Tl) detector.

2. Connect to the detector. Configure the MCA settings as recommended in Experiment 1.

3. Using the Acquisition tab, set the acquisition mode to MCS. Set the MCS conversion gain on the MCA tab to 256.

4. Set up the MCS acquisition such that the dwell time is 20s, the number of sweeps is 1 and the discriminator mode is 'Fast Discriminator'. Start the acquisition and stop it when the histogram is acquiring channel 60 (at an acquisition time of 20 minutes).

5. Save the data and then clear.

6. Remove the sample and repeat the measurement to acquire background data.

7. Export the sample and background data to Microsoft Excel or another spreadsheet application and subtract the background from the data.

8. Use Equation 5-4 to calculate the decay constant (and uncertainty). This will require plotting $ln(A/A_0)$ against t and determining the gradient (and uncertainty).

9. Use Equation 5-9 to calculate the half-life (and uncertainty). Compare this against published values.

→ **NOTES:**

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

⊗ **www.canberra.com**

Experiment 6

Signal Processing with Digital Signal Electronics

→ Purpose:

1 To show the different steps of signal processing in a Digital Signal Processor.

2 To demonstrate the use of the Digital Oscilloscope.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
802-2x2:	NaI Detector 2" x 2"
2007P:	Photomultiplier Tube Base/Preamplifier
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
Lynx-MCA:	Lynx-Digital Signal Analyzer
RCP-CABLE-10:	CP Preamp 10 FT. Cable Set
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc
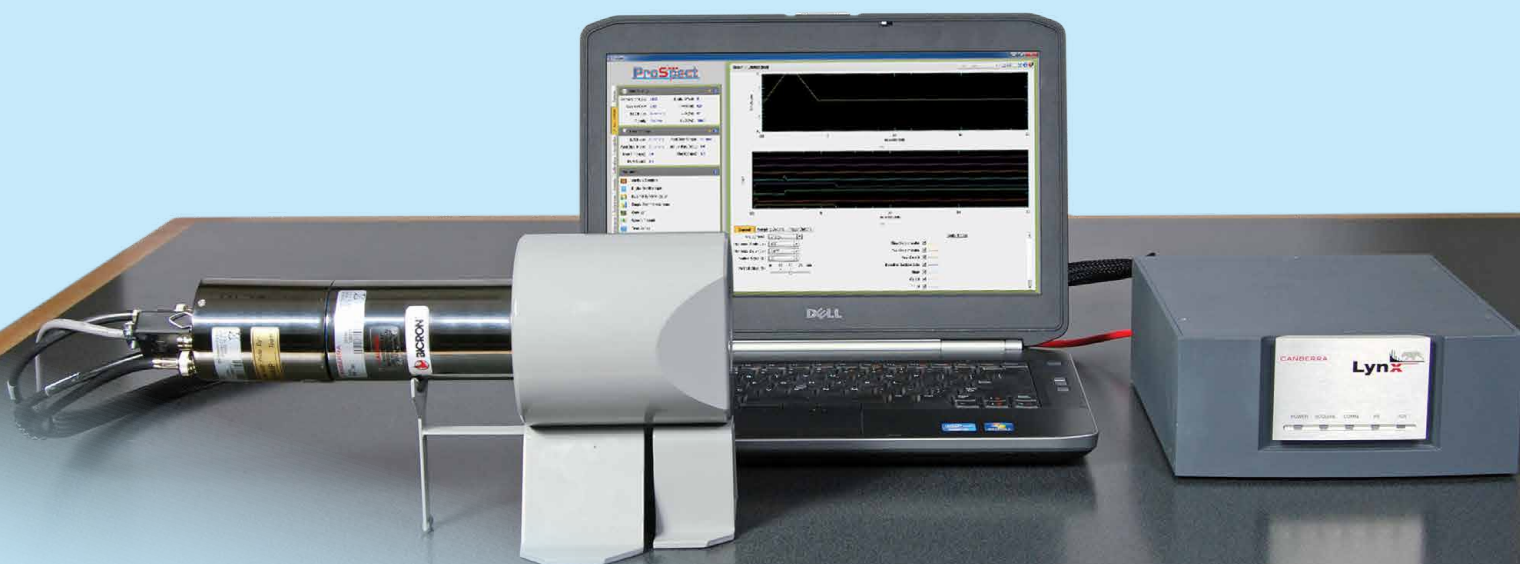
→ Theoretical Overview:

Detector and amplifier functions

The detection and analysis of charged particles, gamma rays, and x-rays is very much the same. A detector is basically a sensor which produces a signal when a particle or photon enters it. For a semiconductor device, the detector typically requires a bias voltage to provide an electric field to collect the charge produced in the detector volume. In scintillator detectors, a bias voltage is needed for operation of the photomultiplier tube. A detector that is used for spectroscopy produces a signal proportional to the energy of the photon deposited in the detector. This pulse is very weak and must be amplified and matched to the analysis equipment. Amplification is typically accomplished in two steps: a pre-amplification stage and a primary amplification stage.

The preamplifier is usually located very close to the detector, while the primary amplification, typically performed using a Multi-Channel Analyzer (MCA), may be at some distance from the detector, sometimes many meters. Different kinds of detector require particular types of preamplifiers, but the basic operating principles are generally similar. The preamplifier integrates the detector charge pulse to produce a voltage pulse that has a rise time consistent with the response time of the detector, typically 10 – 200 nanoseconds, followed by longer decay time, ranging from several to many microseconds, which represents the discharge of the preamplifier feedback loop and is designed to reset the system for the next pulse. A transistor reset preamplifier is not discharged after every event, but only after several volts have been collected, representing dozens of individual events. While there may be differences in the discharge of the preamplifier, the basic principle still applies that the amount of voltage induced by the pulse is proportional to the amount of ionizing energy injected into the detector by the incident radiation.

While the preamplifier is designed to provide an immediate amplification of the weak detector signal and a reset of the system, this signal is typically not sufficient to be able extract a reliable energy signature of the pulse. A primary or shaping amplification stage is still required to further refine the pulse to be able to obtain the most accurate measure of the voltage. In traditional analog shaping the preamplifier pulse is passed through differentiation (CR) and integration (RC) filters to produce a semi-Gaussian shaped pulse signal suitable for digitization in an Analog-to-Digital converter.

Modern signal processing techniques involve the digitization of the signal direct from the output of the preamplifier stage. This digitized pulse can then be digitally manipulated to extract the most accurate pulse height. Digital pulse processing (DPP) allows for the development of filtering functions that are not possible through traditional analog processing. In addition, because of the early stage of digitization, DPP is generally more stable against changes in the environment, temperature and humidity, and faster than analog processing.

One common DPP implementation filtering function that gives optimum energy resolution is the trapezoidal filter. The basic principles of a trapezoidal filter consider two rolling averages of a determined number channels from the input digitized signal. The first average covers a time range determined by the trapezoidal "rise time". The second average is taken for the same rise time, but starting at a time following the end of the rise time, as defined by the trapezoidal "flat top". These two time ranges are seen in the left panel of Figure 6-1. The filtered signal is then a difference of these two signals; as seen in the right panel of this figure. The trapezoidal filter can then be represented as:

$$V_{out}(i) = V_{av2}(i) - V_{av1}(i) \qquad \text{Equation 6-1}$$

where:

$$V_{av1}(i) = \frac{1}{RT}\sum_{j=0}^{RT-1} V_{in}(i+j) \qquad \text{Equation 6-2}$$

and:

$$V_{av2}(i) = \frac{1}{RT}\sum_{j=0}^{RT-1} V_{in}(RT + FT + i + j). \qquad \text{Equation 6-3}$$
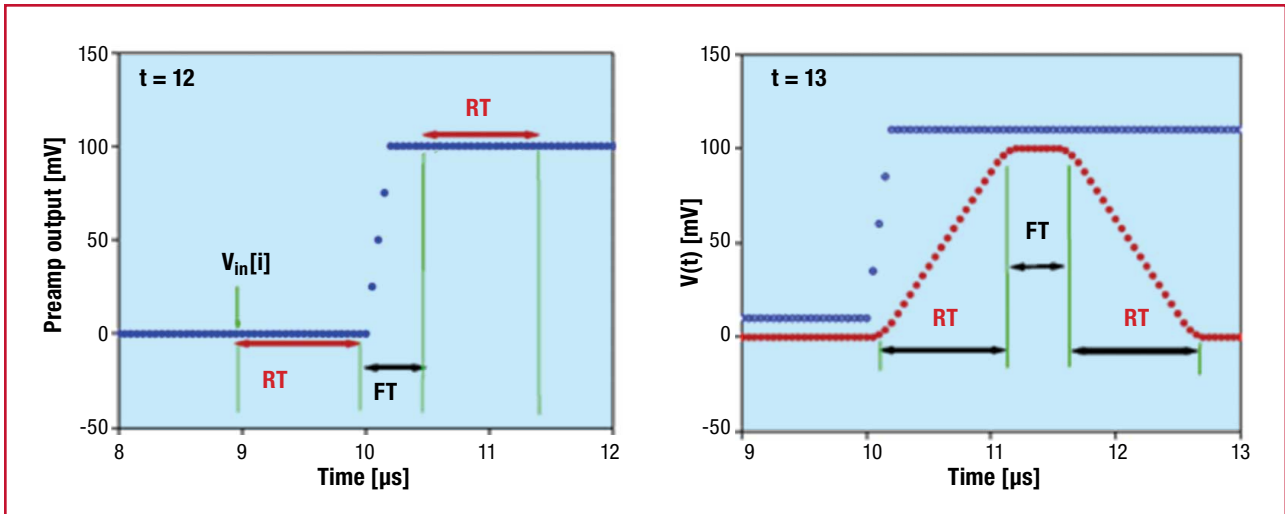
In these equations:

V_{in} is the voltage input to the filter.

V_{out} is the voltage output by the filter.

RT is the user-defined rise time.

FT is the user-defined flat top.

Figure 6-1:
The left panel shows the trapezoidal filter parameters and the resulting output of the filter is displayed in the right panel.
The blue trace represents the input signal, while the red trace represents the shaped signal.

It can be observed that the rise-time parameter represents the filter to smooth the input signal and filter out high-frequency noise that can impact the extraction of the energy signal. The flat-top parameter is usually set to be larger than the charge collection time of the detector. The rise time and flat top can be optimized to achieve the required energy resolution or throughput.

It should also be noted in the above examples, that a pure step function is used. This is a good approximation for preamplifier input pulses (on the scale of the signal rise time), but does not consider the decay time of the pulse, which is compensated for by a pole-zero correction.

Once an energy signal has been determined, there are several options available for how to utilize this signal:

> **Single-Channel Analysis (SCA):** A digital signal is output if the energy signal is between a range of channels designated by a Lower-Level Discriminator (LLD) and Upper-Level Discriminator (ULD) range. The numbers of counts per second are typically displayed.

> **Multi-Channel Scaling (MCS):** Similar to the SCA mode, but the data are recorded in a time histogram in which successive count rates are recorded.

> **Pulse-Height Analysis (PHA):** Energies are recorded in an energy histogram in which pulse heights are categorized by channel and the number in each channel represents the number of times a particular pulse height was recorded within the given measurement time.

> **Multi-Spectral Scaling (MSS):** This is similar to PHA mode, but an energy histogram is saved at short time intervals as defined by the system dwell time.

> **Time-Stamped List Mode (TLIST):** In this mode, the time that an event occurs, to within 100 ns, is recorded along with the energy of the event. These data are stored as a list of time-energy pairs that can later be processed into any of the above four types of data. While this is the most general of the data storage options, this also uses the greatest amount of memory.

→ **Experiment** **6** **Guide:**

Effect of rise time and flat top

1. Connect the NaI(Tl) detector to the Lynx via the 2007P preamplifier and connect the Lynx to the PC either directly or via your local network. See Figure 6-2.

2. Place the ^{137}Cs source in front of the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Lynx.

4. Configure the MCA settings as recommended in Experiment 1.

5. Use the software to apply the recommended detector bias to the NaI(Tl) detector.

6. On the MCA settings tab, start the Digital Oscilloscope (DSO) feature of ProSpect to view the analog input signal.

7. Set the analog trace to ADC to view the analog input signal.

8. Note how long it takes the signal to rise to its maximum and then how long it takes to fall back to the original baseline.

9. With the DSO, set the analog trace to Energy to view the digital trapezoidal figure.

10. Measure the RT and FT on the DSO.

11. On the MCA settings tab under filter settings read the RT and FT. Confirm that these match the values from step 10.

12. Change the RT setting. Record the actual rise time on the DSO.

13. Change the FT setting. Record the actual flat top on the DSO.

14. Set RT and FT back to the original values.

Effect of optimizing rise-time and flat-top settings

1. On the Acquisition setting tab of the ProSpect software, set the acquisition mode to PHA mode.

2. Set the coarse and fine gain such that the full-energy peak is close to the center of the spectrum.

3. Adjust the energy calibration such that the photopeak is about 662 keV. Please note that during this section of the experiment, the spectrum may shift from the energy calibration, and so reported values should be considered carefully.

4. On the MCA settings tab, filter settings, set a 0.6 µs RT and a 0.1 µs FT.

5. Clear the spectrum.

6. Acquire spectrum for one minute (count for longer if there is less than 3000 counts in the peak).

7. Create a Region of Interest (ROI) around the full-energy peak. Using the tooltip, record the FWHM, FWTM and centroid of the peak.

8. Change RT from 0.6 µs to 3.0 µs in increments of 0.6 µs and repeat steps 5 through 7.

9. Change FT from 0.1 µs to 1.1 µs in increments of 0.2 µs and repeat steps 5 through 8.

10. For each flat-top setting plot the energy resolution in percent, FWHM/centroid *100, versus rise time. This will remove dependency from the energy calibration and is standard practice for reporting energy resolution of scintillator detectors.

11. Determine which combination of RT and FT produces the lowest (i.e. best) energy resolution. Set RT and FT to these settings.

Figure 6-2:
Cable connections

Single-Channel Analyzer (SCA)

1. On the Acquisition setting tab of the ProSpect software, set the acquisition mode to PHA mode.

2. Set the amplifier gain such that the full-energy peak is close to the center of the spectrum.

3. Clear the spectrum.

4. Acquire spectrum for one minute (count for longer if there is less than 3000 counts in the peak).

5. Make a Region of Interest (ROI) around the peak.

6. Record the peak area, total peak counts and the live time. Also record the lower and upper channels of the ROI.

7. Select Single Channel Analyzers under the MCA settings options menu.

8. Compute the LLD by taking the lower ROI channel, dividing by the full channel range (2048), and multiplying by 100. The converts the lower ROI channel to a percentage of the full range which is the required LLD input. Set the LLD to this value.

9. Compute and set the ULD in a similar manner as step 8, but with the upper ROI channel.

10. Select the Enable checkbox to start the SCA acquisition. Open the Time Series viewer from the MCA settings tab and record the SCA count rate, i.e. counts/sec. The count rate is displayed as the mean in the statistics box.

11. Compare this count rate to the total peak count rate in the PHA analysis in Step 6.

12. Before continuing, be sure to deselect the Enable checkbox on the SCA dialog.

Multi-Channel Scaler (MCS)

1. On the Acquisition setting tab of the ProSpect software, set the acquisition mode to PHA mode.

2. On the MCA setting tab of the ProSpect software set the Standard Conv Gain to the maximum value allowed by your MCA.

3. On the MCA settings tab of the ProSpect software and change the "MCS Conversion Gain" to the same value as the "Standard Conversion Gain".

4. On the MCA setting tab of the ProSpect software adjust the "Coarse Gain" and "Fine Gain" such that the full-energy peak is close to the center of the spectrum.

5. Clear the spectrum. ***NOTE: do not change the gain once you have set it.***

6. On the Acquisition setting tab of the ProSpect software, set the Preset Live time to 60 seconds.

7. Press Start and acquire the spectrum. Make sure the full-energy peak has more than 3000 counts. Adjust the Preset Live time if there are less than 3000 counts in the full-energy peak.

8. Record the total number of counts in the spectrum, hover over the deadtime bar for a tooltip or make an ROI of the full spectrum.

9. Clear the spectrum.

10. On the Acquisition tab of the ProSpect software, change the Acquisition Mode from PHA to MCS.

11. On the Acquisition tab, enter the dwell time, which is the counting time for each memory location (channel). Select a dwell time such that the total acquisition time is comparable to the acquisition time in Step 6. Remember that for the MCS mode, the total acquisition time will be equal to the total number of channels (which is given by your MCS conversion gain setting) multiplied by the dwell time (assuming a single sweep).

12. On the "Preset Options" select "Sweeps". Enter the Preset Limit for the sweep to 1.

13. On the Disc Mode, select "MCS Fast Discriminator".

14. Press Start to acquire the spectrum.

15. Record the total number of counts in the MCS spectrum.

16. Compare MCS counts to total number of PHA counts from Step 7, remember to correct for different count times.

>> **Experiment 6 Guide**

Continued

Multi-Spectral Scaling (MSS)

1. On the Acquisition setting tab of the ProSpect software, set the acquisition mode to PHA mode.

2. On the MCA setting tab of the ProSpect software set the Standard Coarse Gain to the maximum value allowed by the MCA.

3. On the MCA setting tab of the ProSpect software adjust the Coarse and fine gain such that the full-energy peak is close to the center of the spectrum.

4. Clear the spectrum. *NOTE: Do not change the gain once you have set it.*

5. Go on the Acquisition setting tab of the ProSpect software and set the Preset Live time to 60 seconds.

6. Press Start and acquire the spectrum. Make sure the full-energy peak has more than 3000 counts. Adjust the Preset Live time if there are less than 3000 counts in the full-energy peak.

7. Make a Region of Interest (ROI) around the peak.

8. Record the net peak area and total peak area. Also record the lower and upper channels of the ROI.

9. Clear the spectrum.

10. Go to the Acquisition tab of the ProSpect software and change the Acquisition Mode from PHA to MSS. Set the Preset to Live and for the Preset Limit enter 10 seconds.

11. Go to the Spectrogram tab and set the "Data to View" to MSS Buffer and the "Number of Datasets" to 8.

12. Start acquisition and continue counting until the total acquisition time is the same as the PHA spectrum in Step 6. Remember that for MSS the total acquisition time is equal to the number of data sets measured multiplied by the preset live time.

13. On the Spectrogram tab of the ProSpect software, use the mouse and click and drag on the spectrogram plot to move through each of the MSS spectra.

14. In each MSS spectrum, record the number of peak counts in the same ROI as the PHA analysis.

15. Add the peak counts from all the MSS spectra together and record them.

16. Compare total of the MSS peak counts to the PHA peak counts.

→ **NOTES:**

_____

_____

_____

_____

_____

_____

_____

Experiment 7

High-Resolution Gamma-Ray Spectroscopy with HPGe Detectors

→ Purpose:

1 To demonstrate the measurement of gamma-ray energies with high resolution provided by a High-purity Germanium (HPGe) detector.

2 To understand the performance differences between counting with a high-resolution system (HPGe) and a low-resolution system (NaI).

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
BE2825:	BE2825 Broad Energy Germanium Detector System
LABKIT-SRCEHLD:	Set of Two HPGe Source Holders
Lynx-MCA:	Lynx-Digital Signal Analyzer
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc
Radioisotope:	^{60}Co button source 1 microcurie, ± 20% unc
Radioisotope:	^{57}Co button source 1 microcurie, ± 20% unc

→ Theoretical Overview:

Semiconductor detectors

The use of semiconductor detectors for gamma-ray detection has provided tremendous gains in measurement capability. The gamma-ray peaks obtained with NaI detectors are very broad by comparison, so that two peaks close to each other cannot be resolved and low-energy peaks may not be easily observed. Semiconductor detectors made of germanium or silicon compensated with lithium provide significantly better energy resolution.

For semiconductor detectors the thickness of the depletion region (depletion depth) d is given by the following equation:

$$d = \left(\frac{2\epsilon V}{eN}\right)^{1/2}$$

Equation 7-1

where:

ϵ is the dielectric constant.

V is the reverse bias voltage.

N is the net impurity concentration in the semiconductor material.

e is the electron charge.

For gamma-ray spectroscopy a large depletion region is required for complete charge collection and increased efficiency. Here for a given reverse bias voltage, the value of N needs to be reduced as much as possible. The high-purity germanium detectors that are being manufactured today can achieve net impurity concentration as low as $0.8 \times 10^{10} \text{cm}^{-3}$.

In insulators, the band gap between the valence band (fully occupied) and conduction band (completely empty) is high, and no electric field or temperature rise can provide enough energy for electrons in the valence band to cross the gap and reach the conduction band (Figure 7-1). However in semiconductors the band gap is small, and increased temperature, incident charged particles, or applied electric field can impart enough energy to electrons to move them from the valence band to the conduction band. When an electron moves from the valence band to the conduction band, a hole is created in its place in the valence band. Holes behave like particles with positive charge, and they contribute to the overall conductivity of the semiconductor.
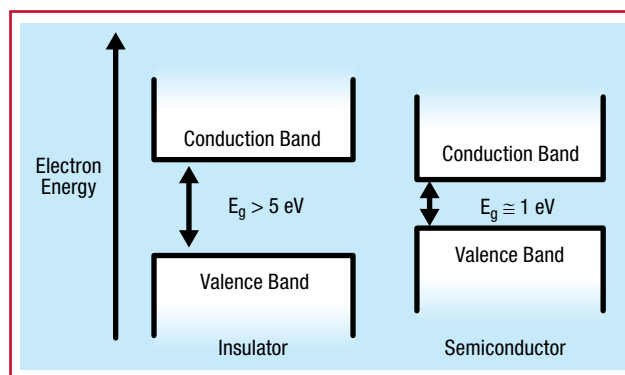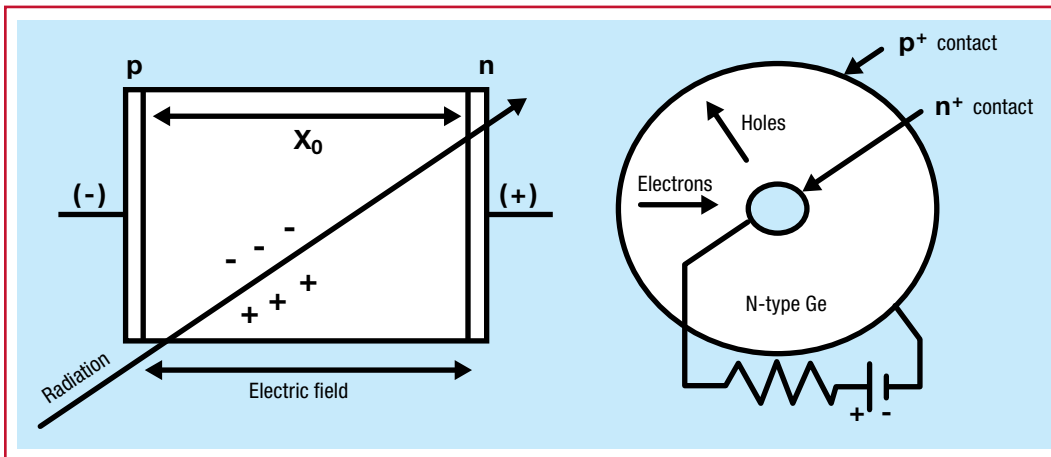

Figure 7-1:
Band structure in insulators and semiconductors. E_g is the band gap energy.

High-purity Germanium (HPGe) detectors

Germanium detectors are semiconductor diodes having a p-i-n structure (P-type contact, intrinsic layer, and N-type contact), in which the intrinsic (i) region is sensitive to ionizing radiation, particularly x-rays and gamma rays. Under reverse bias, an electric field extends across the intrinsic or depleted region. When photons interact with the material within the depleted volume of a detector, charge carriers (holes and electrons) are produced and are swept by the electric field to the p and n electrodes. This charge, which is in proportion to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge-sensitive preamplifier. For a coaxial detector (Figure 7-2) the rectifying contact that forms the semiconductor junction is typically placed at the outer surface of the crystal. Thus, the outer contact for an n-type HPGe will be p+ and the inner surface will be n+. The depletion layer for such a detector grows inwards as the voltage is increased.

Since Germanium has a relatively low band gap, these detectors must be cooled in order to reduce the thermal generation of charge carriers (thus reverse leakage current) to an acceptable level. Otherwise, leakage-current-induced noise destroys the energy resolution of the detector. Liquid nitrogen, which has a temperature of 77K, has traditionally been the cooling medium for such detectors. Many modern detectors are supplied with an electrical cooling system, thus removing the need for liquid nitrogen. There are two disadvantages with semiconductor detectors. First, high-purity or lithium-compensated crystals cannot be made as large as NaI, so it is not possible to make detectors with the same efficiency. Second, the semiconductor detector must be cooled to near-liquid-nitrogen temperature when in use which adds to the cost and complexity of the system.

Figure 7-2:
A typical p-i-n junction detector (left) with reverse bias. A cross section of an n-type coaxial detector perpendicular to the cylindrical axis (right).

» Theoretical Overview

Continued

Energy resolution

The energy resolution of a germanium detector can be described as:

$$FWHM = \sqrt{(w_d^2 + w_e^2)} \qquad \textit{Equation 7-2}$$

where:

w_d is the peak width due to detector effects.

w_e is the peak width due to electronics effects.

The width w_d is energy dependent and is given by:

$$w_d = 2\sqrt{(2\,ln2)F * E(keV) * w} \qquad \textit{Equation 7-3}$$

where:

F is the fano factor.

w is the energy required to produce an electron-hole pair.

In case of germanium w (≈3 eV) is low and thus a large number of electron-hole pairs are produced which results in good statistics from the charge collection and therefore a good energy resolution.

The width w_e is dependent on both the detector capacitance, which in turn depends on the size of the detector, and the bias voltage. Overall the resolution improves with decreasing capacitance.
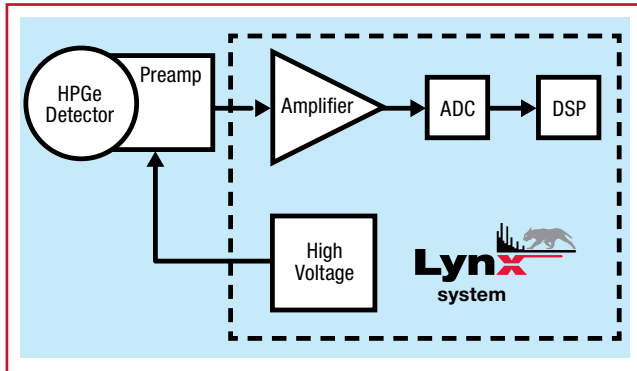
In a typical broad-energy detector (BE2825) the resolution is 0.4 keV and 2.0 keV at 5.9 keV and 1332 keV respectively.

→ Experiment **7** Guide:

Resolution comparison

Figure 7-3:
Setup for HPGE detector

1. Ensure that the HPGe detector is connected (via the Lynx MCA) to the measurement PC either directly or via your local network.

2. Place the ^{137}Cs source in front of the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the HPGe detector.

4. Configure the MCA settings as listed in Table 7-1.

5. Use the software to apply the recommended detector bias to the HPGe detector. This can be found on the detector specification sheet or listed on the side of the detector itself.

6. Set the amplifier gain such that the full-energy peak is at 40% of the range of the spectrum.

7. Acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

8. Adjust the energy calibration such that the photopeak is at an energy of close to 662 keV.

9. For the ^{137}Cs photopeak record/determine:
   a. Centroid channel and energy
   b. ROI range (both channel and energy)
   c. FWHM
   d. Peak Areas (including the net area, net area uncertainty, and total area)
   e. Resolution (calculated in % by taking the FWHM in keV * 100 / centroid in keV)

10. Load the ^{137}Cs spectrum from Experiment 1, obtained using a NaI detector. On the preference tab choose to compare it to the spectrum acquired in step 7. Compare the FWHM values for the full-energy peaks from both spectra.

11. Position the ^{60}Co source and collect a spectrum with the 1173 keV peak and the 1332 peak, the two largest peaks, such that they are in the upper third of the spectrum.

12. Calibrate the energy of the spectrum using the 1173 and 1332 keV peaks.

13. Record the FWHM of the 1332 keV peak in keV. Compare this value against the detector specification sheet, if available. The resolution of germanium detectors is often specified at 1332 keV for high energy applications.

14. Position the [57]Co source and collect a spectrum. Observe a peak at 121 keV.

15. Record the FWHM of the 121 keV peak in keV. Compare this value against the detector specification sheet, if available. The resolution of germanium detectors is often specified at this energy for low- to medium-energy applications.

Table 7-1:
Standard Gain and Filter Settings for HPGe with Lynx MCA

Parameter	Setting
Acquisition Mode	PHA
LLD Mode	Automatic
LLD %	0.1
Polarity	Positive
ULD %	100.0
BLR Mode	Automatic
Fast Disc Shape	Normal
Fast Disc Mode	Automatic
Manual Fast Disc	1.0
Rise Time	8.8
Flat Top	1.2
PUR Guard	1.1
TRP Inhibit	Automatic
TRP Gate Polarity	Positive
LT Trim	500
Conversion Gain	32768

→ **NOTES:**

Experiment ⑧

Gamma-Ray Efficiency Calibration

→ Purpose:

① To demonstrate the procedure for measuring the efficiency of a NaI and a HPGe detector as a function of gamma-ray energy.

② To introduce the concept of efficiency calibration.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
BE2825:	BE2825 Broad Energy Germanium Detector System
Lynx-MCA:	Lynx-Digital Signal Analyzer
LABKIT-SRCEHLD:	Set of Two HPGe Source Holders
Radioisotope:	^{152}Eu reference standard ± 5% unc
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc
Radioisotope:	^{60}Co button source 1 microcurie, ± 20% unc
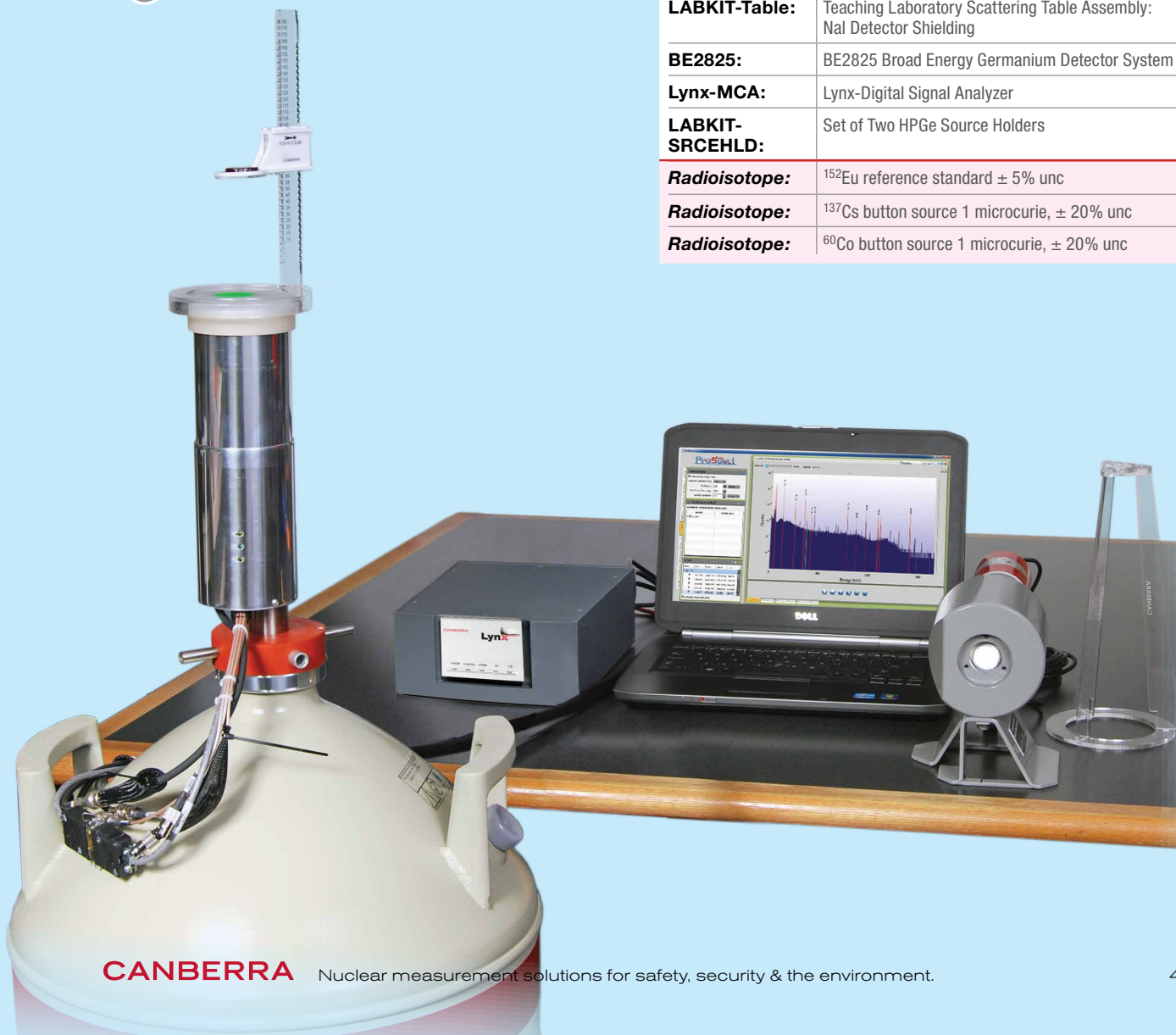
→ Theoretical Overview:

A radioactive source emits a certain number of photons (gamma radiation) and the detector (e.g. NaI scintillation or HPGe detector) is used to detect these photons. The number of photons emitted by the radioactive source is always larger than the number of photons observed by the detector, and the ratio of the number of photons detected or observed by the detector with respect to the number of photons emitted by the source is known as the detection efficiency. The detection efficiency, ε, can be stated as follows:

$$\varepsilon = \frac{N_{meas}}{N_{emit}} \qquad \textit{Equation 8-1}$$

where:

N_{meas} is the number of counts (photons) observed by the detector.

N_{emit} is the number of photons emitted by the source.

In the majority of applications the full-energy peak efficiency is of interest; in that case the N_{meas} is the number of counts in the full-energy peak and N_{emit} is the number of photons emitted for a specific energy.

The number of counts observed in the detector depends largely upon the characteristics of the detector such as size, atomic number and density. The number of counts observed also depends on the depends on the activity of the source, the source-to-detector distance and the materials between the source and the detector. The activity of the source defines the rate of decay (or disintegration) of the source; this is usually expressed in units of becquerel or Curie. One becquerel is equivalent to one disintegration per second while one Curie is equivalent to 3.7 x 10^{10} disintegrations per second. For most nuclei, the number of photons emitted per second for a certain energy is not the same as the number of disintegrations per second, it is usually less. There may be different decay paths in the daughter nucleus and the transition of interest might be bypassed by other transitions. The total number of gamma rays emitted from a disintegration can be larger than one. Other decay mechanisms such as internal conversion compete with the gamma-ray emission. The parameter used to describe the number of gammas per disintegration for a gamma-ray energy is known as the intensity or yield. The number of counts expected can be defined as shown in Equation 8-2.
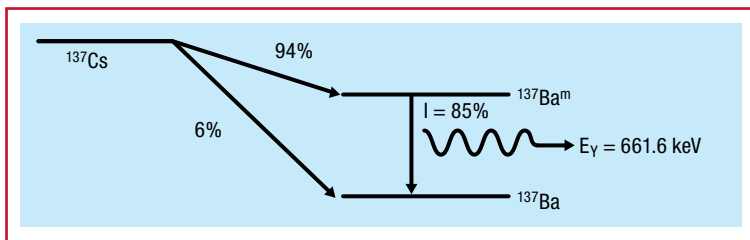
$$N_{emit} = A\,Y\,t \qquad \textit{Equation 8-2}$$

where:

A is the activity in disintegrations per second (or Bq).

Y is the gamma-ray yield.

t is the time in seconds.

Figure 8-1:
Decay scheme of ^{137}Cs

The activity of the source is usually specified with respect to a certain date. The current activity at the time of experiment has to be decay corrected using Equation 8-3.

$$A = A_0 \exp\left(-\ln(2)t/t_{1/2}\right) \quad \textit{Equation 8-3}$$

where:

A is the current activity.

A_0 is the activity on the reference date.

t is the time elapse since the reference date.

$t_{1/2}$ is the half-life of the nuclide under consideration.

All traceable radioactive sources have source certificates, which provide the source activity stated in becquerel or Curie on the date the activity was measured. However, some certificates state the emission rate in gammas per second, which implies that the yield or intensity has been factored into the values given. This is common with mixed-gamma sources, as is shown in Table 8-1.

Table 8-1:

Typical source certificate for a mixed gamma source

Nuclide	Gamma-Ray Energy (keV)	Half-Life, Days	Master Source gps/gram	This Source, gps	Uncertainty (%)	Calibration Method
109Cd	88	4.646E+02	1.677E+05	4.960E+03	4.7	HPGe
57Co	122.1	2.718E+02	8.795E+05	2.601E+03	4.1	HPGe
139Ce	165.9	1.376E+02	1.245E+05	3.682E+03	3.9	HPGe
203Hg	279.2	4.661E+01	2.707E+05	8.006E+03	3.8	HPGe
113Sn	391.7	1.151E+02	1.755E+05	5.190E+03	3.9	HPGe
137Cs	661.7	1.098E+04	1.128E+05	3.337E+03	4	HPGe
88Y	898	1.066E+02	4.228E+05	1.250E+04	3.9	HPGe
60Co	1173.2	1.925E+03	2.084E+05	6.163E+03	4	HPGe
60Co	1332.5	1.925E+03	2.084E+05	6.164E+03	4	HPGe
88Y	1836.1	1.066E+02	4.476E+05	1.324E+04	3.9	HPGe

» Theoretical Overview

Continued

Efficiencies can be referred to as absolute, intrinsic, or relative. Absolute efficiency is the ratio of the total number of photons detected to the number of photons emitted by the source. Intrinsic efficiency is the ratio of the number of photons detected to the number of photons incident on the detector surface. Absolute and intrinsic efficiencies can be expressed as the full-energy peak efficiency which takes into consideration only the photons which result in counts in the full-energy peaks. Often, Germanium detector efficiencies are expressed as relative efficiencies. This is the efficiency relative to a ^{60}Co source (using the 1332 keV peak) measured with a 3"x 3" NaI(Tl) detector at a distance of 25 cm from the detector.
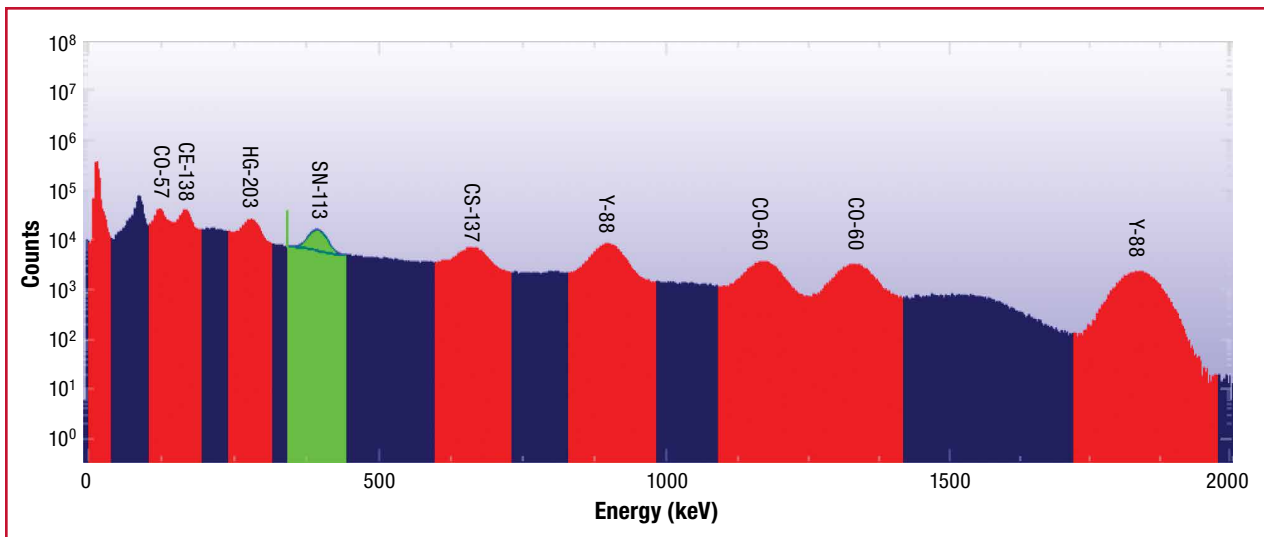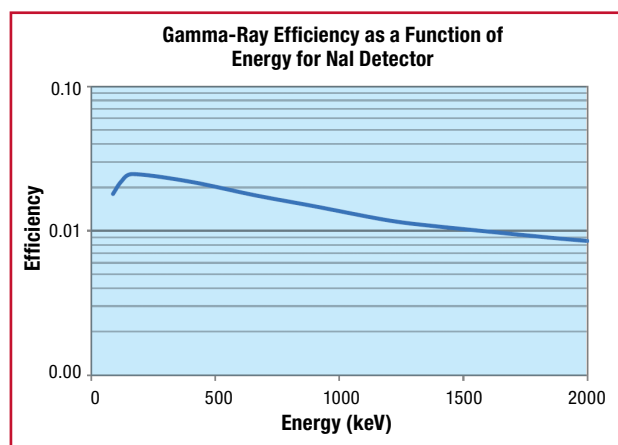

Figure 8-2:
Typical NaI spectrum for a mixed gamma source

→ **Experiment** **8** **Guide:**

Using 2" x 2" NaI detector

1. Place the [152]Eu reference standard at a distance of about 20cm from the surface of a 2"x 2" NaI detector.

2. Configure the MCA settings as recommended in Experiment 1.

3. Adjust the coarse and fine gain of the MCA such that the 1408 keV peak is visible in the high-energy region of the spectrum.

4. Acquire data, ensuring that at least 10 000 counts are achieved in several of the major peaks throughout the spectrum. By referring to Experiment 2 if needed, perform an energy calibration.

5. Measure the net peak area and uncertainty for each of the major peaks listed in the certificate file. For each gamma-ray peak, use Equation 8-1 to determine the efficiency. Also calculate the uncertainty in the efficiency (use Reference 4 on Page 77 if needed). Note if counts (rather than counts per second) is to be used for this calculation (as per Equation 8-1) then the gamma-ray emission rates in the certificate file should first be converted to number of gamma rays emitted during the acquisition (by multiplying by the time of the acquisition). The photon intensities are provided in Table 8-2 for easy reference.

6. Plot the efficiency (and uncertainty) against energy in Microsoft Excel or other program. The result should be similar to Figure 8-3. Comment on the shape of the curve.

Figure 8-3:
Representative efficiency of NaI detector as a function of energy

Table 8-2:
Branching ratios for major [152]Eu gamma rays

Energy (keV)	Branching Ratio	Uncertainty
121.8	0.2867	0.0015
244.7	0.0761	0.0004
344.3	0.266	0.005
778.9	0.1296	0.0014
964.1	0.1465	0.0007
1112.1	0.1369	0.0007
1408.0	0.2107	0.001

Experiment 8 Guide

Using the HPGe detector

The determination of the efficiencies using the HPGe detectors is similar to that of the 2"x 2" NaI detector.

The main difference in the results obtained is that the resolution of the HPGe detector is much better than that of a NaI detector. Typical resolution of a HPGe detector is less than 0.2% while it is about 7.5% for a NaI detector.

1. Ensure that the Lynx (with the HPGe detector connected) is connected to the measurement PC either directly or via your local network.

2. Using the adjustable source holder, place the ^{152}Eu reference standard at a distance of about 20cm from the endcap of the high-purity germanium detector. Record this distance. Remove the plastic cap from the detector before counting.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Lynx.

4. Configure the MCA as recommended in Experiment 7 for a HPGe detector.

5. Use the software to apply the recommended detector bias to the HPGe detector.

6. Set the PHA conversion gain to 32768 channels.

7. Adjust the coarse and fine gain of the MCA such that the 1408 keV peak is visible in the upper part of the spectrum.

8. Acquire data, ensuring that at least 10 000 counts are achieved in several of the major peaks throughout the spectrum. Energy calibrate the system, referring the Experiment 1 if needed.

9. Measure the net peak area and uncertainty for each of the major peaks listed in Table 8-2. For each full-energy peak, use Equation 8-1 to determine the efficiency. Also calculate the uncertainty in the efficiency (use Reference 4 on Page 77 if needed). Note if counts (rather than counts per second) is to be used for this calculation (as per Equation 8-1) then the gamma-ray emission rates in the certificate file should first be converted to number of gamma rays emitted during the acquisition (by multiplying by the time of the acquisition). The photon intensities are provided in Table 8-2 for easy reference.

10. Plot the efficiency (and uncertainty) against energy in Microsoft Excel or other program. Compare the results to the efficiency determined from the NaI measurement.

11. Remove the ^{152}Eu reference standard and replace with the ^{60}Co source at the same distance. Count until at least 10 000 counts are in each of the two primary peaks. Using Equations 8-2 and 8-3 and by interpolating using the efficiency curve calculated in Step 10, determine the activity of the ^{60}Co source. How does this compare against the ^{60}Co source certificate?

12. Repeat Step 11 with ^{137}Cs source. Again, how does this compare against the activity on the source certificate?

13. Using one of the sources, place the source at a distance of 10 cm and 25 cm. For each position, count until there are about 10 000 counts in the primary peaks. Calculate the efficiency curve for each geometry. How do they compare? Do they demonstrate that efficiency is proportional to the inverse of the distance squared?

Experiment ⑨

Gamma-Ray Coincidence Counting Techniques

→ Purpose:

① To use the technique of coincidence detection and demonstrate the basic principles of coincidence measurements.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly: NaI Detector Shielding
Lynx-MCA:	Lynx-Digital Signal Analyzer

802-2x2:	Extra 802 2x2 NaI Detector 2" x 2"
2007P:	Photomultiplier Tube Base/Preamplifier
RCP-CABLE-10:	CP Preamp 10 FT. Cable Set
LABKIT-NAICOLL:	Teaching Laboratory Additional NaI Detector Shielding
BE2825:	BE2825 Broad Energy Germanium Detector System
Radioisotope:	^{22}Na button source 1 microcurie, ± 20% unc
Radioisotope:	^{137}Cs button source 1 microcurie, ± 20% unc

→ Theoretical Overview:

Coincidence measurements are an important tool in the detection of ionizing radiation for a wide range of applications. Many nuclear processes produce two photons simultaneously, while other processes produce two or more photons in quick succession. In such cases, it is possible to study the temporal and angular correlations between the two photons by setting up a coincidence detector system. These emissions can occur simultaneously or within a time period that is very short compared to the time resolution of the detection system. For example, decay by beta emission to a daughter nucleus, which in turn decays by gamma emission, produces the beta particle and the gamma ray at essentially the same time. Similarly, one nucleus may emit several gamma rays in cascade, which are effectively simultaneous because the delay between the events is short. Delays of 10^{-9} seconds are common.

In nuclear physics applications, coincidence systems are used to detect and identify weak detection signals or to distinguish a physics signal from background signals, as is done in Compton suppression or cosmic veto systems. In high-energy or particle physics, detection systems consisting of thousands of detectors and electronics channels are all operated in coincidence when two accelerated beams collide to search for newly formed particles or new decay pathways.

Time-coincidence measurements

In addition to radiation detector characteristics such as efficiency or energy resolution, time resolution is important to measure. This is required to determine the time dependence of nuclear decays as discussed above. It reflects the ability to measure the arrival time of the incident particle or the time of a specific interaction and its associated signal. The time resolution of a specific detector depends on several parameters such as signal shape called "walk time" and signal noise called "jitter time".

In some cases the actual time difference between the two events can be measured, but in many cases it is only necessary to determine that the events are correlated in time.

The determination that two nuclear events occur at the same time is made electronically with a coincidence system. This unit operates on standardized pulses and determines whether events occur within a certain time interval, called the resolving time. The standard pulses from any single channel analyzer are used as input, with one input from each detector.

The number of coincidences that are real, not random, is determined by the physics of the decay and the solid angles and efficiencies of the detectors. These are the true coincidences.

In some experiments, the number of coincidences is the only information needed. Often, however, the coincidence signal is used to open the linear gate in a multichannel analyzer so that a spectrum is acquired under coincidence conditions.

This experiment has three separate parts which use the coincidence technique in different ways.

γγ **Angular correlations**

The angular correlation of two gamma rays, γ_1 and γ_2 may be defined as the probability of γ_2 being emitted at an angle relative to the direction of γ_1. The emission of gamma rays from excited nuclei can be treated mathematically as the classical radiation of electromagnetic energy from a charged system. The electric field can be expanded in vector spherical harmonics, corresponding to the various multipoles of the charge distribution. The shape of the angular distribution of the radiation with respect to the radiating system is uniquely determined by the order of the multipole.

In nuclear systems, the order of the multipole depends upon the angular momentum numbers and the parities of the initial and final states involved in the transition. Thus, if all nuclei in a radioactive sample could be oriented so that their nuclear angular momenta were aligned, the shape of the angular distribution of gamma rays could be used to determine the multipolarity of the transition.

However, nuclei are randomly oriented. Very strong magnetic fields at low temperature could be used to provide orientation, but a simpler method is to use coincidence technique for cases in which two or more gamma rays are emitted in cascade. The first gamma ray establishes the direction of the spin axis of the nucleus; hence the second gamma ray will have a definite distribution with respect to this axis. One needs only to measure the angular correlation for the two gamma rays and compare it with the tabulated values for various multipolarities.

In nuclear physics experiments the angular correlation is measured between two gamma rays, which are emitted almost simultaneously in the cascade from the decay of a radioactive nucleus. The gamma rays are detected using two NaI scintillation counters in which the height of the electronic output pulses is proportional to the incident gamma ray energies. By pulse height selection, in "single channel analyzer mode", one counter will be used to record γ_1 and the other γ_2. The counting rate of each counter, R_i, for detecting its selected gamma ray is given by:

$$R_i = N_0\, \varepsilon_i\, \frac{\Omega_i}{4\pi} \qquad i = 1,2 \qquad \textit{Equation 9-1}$$

where:
N_0 is the number of decays per second in the radioactive source.
ε_i is the efficiency of the detector.
Ω_i is the geometrical solid angle subtended by the detector.

In the absence of the angular correlations, the true rate of detected gamma-ray coincidences is:

$$R_{true} = R_1\, \varepsilon_2\, \frac{\Omega_2}{4\pi} = N_0\, \varepsilon_1\, \frac{\Omega_1}{4\pi}\, \varepsilon_2\, \frac{\Omega_2}{4\pi} \quad \textit{Equation 9-2}$$

The random coincidence rate between a gamma ray detected in Detector 1 and a gamma ray detected in Detector 2 is:

$$R_{random} = R_1\, R_2\, \Delta t = N_0^2\, \varepsilon_1\, \frac{\Omega_1}{4\pi}\, \varepsilon_2\, \frac{\Omega_2}{4\pi}\, \Delta t \quad \textit{Equation 9-3}$$

where Δt is the resolving time of the coincidence counting system between the two detectors. If both detectors are set to respond to both gamma rays, the counting rate in each detector is the sum of counting rates for different gamma rays.

→ **Experiment 9 Guide:**

Time-coincidence measurements using TLIST acquisition mode
NaI-NaI coincidences

Energy calibration

1. Use two NaI Detectors (one connected via an Osprey and the other with the 2007P Preamp and Lynx) connected to the measurement PC either directly or via your local network.

2. Open the ProSpect Gamma Spectroscopy Software and connect to both MCAs.

3. Configure both MCAs as recommended in Experiment 1 for configuration to a NaI detector.

4. Select the High Voltage Settings on the Detector tab on the ProSpect software to apply the recommended high voltage on both detectors.

5. Place the ^{22}Na source between the two detectors in a close geometry.

6. Set the Conversion gain on the MCA tab of the ProSpect software to 2048 channels for both MCAs.

7. Adjust the coarse and fine gain settings on the MCA tab of the ProSpect on both MCAs such that the 1275 keV full-energy peak is in the upper part each spectrum.

8. Click on Start (on the top of each Spectral Display) to start accumulating the two spectra. Use a count time such that there is at least 10 000 counts in the full-energy peak.

9. Perform an energy calibration using the 511.0 and 1274.5 keV peaks of ^{22}Na, referring to Experiment 1 if necessary.

Decay spectra

10. On the acquisition tab set the acquisition mode to TLIST mode. The TLIST mode allows acquisition of event data which provide the energy and time for each event.

11. Set the two devices up according to Table 9-1. Note that the external sync setting needs to be applied first. Connect the Sync BNC connector on the Lynx rear panel to the GPIO input channel 1 of the Osprey. See Figure 9-1. (If necessary, utilize a 50 ohm terminator to reduce reflections.)

12. Press Control-Start to begin acquisition simultaneously on both devices.

Figure 9-1:
Cable configuration for synchronization of Lynx and Osprey MCAs

13. Ensure that both detectors go into waiting mode (blue backgrounds on the datasource thumbnails). Rapidly (before the 20 second timeout is reached), switch the Lynx External Synchronization from Slave to Master B.

14. Ensure that both detectors begin acquiring data (PHA data appears in the display and both backgrounds turn green in the datasource thumbnail view).

15. Acquire data for around 5 minutes, press Control-Stop to stop both MCAs from acquiring data and save the PHA data. The TLIST data is saved automatically during the acquisition.

Table 9-1:
Settings of synchronized TLIST mode acquisition with an Osprey and a Lynx MCA

Osprey	Lynx
Acquire Settings	**Acquire Settings**
Acquire Mode: TLIST	Acquire Mode: TLIST
Acquire Presets : None	Acquire Presets : None
Latch : Fast Discriminator	Latch : Fast Discriminator
Timebase : 100ns	Timebase : 100ns
Clock: External	Clock: Internal
External Sync Settings	**External Sync Settings**
External Sync Status: Independent (to enable external clock	External Sync Status: Enable
Mode: Slave	Mode: Slave
Pulse: 1000ms	Pulse: 1000ms
Timeout : 20000 ms	Timeout : 20000 ms
Polarity: Positive	Polarity: Positive
GPIO Settings	
Ext Sync In assigned to Channel 1	

Analysis

16. To analyze the TLIST mode data and see the results of the coincidence measurement use the application called ProSpect Data Scanner (downloadable from CANBERRA website www.canberra.com). Follow the steps below to run the ProSpect Data Scanner.

17. Select the folder of interest, where the data are stored.

18. Select the Pre-Scan option to sort the events by the time stamp. Note that for each file the elapsed and the live time is displayed. Additionally, the total number of events in PHA and TLIST mode data and the elapsed real and live times for the TLIST mode data file are displayed.

19. Enter the energy calibration equations for both detectors, found on the energy calibration tab. Select Energy-Scan to reconstruct the energy spectra for both devices from the TLIST events.

20. To ensure the time correlations between the events can be observed, set a gate around the 511 keV full-energy peak.

21. Select the Time-Scan to generate the time coincidence spectrum. The display spectrum will show the time correlation between the events recorded in both detectors.

22. Comment on the time-correlated spectrum.

≫ Experiment 9 Guide

Continued

NaI-HPGe coincidences

Energy calibration

1. Connect the Lynx (with the HPGe detector connected) to the measurement PC or via your local network using the Ethernet connection.

2. Connect the Osprey (with the NaI(Tl) detector connected) to the measurement PC either directly or via your local network.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Lynx and Osprey MCA's.

4. Configure the NaI detector as recommended in Experiment 1, and the HPGe detector as recommended in Experiment 7.

5. Select the High Voltage Settings on the Detector tab on the ProSpect software to apply the recommended high voltage on both detectors.

6. For each detector perform an energy calibration using the 511.0 and 1274.5 keV peaks of ^{22}Na, referring to Experiment 1 if necessary.

7. Save both spectra. **Once you have set the gain and the energy calibration coefficients do not change it, otherwise you will have to redo the calibration.**

Decay spectra

16. On the ProSpect software set the data acquisition to TLIST mode. The TLIST mode allows simultaneous acquisition of event data which provide the energy and time for each event.

17. To acquire data in TLIST mode set both detectors as shown in Table 9-1.

18. After the two devices are setup as described in Table 9-1, make sure to connect the Sync BNC connector on the Lynx rear panel (add a 50 ohm terminator to prevent reflections) to the GPIO input channel 1 of the Osprey.

19. Select Control-Start to begin acquisition simultaneously on both devices.

20. Ensure that both detectors go into waiting mode (blue backgrounds on the datasource thumbnails). Rapidly (before the 20 second timeout is reached) switch the Lynx External Synchronization from Slave to Master B.

21. Ensure that the both detectors begin acquiring data (PHA data appears in the display and both backgrounds turn green in the datasource thumbnail view).

22. Acquire data for around 5 minutes and save the data.

Analysis

23. To analyze the TLIST mode data and see the results of the coincidence measurement use the application called the ProSpect TLIST Data Scanner (downloadable from the CANBERRA website). Follow the steps below to run the ProSpect TLIST Data Scanner.

24. In the Search Directories tab, identify the directory with the acquired TLIST data. Press the start button to begin analyzing.

25. In the Scan Results tab, select the appropriate acquisitions and set the beginning time Range to -6000 ns, maximum time range to 6000 ns, and the Time Bins to 1000.

26. On the Analysis tab, select the two acquisitions using the Device and Acq Start tabs. Plot Energy on the X-axis and Time on the Y-Axis to observe the coincident counts. Comment on the graph that is observed. Note you can copy the graph to your clipboard for further analysis.

27. Comment on the time coincidence spectrum and compare with the spectrum acquired for the two Ospreys above.

Experiment 9 Guide
Continued

Time-coincidence measurements using the hardware gating of the Lynx MCA

This section requires the following:
ProSpect Version 1.1
Lynx Firmware Version 1.3

1. Make sure the high-purity germanium (HPGe) and NaI detectors are energy calibrated.

2. Place ^{137}Cs and ^{22}Na sources between the two counter detectors in a closed geometry.

3. Connect the GPIO 1 unit of the Osprey to the gate input of the Lynx.

4. For the NaI detector, open the GPIO dialog on the MCA tab of the ProSpect software and set the GPIO to the single-channel analyzer, SCA 1.

5. For the NaI detector, go to the Single-Channel Analyzer under the MCA tab of the Prospect software and Enable the SCA.

6. Go to the Acquisition tab of the Prospect software for the Lynx unit and set the coincidence gate parameters as follows:

   Table 9-2:
   ProSpect Settings for Step 6

Coincidence
Mode: Coincidence
Polarity: Positive
Gate Delay (μs): 0
Gate Delay Ext (μs): 0
Pulse Width Ext (μs): 500 ns

7. Launch the Digital Oscilloscope and look at the Lynx traces. Set the trigger on the Store pulse and make sure the external gate is overlapping with the peak detect pulse. Increase the Gate Delay Ext such that the edge of the peak detected will overlap with the edge of the external gate.

8. Acquire an energy-gated spectrum in the HPGe detector. Use a count time such that there are at least 10 000 counts in each photopeak.

9. Save the spectrum.

10. Set the coincidence gate settings as follows:

    Table 9-3:
    ProSpect Settings for Step 10

Coincidence
Mode: Anticoincidence
Polarity: Positive
Gate Delay (μs): 0
Gate Delay Ext (μs): the value which was determined at step 65.
Pulse Width Ext (μs): 500 ns

11. Acquire an energy-gated spectrum in the HPGe detector. Use a count time such that there are at least 10 000 counts in each photopeak.

12. Save the spectrum.

13. Set the coincidence gate settings as follows:

    Table 9-4:
    ProSpect Settings for Step 13

Coincidence
Mode: NONE
Polarity: Positive
Gate Delay (μs): 0
Gate Delay Ext (μs): the value which was determined at step 65.
Pulse Width Ext (μs): 500 ns

14. Acquire an energy-gated spectrum in the HPGe detector. Use a count time such that there are at least 10 000 counts in each photopeak.

15. Save the spectrum.

16. Plot the energy spectra acquired with different coincidence-gating conditions and compare the number of counts in the photopeaks for the different gating conditions.

Experiment (10)

Positron Annihilation

→ Purpose:

(1) To study the phenomenon of positron annihilation.

(2) To measure the two 511 keV photons that are emitted in true coincidence with a 180° angular separation.

→ Equipment Required:

ProSpect:	ProSpect Gamma Spectroscopy Software
Osprey:	Osprey Digital Tube Base with connectors
802-2x2:	NaI Detector 2" x 2"
LABKIT-Table:	Teaching Laboratory Scattering Table Assembly (Includes Table, NaI Detector Shielding, Source Collimation, and Scattering Pillar)
802-2x2:	Extra 802 2x2 NaI Detector 2" x 2"
2007P:	Photomultiplier Tube Base/Preamplifier
LABKIT-NAICOLL:	Teaching Laboratory Additional NaI Detector Shielding
Lynx-MCA:	Lynx-Digital Signal Analyzer
RCP-CABLE-10:	CP Preamp 10 FT. Cable Set
Radioisotope:	^{22}Na button source 1 microcurie, ± 20% unc

→ Theoretical Overview:

Positrons are most commonly produced from β+ decays or from pair production. The positron is the anti-particle of the electron, meaning that it has the same mass but opposite charge and quantum numbers. Positrons created from the β+ decays or from pair production will slow down in the medium in which they were created until their energy has been reduced sufficiently to allow formation of a bound state with an electron. This bound state is called positronium and is unstable with a mean lifetime of 125 picoseconds and the positron and electron will annihilate. The annihilation has to conserve charge, energy, momentum and all other quantum numbers. A reference system can be constructed such that the net momentum is zero and

in this system the momentum of the photons from the annihilation has to add up to zero. As a consequence the photons emitted from two-photon annihilation have to be emitted in opposite directions. The conservation of energy and momentum requires the two photons to have the same energy, the electron mass or 511 keV. Since the electron and positron are not completely at rest, when the annihilation occurs there might be a slight change in the energy and angle between the two photons. This can be observed by the increase of the FWHM of 511 keV annihilation photons when compared to other gamma-ray peaks of similar energies.

→ **Experiment** **10** **Guide:**

Using 2" x 2" NaI detector

1. Configure the 2 NaI detectors (one with the Osprey MCA and one with the 2007P Preamp and Lynx MCA). Connect the two MCAs to the measurement PC either directly or via your local network.

2. Configure the NaI detector shielding around each detector. Using the scattering table, remove the scattering pillar if present. Position the two detectors on the scattering table, with a separation of ~16 inches (400 mm) between them. Ensure that the axis of symmetry of the 2 detectors are aligned with each other, and with the position of the source. (Figure 10-1).

3. Locate the [22]Na source at the center line between the 2 detectors and at half the distance of separation. The angle subtended by the collimator is given by the following equation:

$$\theta = tan^{-1}\left(\frac{d}{2L}\right)$$ *Equation 10-1*

where:

d is the diameter of the collimator aperture.

L is the source-to-detector distance.
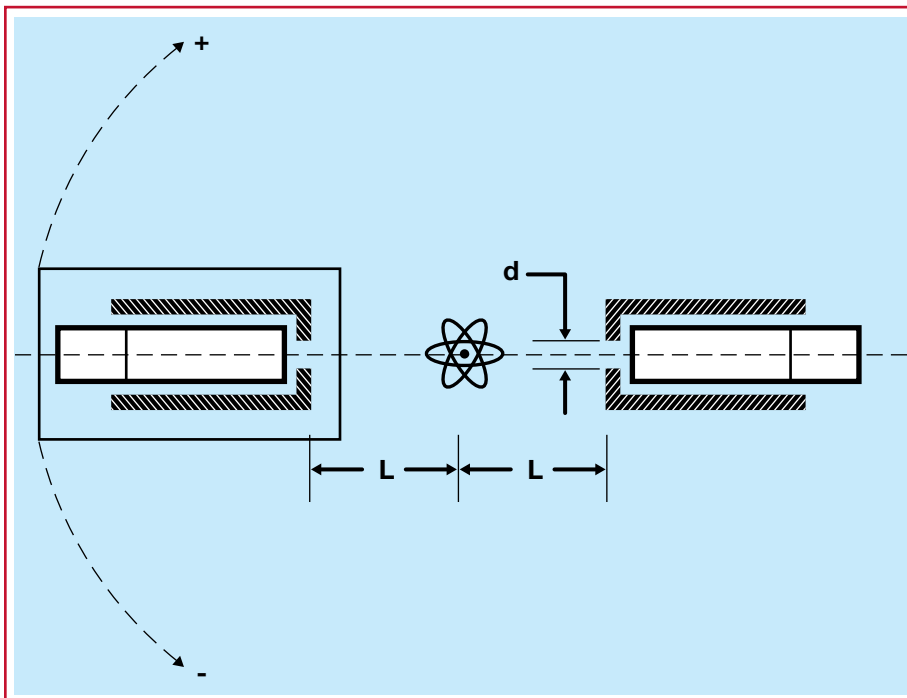
Figure 10-1:
Schematic of set up for Positron Annihilation experiment

Energy calibration

1. Open the ProSpect Gamma Spectroscopy Software and establish communication with the two MCAs.

2. Select the High Voltage Settings on the Detector tab on the ProSpect software to apply the recommended high voltage on both detectors connected to the MCA devices.

3. Set the Conversion gain on the MCA tab of the ProSpect software to 2048 channels for both the Osprey and the Lynx MCA.

4. Adjust the coarse and fine gain settings on the MCA tab of the ProSpect on both detectors such that the photopeak is close to the center of the spectrum.

5. Click on Start (on the top of the Spectral Display) to start accumulating a spectrum. Use a count time such that there is at least 10 000 counts in the photopeak.

6. For each detector perform an energy calibration using the 511.0 and 1274.5 keV peaks of ^{22}Na, referring to Experiment 1 if necessary.

7. Save the spectrum. Once you have set the gain and the energy calibration coefficients do not change them, otherwise you will change the calibration.

Time-coincidence measurements using TLIST acquisition mode

1. On the ProSpect software page set the data acquisition to TLIST mode. The TLIST mode allows storage of events which have information about energy and time for each event.

2. To acquire data in TLIST mode set up both detectors as shown in Table 10-1.

Table 10-1:
Settings synchronized TLIST mode acquisition with Lynx and Osprey MCA's

Osprey	Lynx
Acquire Settings	**Acquire Settings**
Acquire Mode: TLIST	Acquire Mode: TLIST
Acquire Presets : None	Acquire Presets : None
Latch : Fast Discriminator	Latch : Fast Discriminator
Timebase : 100ns	Timebase : 100ns
Clock: External	Clock: Internal
External Sync Settings	**External Sync Settings**
External Sync Status: Independent (to enable external clock	External Sync Status: Enable
Mode: Slave	Mode: Slave
Pulse: 1000ms	Pulse: 1000ms
Timeout : 20 seconds	Timeout : 20 seconds
GPIO Settings	
Ext Sync In assigned to Channel 1	

3. After the two devices are setup as described in Table 10-1, make sure to connect the Sync BNC connector on the Lynx rear panel (if needed add a 50 ohm terminator to prevent reflections) to the GPIO input channel 1 of the Osprey.

4. Select Control-Start to begin acquisition simultaneously on both devices.

5. Ensure that both detectors go into waiting mode (blue backgrounds on the datasource thumbnails). Rapidly (before the 20 second timeout is reached) switch the Lynx External Synchronization from Slave to Master B.

6. Ensure that both detectors begin acquiring data (PHA data appears in the display and both backgrounds turn green in the datasource thumbnail view).

7. Acquire data for around 5 minutes and save the data.

8. To analyze the TLIST mode data and see the results of the coincidence measurement, use the ProSpect TLIST Data Scanner. Follow the steps below to run the ProSpect Data Scanner.

9. In the Search Directories tab, identify the directory with the acquired TLIST data. Press the start button to begin analyzing.

10. In the Scan Results tab, select the appropriate acquisitions and set the beginning time Range to -6000 ns, maximum time range to 6000 ns, and the Time Bins to 1000.

11. On the Analysis tab, select the two acquisitions using the Device and Acq Start tabs. Plot Energy on the X-axis and Time on the Y-Axis to observe the coincident counts. Comment on the graph that is observed. Note you can copy the graph to your clipboard for further analysis.

Experiment 10 Guide

Continued

Angular dependence of coincidence counts

1. Locate one of the NaI detectors at angular positions of 5°, 10°, 15°, 20°, 25°, 30°, and -5°,-10°, -15°, -20°, -25°, -30° with respect to the axis of symmetry of the other NaI detector. At each angle repeat steps 19 through 28 as given above, and record the time coincidences for detecting the 511 keV gamma ray.

2. Determine the spread of angle in which a significant amount of coincident counts are detected. Plot the two coincidence counts for the 511 keV gamma ray as a function of angle between the 2 detectors. You should observe that the coincidence counts peak sharply at the 180° angle between the two detectors, and drop off quickly as the angle between the two detectors deviates from 180°.

3. Use Equation 10-1 to determine the angle subtended by the collimator. How does this compare the the angular spread observed in Step 2?

→ NOTES:

_____

_____

_____

_____

_____

_____

_____

_____

_____

Experiment ⑪

Mathematical Efficiency Calibration

→ Purpose:

① **To demonstrate how to use mathematical modeling to do efficiency calibrations and to verify the result with a radioactive source.**

→ Equipment Required:

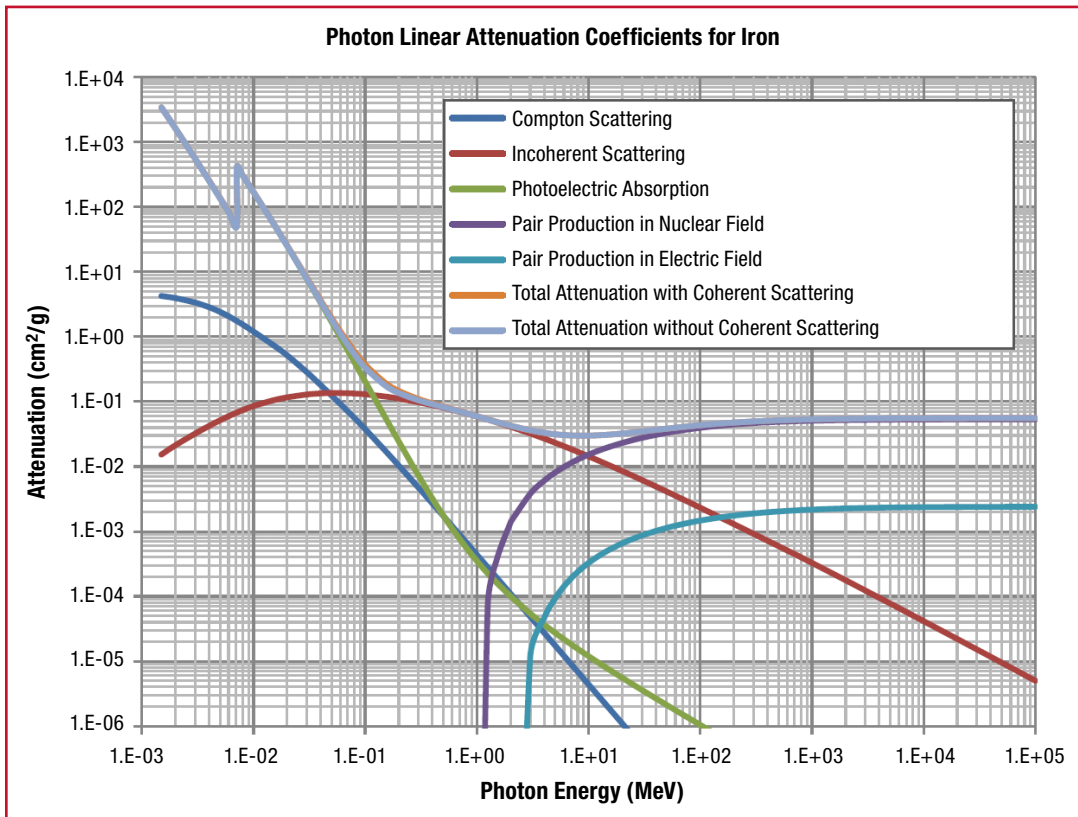|	
ProSpect:	ProSpect Gamma Spectroscopy Software
S574:	LabSOCS Mathematical Efficiency Calibration Software
BE2825:	BE2825 Broad Energy Germanium Detector System
Lynx-MCA:	Lynx-Digital Signal Analyzer
LABKIT-SRCEHLD:	Set of Two HPGe Source Holders
LABKIT-Abs:	Teaching Laboratory Absorber Set
Radioisotope:	^{152}Eu reference standard ± 5% unc
Radioisotope:	Unknown volumetric sample (such as Marinelli Beaker)

11

→ Theoretical Overview:

Measuring the efficiency with sources requires an inventory of sources that matches the geometries that are being measured. It is possible to acquire sources of common laboratory geometries, for example liquid solutions for beakers or epoxy matrices for Marinelli beakers. But there are geometries that are not practical to manufacture with sources or there may be cases of odd-shaped sources that are only going to be measured a few times or when parameters of the sample are different from the calibration source. In all of these cases mathematical calibrations can be used instead, such as Monte-Carlo simulation (e.g. Monte Carlo N-Particle eXtended [MCNPX] transport code) or CANBERRA's LabSOCS (Laboratory SOurceless Calibration Software) and ISOCS (In-Situ Object Counting Systems) methodology.

The interaction of photons with matter and its cross sections is well known and is tabulated for all naturally-occurring atoms for a wide range of energies. See Figure 11-1 and Experiment 3.

Using the equation:

$$I(x) = I_0 e^{-\mu x}$$ *Equation 11-1*

the attenuation of photons passing through a material of length x can be calculated. The attenuation of photons for a particular energy originating from a point in space directed to a point on the detector can be calculated from the cross sections, the densities, the atomic composition and the path length through all the materials between the point and the detector. This method, utilized

Photon Linear Attenuation Coefficients for Iron

- Compton Scattering
- Incoherent Scattering
- Photoelectric Absorption
- Pair Production in Nuclear Field
- Pair Production in Electric Field
- Total Attenuation with Coherent Scattering
- Total Attenuation without Coherent Scattering

Figure 11-1:
Linear attenuation coefficient of photon interaction in iron as a function of energy

by LabSOCS and ISOCS, is called ray tracing. In order to calculate the efficiency for the point it is also necessary to know the efficiency of the point without the materials, i.e. in a vacuum. With all of these parameters known it is possible to calculate the efficiency for this point in the measurement scenario. Points are generated uniformly in the radioactive part of the geometry and the efficiency is calculated for each of these points. The efficiency for the whole sample is the average of these points. When additional points are generated the sample efficiency will converge and the calculation finishes.

One of many benefits of mathematical modeling is that it is easy to refine the model if the sample does not agree with the modeled geometry. For example if the fill height of a beaker is not the same as the modeled fill height, the model can change to accommodate the difference. This contrasts a source-based calibration, where either the reference source or the sample measurement geometry must be physically modified, or the uncertainty in the sample activity must be increased significantly to accommodate the bias introduced by the discrepancy between the reference source and the sample. All other parameters can be changed in a similar manner for modeled efficiencies.

Introduction to LabSOCS (Mathematical Efficiency)

LabSOCS and ISOCS require that the detector to be used has been characterized by the detector manufacturer; the characterization is based on high-precision measurements and simulation optimization. This provides the vacuum-point efficiencies unique to each detector, and the calibration software then determines the attenuation correction for the specific measurement geometry. LabSOCS and ISOCS include a number of source templates to choose from such as point source, sphere, cylinder, beaker, box etc.

The user selects a template geometry, determines the relevant physical dimensions, and identifies a range of energies to calculate efficiency values. Figure 11-2 shows a picture of the different source geometries available in LabSOCS. Table 11-1 shows a typical listing of the energies and efficiencies from LabSOCS while Figure 11-3 shows a typical efficiency graph based on the values in the table. Refer to References 9 and 10 on Page 77 for more information on setting up and executing LabSOCS geometries.
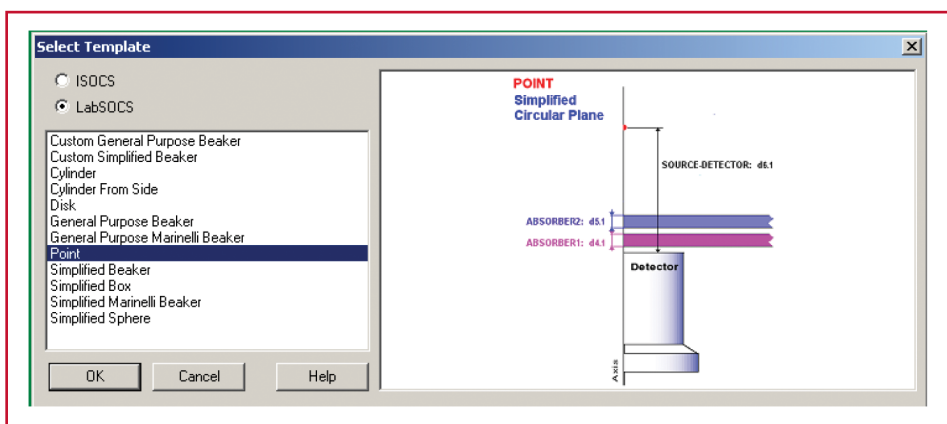
Figure 11-2:
Selection of LabSOCS sample geometry templates

Theoretical Overview
Continued

For an efficiency calibration to be accurate it is critical that the geometry used to generate the efficiency agrees with the geometry of the sample count. For mathematical modeling this means that the model created needs to resemble as closely as possible the measured sample. This includes the dimensions of the detector, the sample, any absorbers or collimators, the material composition and density. Extra care should be taken to accurately model the materials between the source and detector and the location of the source and materials (particularly close to the detector where the

efficiency is sensitive to small changes in location). Many commonly-used beakers don't have flat bottoms but a slightly curved bottom. If the sample is positioned directly on the end cap and the bottom of the beaker is not accurately modeled then this can lead to significant bias in the calculated efficiency and therefore the final measurement result. Parts of the sample that are not directly between the radioactive part of the geometry and the detector crystal do not influence the peak efficiency and therefore do not require as much attention.

Table 11-1:
LabSOCS calculated efficiencies for a point source at 20 cm from the surface of a 2x2 NaI detector

Energy (keV)	Efficiency
88.1	3.47E-03
122.1	3.49E-03
165.9	3.40E-03
279.2	2.72E-03
391.7	2.00E-03
661.7	1.16E-03
898	8.23E-04
1173.2	6.24E-04
1332.5	5.47E-04
1836.1	4.07E-04
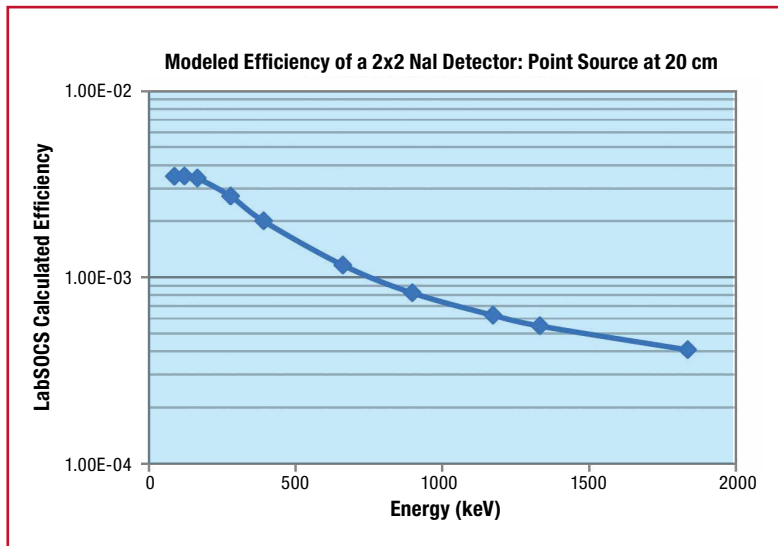
Figure 11-3:
Modeled efficiency for a 2x2 NaI detector with a point source located 20cm from the endcap

→ **Experiment** **11** **Guide:**

Exercise 1

1. Using LabSOCS, replicate the germanium detector experimental set-up of Experiment 8 and extract the efficiency values.

2. Plot these in Excel or another graphing application.

3. Compare the modeled efficiency curve with the measured efficiency curve from Experiment 8. Comment on any differences.

4. Estimate the uncertainties in the measured efficiency (statistical uncertainty and certificate uncertainty). See the LabSOCS manual for the modeled uncertainties. Do the measured and calculated efficiencies agree within the uncertainties? If not measure the dimensions of the sample again and refine the model.

Exercise 2

1. Ensure that the Lynx (with the HPGe detector connected) is connected to the measurement PC either directly or via your local network.

2. Using the adjustable source holder, place the ^{152}Eu reference standard at a distance of about 20cm from the endcap of the high-purity germanium detector. Record this distance. Remove any material between the source and detector before counting. Place one of the materials from the absorber kit between the source and the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Lynx.

4. Configure the MCA settings as recommended in Experiment 7.

5. Use the software to apply the recommended detector bias to the HPGe detector.

6. Set the PHA conversion gain to 32768 channels.

7. Adjust the coarse and fine gain of the MCA such that the 1408 keV peak is visible in the upper part of the spectrum.

8. Acquire data, ensuring that at least 10 000 counts are achieved in several of the major peaks throughout the spectrum. Use the spreadsheet to calculate the energy calibration coefficients. Enter these into ProSpect using the Energy Calibration tab.

9. Measure the net peak area and uncertainty for each of the major peaks. Calculate the ratio of count rates for each peak to the count rates for the data collected in Experiment 8.

10. Model the experiment setup of Step 2 in LabSOCS Geometry Composer and extract the efficiency values. Calculate the ratio of the efficiency values for this geometry to the efficiency values extracted in Exercise 1. How do these compare to the ratios calculated in Step 9?
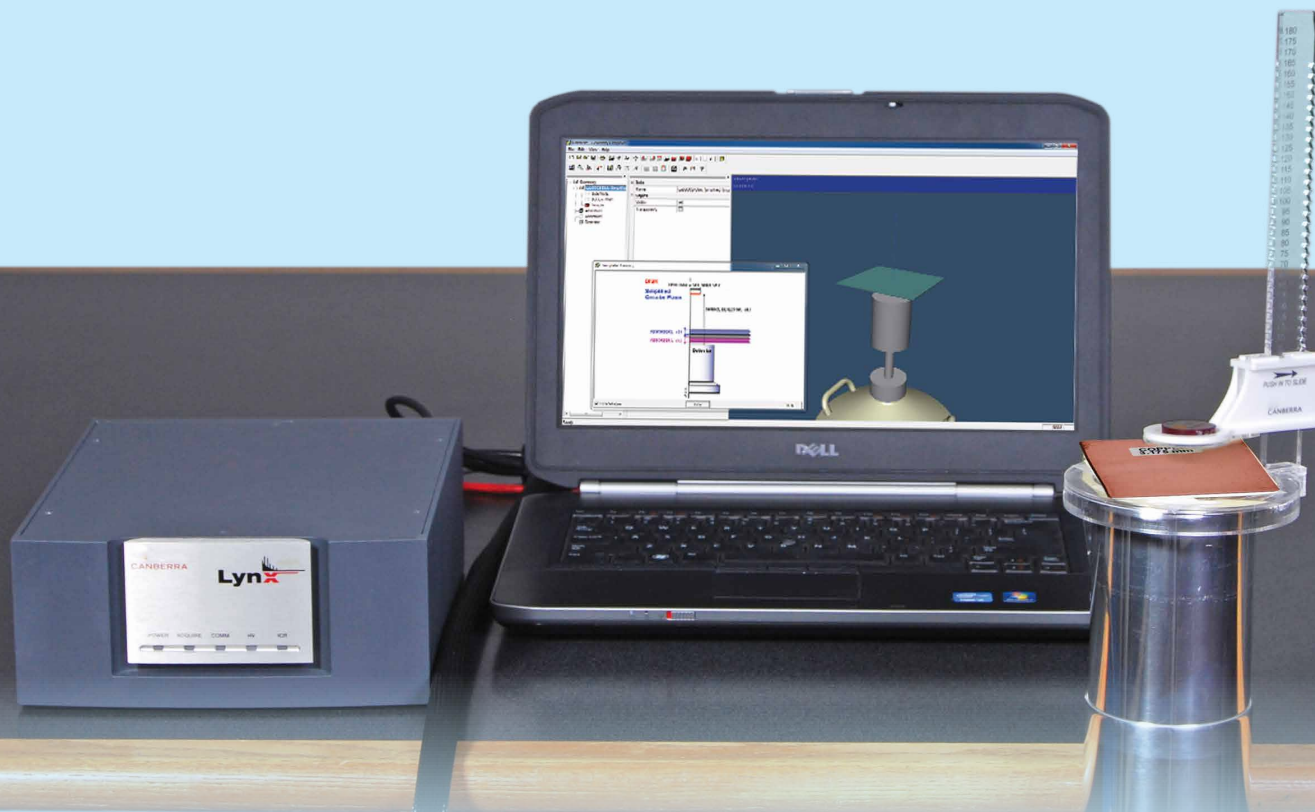
>> **Experiment 11 Guide**

Continued

Exercise 3

1. Place a volumetric sample of unknown activity on the germanium detector.

2. Count the sample for enough time to collect 10 000 counts in several significant peaks. Measure the net peak area and uncertainty for each of the major peaks, and identify candidate nuclides in the sample.

3. Using LabSOCS Geometry Composer, identify a template that is consistent with the measurement geometry. Measure the physical parameters and input them into LabSOCS. Extract the efficiency results.

4. Use the LabSOCS efficiency results, the peak area counts, and known photon intensities for the candidate nuclides, calculate the activity of the nuclides in the sample. Discuss the possible sources of error and uncertainty.

Exercise 4

1. In LabSOCS Geometry Composer create a model of a volumetric sample (such as the simple beaker template) on the detector end cap or use the one from the previous exercise and calculate the efficiency for a range of photon energies.

2. Calculate the efficiency of the same sample in Step 1 but at a distance of 10 cm from the detector.

3. Calculate the efficiency of the same sample in Step 1 but at a distance of 10 cm from the detector and with an absorber between the sample and the detector.

4. Compare the three modeled efficiencies to the two measured efficiencies for a low-, a medium- and a high-energy peak. For the different energies which is the most important parameter, the source-to-detector distance or the materials between the source and the detector?

5. In one of the models created decrease the fill height of the sample by 50% and calculate the efficiencies. Then compare it with the original model for a high-, medium- and low-energy peak. For which energy does the efficiency change the most? Explain the result.

→ **NOTES:**

_____

_____

_____

_____

_____

_____

_____

Experiment ⑫

True Coincidence Summing

→ Purpose:

① **To demonstrate true-coincidence summing.**

→ Equipment Required:

|	
ProSpect:	ProSpect Gamma Spectroscopy Software
S574:	LabSOCS Mathematical Efficiency Calibration Software
BE2825:	BE2825 Broad Energy Germanium Detector System
Lynx-MCA:	Lynx-Digital Signal Analyzer
LABKIT-SRCEHLD:	Set of Two HPGe Source Holders
LABKIT-Abs:	Teaching Laboratory Absorber Set
Radioisotope:	^{152}Eu reference standard ± 5% unc
Radioisotope:	^{22}Na button source 1 microcurie, ± 20% unc
Radioisotope:	^{60}Co button source 1 microcurie, ± 20% unc

→ Theoretical Overview:

Gamma-Gamma coincidences

Many common nuclides emit two or more photons from the same decay, often called a cascade. The initial decay (it could be α, β-, β+ or electron capture) populates an excited state in the daughter nucleus. This state will decay by photon emission or internal conversion to a less-excited state in the nucleus (which could be the ground state).
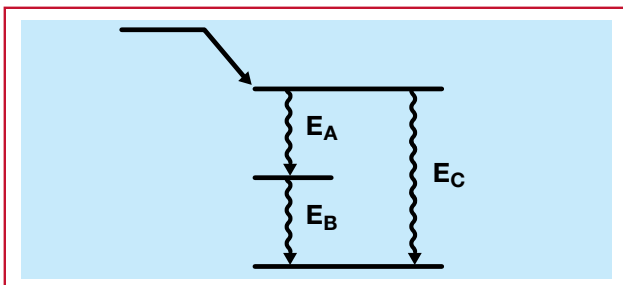
Figure 12-1 shows the decay schema of ^{60}Co, where the sequential decays from the excited states can be seen.
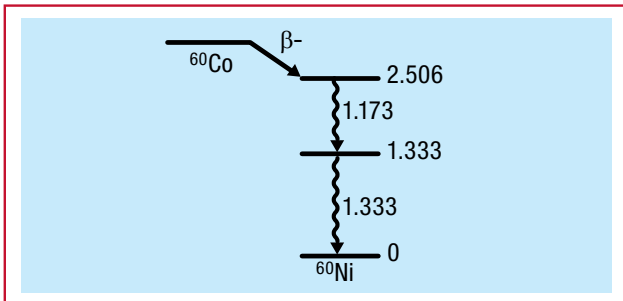
Figure 12-1:
The decay schema of ^{60}Co decay
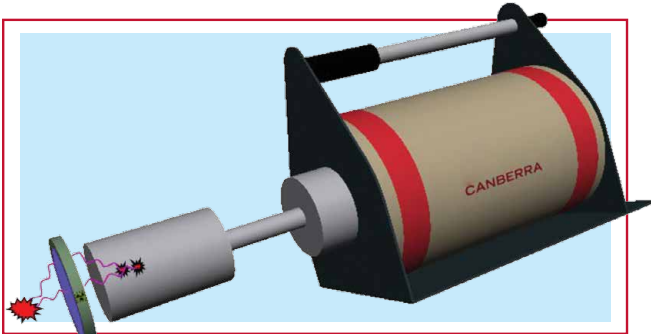
Figure 12-2:
A decay emitting two photons and both of them depositing energy in the detector

Figure 12-3:
Decay schema demonstrating "summing in" effect for energy E_C

The typical lifetime of excited states in a nucleus is in the picosecond time scale. The typical response time for a detector, i.e. the minimum time between two photon events that is needed for the detector to recognize these as two separate events, is in the order of microseconds. Note that this is several orders of magnitude longer than the typical lifetime of the excited states. For decays where more than one photon is emitted there is a significant probability that multiple photons will interact with and deposit energy in the detector. Since the time between the photon emissions is much shorter than the response time for the detector, it is not possible for the detector to distinguish the photons as separate events and only one pulse is generated, which corresponds to the sum of the individual deposited energies. Figure 12-2 shows an example of a decay emitting two photons with both photons depositing energy in the detector within the detector's resolving time. This event is called true-coincidence summing, or cascade summing. Two cases require special attention:

1. **"Summing Out"** In this event, one of the photons deposits all of its energy in the detector (for example the 1173 keV gamma ray in Fig 12-1) and the other photon (for example the 1332 keV gamma ray) deposits some or all of its energy in the detector. This will move a count from the full-energy peak of the first photon (at 1173 keV for this example) to a higher energy in the spectrum. This reduces the count rate of the first photon compared to the detection of only a single photon. This phenomenon is called summing out.

2. **"Summing In"** This effect is relevant when the gamma energy of interest is equal to the sum of the energy of two other gamma rays in the decay schema like the example in Fig 12-3. Here summing between gamma rays of energy E_A and E_B will cause an increase in the count rate of the peak at energy E_C. This is called summing in.

Gamma-x-ray coincidence

There are two ways that x-rays can be produced so that they will contribute to true-coincidence summing.

1. **"Electron Capture"** Here one of the closely-bound electrons is captured, creating a vacancy on one of the inner electron shells. Electrons from the outer shells will fill the inner-shell vacancy and emit x-rays that can be detected. Since these x-rays are created from the initial decay, every photon emitted from the daughter nucleus can be detected in coincidence with the x-rays (including cases where a single photon is emitted). This is an example of summing out.

2. **"Internal Conversion"** Internal conversion is a process when the excited nucleus interacts with the electron cloud around the nucleus and the excess energy is transferred to one of the electrons which will be emitted from the atom. This will create a vacancy in one of the electron shells which will be filled by an outer electron and an x-ray will be emitted, similar to electron capture described above. This is also an example of summing out.

Gamma-annihilation photon coincidence

There are cases where photons created by the decay process (such as in $\beta+$ decay) can sum with the photons from the daughter nuclide. In $\beta+$ decay, positrons are emitted which will slow down in the surrounding material, find an electron and annihilate emitting two back-to-back photons with an energy of 511 keV. The time it takes for the positron to slow down and annihilate is short compared to the response time of the detector. If at least one of the photons from the annihilation deposits energy in the detector in addition to detection of a photon in the daughter nucleus then the count will be moved from the full energy peak. This is another case of summing out as described above.

Probability of true-coincidence summing

Because true-coincidence summing requires the detection of two photons from the same decay it is strongly dependent on the following:

1. The detection efficiency for the photons that participate in the summing process. This is a function of the detector type and the counting geometry that is used. For example, the probability of detecting two photons as a summed event increases with increasing detector size and decreasing source-to-detector distance.

2. The nuclide that is being measured. More specifically, the decay schema of the nuclide. Earlier we have learned that summing in and out depends on the gamma-ray decay schema (e.g. the presence of a cascade and the mode of decay, such as internal conversion or electron capture). There are some nuclei that are unaffected (such as ^{137}Cs) and others (such as ^{60}Co and ^{88}Y) that demonstrate significant summing effects.

≫ Theoretical Overview

Continued

Consequences for source-based efficiency calibrations

Most commercially available multi-gamma sources include nuclides that exhibit true-coincidence summing. For example it is common to use ^{60}Co and ^{88}Y as the high-energy photon-emitting nuclides and both of these suffer from summing out. Using nuclides that have summing-out effects in close geometries will result in peak count rates that are lower than they would have been if the nuclide didn't have summing-out effects. The result of this is that the efficiency at these energies will appear to be lower than the true efficiency. If these efficiency points are used without correction, then then the calculated efficiency will be biased low compared to the true efficiency. As a result, when the efficiency is used to calculate the activity for a summing-free sample measurement the result will be higher than the true activity.

Consequences for sample counts

For sample counts, the summing-out effects will cause a reduction in the measured peak count rates; the measured activities will therefore be lower than the true activities. Summing in has the opposite effect, with measured activities exceeding the true activities. It should be noted that summing-out effects are most common. It is also the more significant effect since the underestimating of nuclide activities can have safety implications.

Reducing the effect of true-coincidence summing

Since the probability of true-coincidence summing is dependent on the detection efficiency, the effect can be reduced by moving the sample away from the detector. However, the impact of reducing the overall efficiency of the counting system can result in increased counting times (in order to maintain counting statistics) and therefore reduced productivity for sample counting.

If the coincidence summing is mainly due to x-rays (as may be the case when the nucleus decays by electron capture) then the coincidence summing can be reduced by introducing an attenuator that will attenuate most low energy photons. The optimum treatment is to use software, such as LabSOCS, to quantify and correct for true-coincidence-summing effects. This approach is applicable for all measurement geometries and all commonly measured nuclides that are known to be affected.

≫ **www.canberra.com**

→ **Experiment** **12** **Guide:**

Measurements

1. Ensure that the Lynx (with the HPGe detector connected) is connected to the measurement PC either directly or via your local network.

2. Place the ^{137}Cs source in front of the detector.

3. Open the ProSpect Gamma Spectroscopy Software and connect to the Lynx .

4. Configure the MCA settings as recommended in Experiment 7.

5. Use the software to apply the recommended detector bias to the HPGe detector.

6. Set the PHA conversion gain to 32768 channels

7. Set the amplifier gain such that the full-energy peak is close to 40% of the spectrum.

8. Make an energy calibration.

9. Position the ^{137}Cs source on the end cap and acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

10. Make a record of the number of counts in the full-energy peak(s).

11. Position the ^{137}Cs source 5 cm from the source and acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

12. Make a record of the number of counts in the full-energy peak(s).

13. Position the ^{137}Cs source 30 cm from the source and acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

14. Make a record of the number of counts in the full-energy peak(s).

15. Position the ^{137}Cs source on a thin copper sheet directly on the end cap and acquire a spectrum (use a count time such that there is at least 10 000 counts in the full-energy peak).

16. Make a record of the number of counts in the full-energy peak(s).

17. Repeat step 16 for a ^{60}Co source.

18. Repeat step 16 for a ^{22}Na source.

19. Repeat step 16 for a ^{152}Eu source.

Analysis

1. In LabSOCS Geometry Composer create a model of the point source at the three different distances and with the copper absorber. Calculate the efficiencies for all the energies for which peak areas were calculated.

2. Using the peak areas, count times and the known photon-emission rate for the sources (it can be found on the source certificate) calculate the efficiencies for all sources and geometries.

3. Calculate the true-coincidence-summing factor (defined as the measured efficiency divided by the calculated efficiency) for all sources and geometries. A factor close to 1 indicates that there is no or negligible true-coincidence summing. A factor less than 1 indicates that there are summing-out coincidences and a factor larger than 1 indicates that there are summing -n coincidences.

4. For each source and geometry explain the value of the true-coincidence-summing factor. If necessary look up the decay scheme from a book or online, for example from the National Nuclear Data Center at Brookhaven National Laboratory http://www.nndc.bnl.gov/nudat2/.

→ Glossary of Terms and Acronyms

ADC: Analog-To-Digital Converter – Device that converts a continuous signal to a digital number that represents the signal's amplitude

ALARA: As Low As Reasonably Achievable – Best practice methodology to reduce radioactive dose

Band gap: Energy range in which no electron states can exist in a solid

Barn: Unit used to describe cross-sectional area equal to 10^{-28} m^2; approximately the size of one uranium nucleus.

Becquerel: SI unit of radioactivity equal to one nuclear decay per second

BEGe: Broad-Energy Germanium Detector – P-type point contact high-purity germanium detector manufactured by CANBERRA

Beta decay: β- (electron), β+ (positron) emission or electron capture by the nucleus

Bias voltage: Degree of voltage to apply to a detector to obtain the desired response

Coincidence: The state in which two or more events are detected in two different detectors within a small time window

Collimator: Shielding surrounding a detector or source designed to restrict the field of view of the detector or source

Compton edge: Maximum energy up to which the Compton scattering is continuous

Compton scattering: Inelastic scattering of a photon by free electrons in a material

Conduction band: Energy range in which an electron is freed from the atomic binding and is able to move freely within the atomic lattice of the material

Cross section: Effective area of a particle that governs the likelihood of an interaction

Curie: Unit of radioactivity equal to 3.7 x 1010 decays per second

Decay constant: Proportionality constant between the rate of radioactive nuclear decay and the number of radioactive nuclei remaining

Depletion region: Region in a semiconductor in which all free charge carriers have been removed, creating an insulating region within a normally-conductive region. In semiconductor detectors the incident radiation interacts in this region producing electron-hole pairs.

Detection efficiency: Ratio of the number of photons detected or observed by the detector with respect to the number of photons emitted by the source

DLFC: Dual-Loss-Free Counting – Dual data acquisition of a dead-time-corrected and uncorrected PHA spectrum

DPP: Digital-Pulse Processing – Method of data processing such that digitization of the signal occurs directly from the output of the preamplifier stage

DSO: Digital-Signal Oscilloscope – Electronic viewer of the traces generated by digital pulse processing

Efficiency calibration: Process of correlating the total number of events to the number of events detected in a spectroscopic measurement

Energy calibration: Process of associating pulse height to incident-particle energy in a spectroscopic measurement

FT: Flat Top – Time duration of the maximum amplitude during the trapezoidal shaping

FWHM: Full-Width Half Maximum – A unit of measure of energy or time resolution for a spectral peak, determined by the width of the peak at one half the peak amplitude

FWTM: Full-Width Tenth Maximum – A unit of measure of energy or time resolution for a spectral peak, determined by the width of the peak at one tenth the peak amplitude

Gamma-ray: High-energy electromagnetic radiation typically produced by a nuclear decay

GPIO: General-Purpose Input/Output connections – Connections that generate a digital signal after software configuration specific to the user's application

Half length: Length at which the photon intensity is reduced to one half the original intensity by attenuation through a material

Half-life: Unit of time for a nucleus to decay to one half its original activity

HPGe: High-Purity Germanium Detector – A semiconductor sensor sensitive to gamma rays and x-rays

Insulator: Material that resists the conduction of electric current under an electric field, as the internal electric charges do not flow freely in the material

Intrinsic efficiency: Relates the counts in the spectrum to the number of events incident on the detector

ISOCS: In-situ Object Counting System – CANBERRA mathematical calibration software

LabSOCS: Laboratory Sourceless Calibration Software – CANBERRA mathematical calibration software

LIST: List Mode Data Acquisition – Records the pulse height of each event

LLD: Lower-Level Discriminator – Threshold for which the pulse height of a count must be greater in order to be registered

MCA: Multi-Channel Analyzer – Device that shapes the signal from the preamplifier and prepares the data for output to the computer

MCNP: Monte Carlo N-Particle Transport Code – Software packaged for simulating nuclear processes developed by Los Alamos National Laboratory

MCS: Multi-Channel Scaling data acquisition – Creates a time histogram for each event detected in a defined dwell time

MSS: Multi-Spectral Scaling data acquisition – A series of continuous PHA-type acquisitions with minimal time loss between acquisitions

NaI(Tl): Thallium-activated sodium iodide detector, which produces a scintillation event in response to ionizing radiation

Pair production: Process whereby a positron and electron pair are produced, requiring an initial minimum photon energy equal to twice the rest mass of an electron

PHA: Pulse Height Analysis – Data acquisition which populates the pulse height of each count into an energy histogram

Photoelectric effect: Phenomenon in which electrons are emitted from an atom when they absorb energy from an incident photon. All of the initial photon energy is transferred to the electron.

≫ Glossary of Terms and Acronyms

Continued

Photon: A particle representing a quantum of light or other electromagnetic radiation. A photon carries energy proportional to the radiation frequency but has zero rest mass.

PMT: Photo-Multiplier Tube – Integral part of scintillator detectors which detects and multiplies light production by as much as 100 million times

Preamplifier: An element in the detector signal chain that amplifies the signal from the detector for further processing

Radioactive activity: Number of nuclei that decay through the emission of particles per unit time

Radioisotope: An atom with a particular number of neutrons and protons, characterized by an unstable nucleus and an availability of excess energy

Relative efficiency: The ratio of the absolute efficiency of a detector at an energy of 1332 keV for a point source at 25 cm relative to the absolute efficiency of a 2x2 NaI(Ti) detector for the same energy and configuration

ROI: Region of Interest – Range between two defined upper- and lower-energy (or channel) values. Usually set to span a full-energy peak to measure the centroid energy, resolution or peak area.

RT: Rise Time – Time duration from baseline to the initial maximum amplitude of the shaped output during trapezoidal shaping

SCA: Single-Channel Analyzer – Data acquisition in which a digital signal is generated if a pulse falls within the range defined by the LLD and ULD

Scintillation: Process whereby a flash of light is generated from a material in response to incident radiation

Semiconductor: Material characterized by an electric conductive behavior between that of an insulator and a conductor

Spectrometry: Process deriving quantitative results of a measurement using spectroscopic techniques

Spectroscopy: Process of collecting and analyzing a spectrum

Steradian: SI unit of solid angle

TLIST: Time-Stamped List Mode – Data acquisition in which both the time and the pulse height for each event are recorded.

ULD: Upper-Level Discriminator – Threshold for which the pulse height of a count must be lower to be registered

Valence band: Highest-energy range in which it is expected to find electrons in a solid with zero excess energy

X-ray: Electromagnetic radiation ranging in energy from 100 eV to 100 keV.

→ References and Further Reading

1. Krane, K. S. (1988). *Introductory Nuclear Physics*. United States: John Wiley & Sons, Inc.

2. Knoll, G. F. (2010). *Radiation Detection and Measurements* (4th ed.). United States: John Wiley & Sons, Inc.

3. Gilmore, G. (2008). *Practical Gamma Ray Spectrometry* (2th ed.). United States: John Wiley & Sons, Inc.

4. Bevington, P. R.; Robinson, D. K. (2003). *Data Reduction and Error Analysis for Physical Sciences* (3rd ed.). Boston, MA: McGraw-Hill, Inc.

5. Berger, M. J., Hubbell, J. H., Seltzer, S. M., Chang, J., Coursey, J. S., Sukumar, R., Zucker, D. S., & Oslen, K. (2010), XCOM: Photon Cross Sections Database (Version 1.5) [Online]. Available from National Institute of Standards and Technology: http://www.nist.gov/pml/data/xcom/index.cfm.

6. X-5 Monte Carlo Team (2003). MCNP – A general Monte Carlo N-Particle Transport Code (Version 5) [Software]. Los Alamos National Laboratory. Available from http://mcnpx.lanl.gov/.

7. National Nuclear Data Center at Brookhaven National Laboratory. NuDat 2.6. [Data Base]. Available from http://www.nndc.bnl.gov/nudat2/.

8. Firestone, R. B., Baglin, C. M., & Chu S. Y. F. (1999). *Table of Isotopes* (8th ed.). United States: John Wiley & Sons, Inc.

9. CANBERRA. (2012). *Model S574 LabSOCS^{TM} Calibration Software: Technical Reference Manual.* Meriden, CT.

10. CANBERRA. (2012). *Geometry Composer: User's Manual*. Meriden, CT.

11. CANBERRA. (2012). *ProSpect Gamma Spectroscopy Software: User's Manual*. Meriden, CT.

12. CANBERRA. (2012). *Osprey^{TM} Universal Digital MCA Tube Base: User's Manual*. Meriden, CT.

13. CANBERRA. (2011). *Lynx^{TM} Digital Signal Analyzer: User's Manual*. Meriden, CT.

CANBERRA

Nuclear Measurement Solutions for Safety, Security and the Environment