EDUCATIONAL LABORATORY

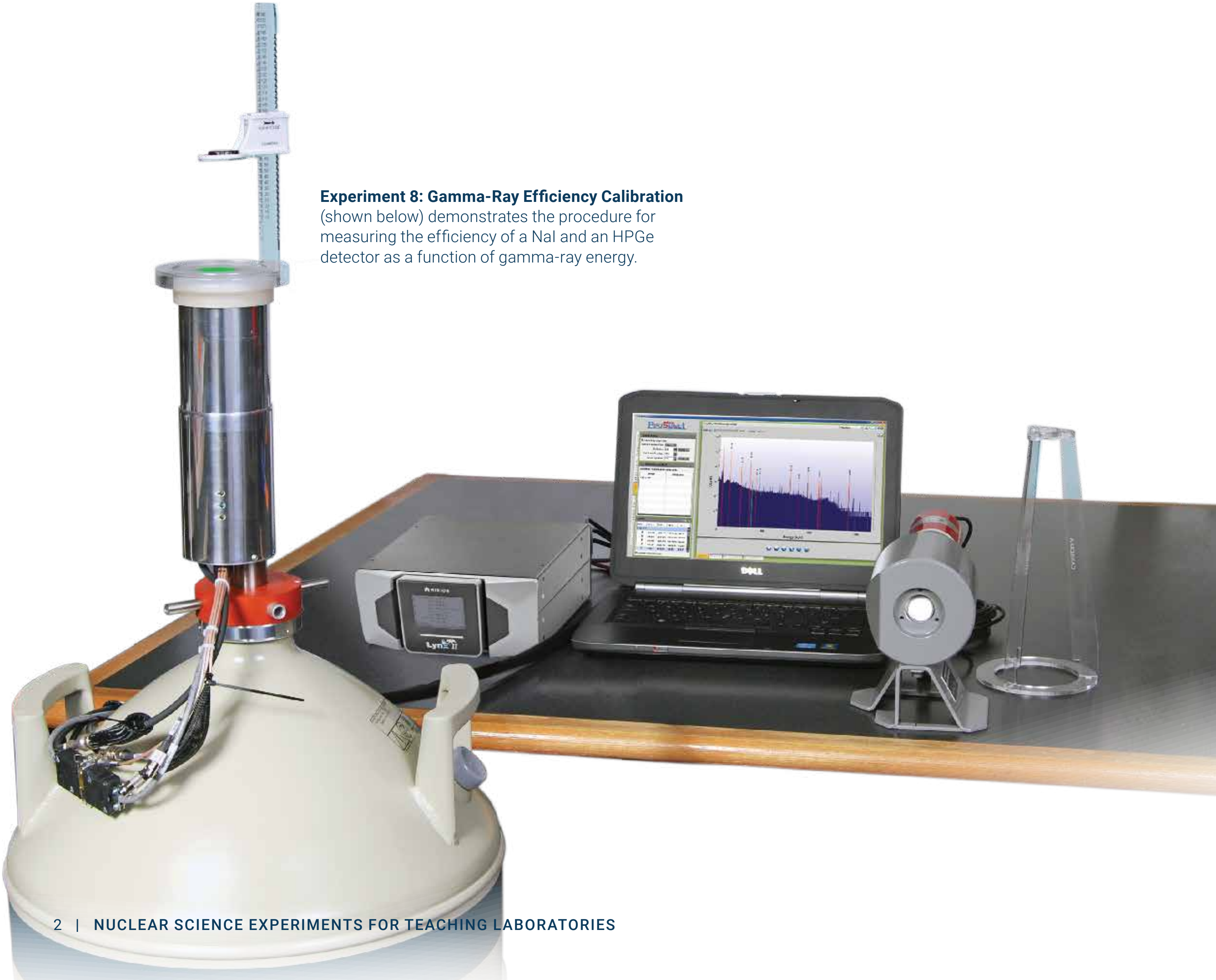
# Nuclear Science Experiments for Teaching Laboratories

# Turn-Key Training Solutions

## Nuclear Science Experiments for Teaching Laboratories

With a half century of experience in the nuclear measurements industry, Mirion Technologies is uniquely qualified to provide educational institutions with the tools for highly productive hands-on training in the fundamentals of nuclear physics through vocationally-relevant experiments.

Mirion offers turn-key solutions to set up and/or refurbish physics teaching facilities with cutting-edge digital technology. A relatively modest investment yields a flexible equipment configuration that can serve undergraduate and post-graduate university training in addition to in-house training for industrial users.



**Experiment 8: Gamma-Ray Efficiency Calibration** (shown below) demonstrates the procedure for measuring the efficiency of a NaI and an HPGe detector as a function of gamma-ray energy.

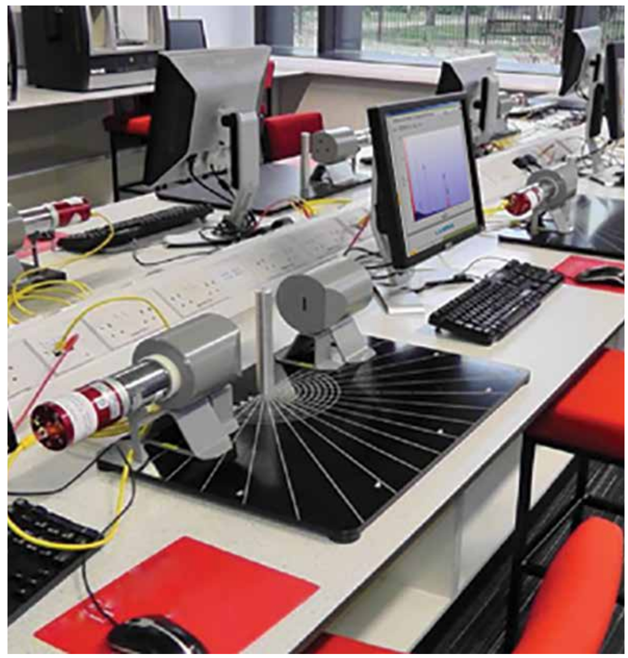
## Mirion Lab Kits

Mirion has packaged a set of 12 experiments, focusing on various aspects of gamma-ray detection and analysis, which provide an understanding of basic principles to more complex nuclear physics applications.

All of these experiments can be executed with Mirion instrumentation and specialized ancillary equipment offered in two Lab Kits. (Please note that most of the recommended radioactive sources are not included and are readily available.) The Nuclear Science Experiments with Digital Electronics Laboratory Manual provides a step-by-step guide to performing the experiments. The Laboratory Manual is available at https://www.mirion.com/learning-center/lab-experiments, and unlimited copies may be printed as needed.

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

The Osprey and Lynx II units 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.

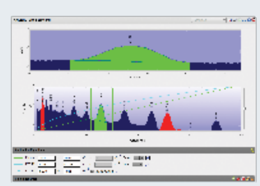


Lynx II Digital Signal Analyzer

Osprey MCA

Lynx II Digital Signal Analyzer

Osprey Universal Digital MCA Tube Base for Scintillation Spectrometry



ProSpect Gamma Spectroscopy Software

## The Laboratory Manual and kits greatly simplify the purchase of equipment and implementation of these experiments (plus other experiments of your own design).

They can be used to create individual student workstations or a central demonstration station, depending on available space and budget. And, of course, lab expansion is just as simple as adding more kits as needs dictate.

### LABKIT-Basic

**STARTER KIT FOR EXPERIMENTS 1 TO 5**

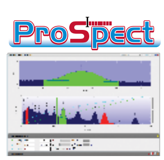
- **Osprey Digital MCA**
- **ProSpect Gamma Spectroscopy Software**
- **802 2x2 NaI Detector**
- **LabKIT-Table:** Apparatus for many of the experiments, including an angular scattering table and base plate, NaI 2"x2" detector shielding, source collimation for LABKIT-SR-CS137, scattering pillar, and absorber holder.
- **LabKIT-Abs:** Set of four generic absorber materials, including aluminum, copper, lead, and polyethylene.
- **LabKIT-SR-Cs137:** 15 MBq (0.5 mCi) Cs-137 source capsule, for use with the LABKIT-Table assembly.

### LABKIT-Advanced

**SUPPLEMENT THE STARTER KIT TO COMPLETE EXPERIMENTS 6 TO 12**

- **LYNX II DSA**
- **BE2825 HPGe Detector System**
- **LabSOCS™ Software**
- **802-2x2 NaI Detector**
- **2007P Preamplifier**
- **LABKIT-SRCEHLD:** Set of two HPGe Source Holders, including a fixed source holder for measurements at 25 cm and an adjustable source holder for measurements from 0 to 18 cm.
- **LABKIT-NAICOLL:** NaI 2" x 2" detector shielding for use with LABKIT-Table assembly.
- **RCP-10-Cable:** 10 ft cable bundle including preamp, SHV-SHV, and two BNC-BNC cables.


Osprey Universal Digital MCA



ProSpect Gamma Spectroscopy Software


802 2x2 NaI Detector

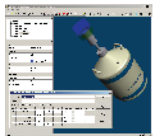

Shown: LabKIT-Table, LABKIT-NAICOLL


LabKIT-Abs


LabKIT-SR-Cs137


Lynx II Digital Signal Analyzer


BE2825 HPGe Detector System


LabSOCS Software


2007P Preamplifier


LABKIT-SRCEHLD


LABKIT-NAICOLL


RCP-10-Cable

## The Laboratory Manual presents the following twelve experiments.

With LABKIT-Basic, students can perform experiments 1-5.
To perform all twelve experiments, LABKIT-Basic and LABKIT-Advanced are required.

### EXPERIMENT 1
**Gamma-Ray Detection with Scintillators**

In this introduction to gamma-ray detection, students will identify photoelectric effect, Compton scattering, and pair production in a spectrum and perform an energy calibration using known reference sources.

### EXPERIMENT 2
**Counting Statistics and Error Prediction**

Students will perform a series of background and gamma-ray measurements with a NaI detector and apply statistical principles to these measurements.

### EXPERIMENT 3
**Gamma-Ray Absorption in Matter (Basic)**

Students will measure the effective attenuation of a set of materials with varying densities and photon absorption cross sections.

### EXPERIMENT 4
**Compton Scattering**

Using the Compton Scattering table developed specially for this exercise, the principle of Compton scattering and the dependence on angular variation is demonstrated.

### EXPERIMENT 5
**Half-Life Measurement**

Students calculate the half-life of a short-lived nuclide using multi-channel scaling acquisition.

### EXPERIMENT 6
**Signal Processing with Digital Signal Electronics**

Using the built-in Digital Signal Oscilloscope feature of the Lynx II DSA, students observe the effects of changing signal processing parameters using several different acquisition modes.

### EXPERIMENT 7
**High-Resolution Gamma-Ray Spectroscopy with HPGe Detectors**

Semiconductor gamma-ray detection is introduced and students compare HPGe resolution to NaI detector resolution.

### EXPERIMENT 8
**Gamma-Ray Efficiency Calibration**

Using both a NaI detector and an HPGe detector, the concept of detection efficiency is explored.

### EXPERIMENT 9
**Gamma-Ray Coincidence Counting Techniques**

Counting with multiple detectors correlated in time can yield incredible information about fundamental nuclear structures. In this experiment, students learn these techniques by acquiring and interpreting time-stamped list mode data for synchronized detectors.

### EXPERIMENT 10
**Positron Annihilation**

By using coincidence counting techniques and the Angular Correlation table, students explore the geometrical behavior of positron annihilation events.

### EXPERIMENT 11
**Mathematical Efficiency Calibration**

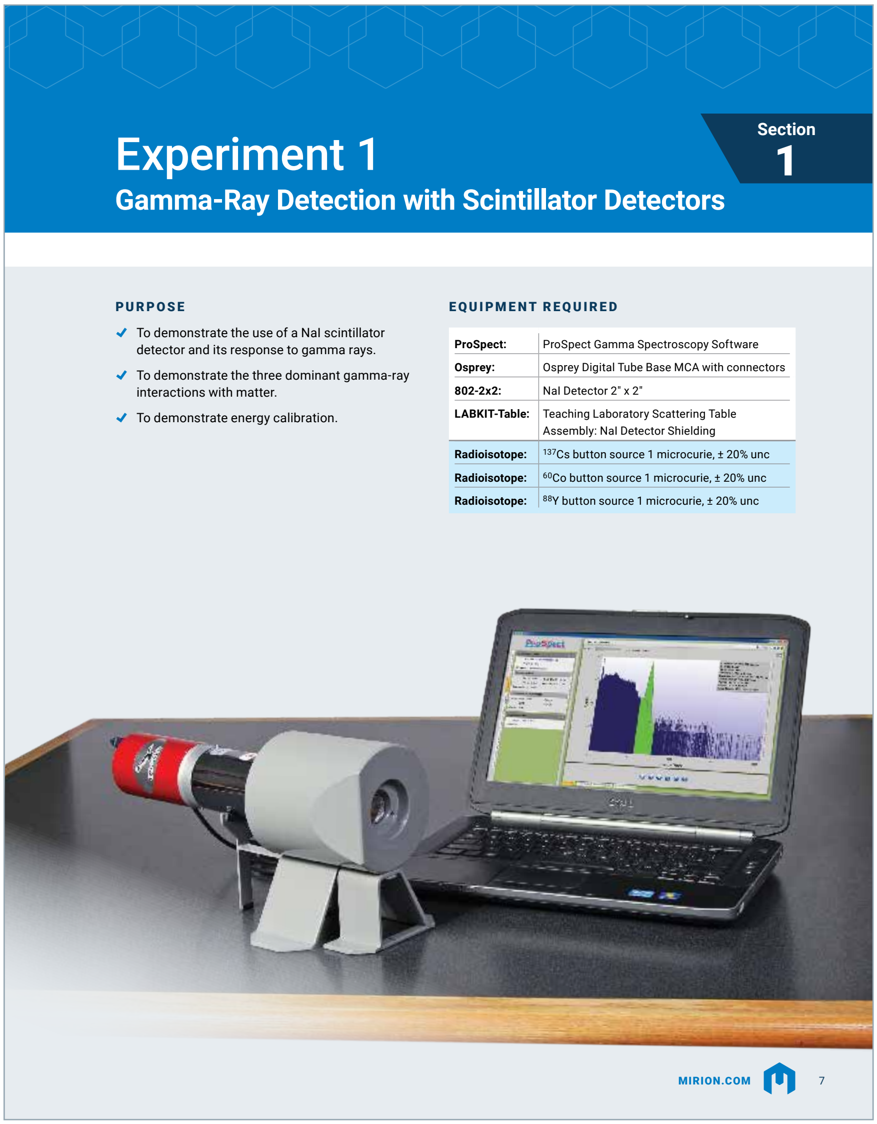
Mathematical modeling is increasingly used instead of source based efficiency calibration for improvement in cost, flexibility, and safety. In this experiment, students generate efficiency calibrations using Mirion LabSOCS efficiency calibration software and compare against traditional source based calibrations.

### EXPERIMENT 12
**True Coincidence Summing**

Students observe true coincidence summing and quantify the effect on observed count rate using LabSOCS mathematical efficiency software.

## As you can see in this sample, the format of each experiment begins with the goal and the equipment required.

Each description includes the required steps together with the format of the data entry and the results. In some cases, the instructor may wish to produce his or her own laboratory script with this as a starting point.



Section 1

# Experiment 1

## Gamma-Ray Detection with Scintillator Detectors

**PURPOSE**

- ✓ To demonstrate the use of a NaI scintillator detector and its response to gamma rays.
- ✓ To demonstrate the three dominant gamma-ray interactions with matter.
- ✓ 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 |

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## 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.

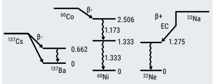


**Figure 1-1:**
Energy level sequences for $^{137}Cs$, $^{60}Co$ and $^{22}Na$ (energy levels in MeV)

### 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.

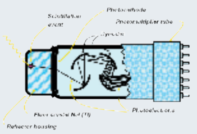


**Figure 1-2:**
Illustration of a scintillation event in a photomultiplier tube





### 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:

$$E' = \frac{E}{1 + \frac{E}{m_0c^2}(1 - \cos\theta)} \qquad \text{Equation 1-1}$$

where $E$ is the incident gamma-ray energy and $\theta$ is the angle of scatter. The term $m_0c^2$ is the rest mass of the electron, equal to 511 keV. The energy given to the electron is:

$$E_e = E - E' \qquad \text{Equation 1-2}$$

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 $\theta$ = 180°:

$$E' = \frac{E}{1 + \frac{2E}{m_0c^2}} \qquad \text{Equation 1-3}$$

and:

$$E_e = E - E' = E - \left[\frac{E}{1 + \frac{2E}{m_0c^2}}\right] \qquad \text{Equation 1-4}$$

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

The actual energy deposited depends upon the angle of scatter as described in the equations on the preceding page. 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.

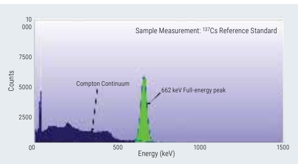


**Figure 1-3:**
Example spectrum of a $^{137}Cs$ source





## Experiment 1 Guide

### PHOTOELECTRIC EFFECT AND COMPTON SCATTERING

1. Ensure that the Osprey unit (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 unit.
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 II units

| 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 |

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