<u>Department of Physics</u> The University of Hong Kong

Physics Laboratory PHYS3851 Atomic and Nuclear Physics Experiment No. 3851-1 Gamma Ray Spectroscopy, Using NaI(Tl) Detector

Name:

University No.

Aims

- 1. To understand the working principle, properties and structure of sodium iodide NaI(Tl) Detector and a multi-channel analyzer (MCA)
- 2. To master the basic techniques used for measuring gamma ray by using NaI(Tl) Detector
- 3. To calibrate the MCA from known gamma sources
- 4. To determine the energy resolution and linearity of the spectroscopy
- 5. To identify an unknown gamma source from its spectrum.

Pre-lab Reading: Theory - Background Information

Principle

(a) Gamma-ray radioactive source - and :





(b) Interactions of gamma ray and matter:

Figure 4. Gamma-ray spectrum of ⁶⁰Co

The gamma spectrum from radioactive sources are due to the gamma ray emitted and the interaction between the gamma photon and the matter. i. Photons

The intensity reduction of electromagnetic radiation in matter is exponential. If photons with an intensity I_0 pass through a material with a mass absorption coefficient μ and thickness x, the intensity of the outcomming photons is given by

$$I(x) = I_0 e^{-\mu x}$$
 with $\mu = \sigma \frac{N_A}{M} \rho$

Here σ is the cross section, N_A is Avogadro's number and *M* is the molar mass of the material.





There are four processes for the interaction of gamma ray with matters when using a scintillation detector:



- 1. Photoelectric Effect
- 2. Compton Scattering plus photoelectric effect
- 3. Compton Scattering followed by the scattered gamma leaving the crystal
- 4. Pair Production

1) Photoelectric Effect:



<u>Before</u>	<u>After</u>
Figure 7 Illustration of Photoelectr	ic Effects

In photoelectric effect, a photon undergoes an interaction with an absorber atom in which the photon completely disappears.

After the absorption of the photon, an energetic photoelectron is ejected from one of the bound shells of the atom.

For gamma rays with sufficient energy, the most probable origin of the photoelectron is the most tightly bound of the atom. It means the bound electron at the lowest energy level has a higher chance to eject as photoelectron.

Due to the conservations of energy and momentum, no photoelectric effect is produced by free electron.

Generally, the photoelectron appears with an energy given by

 $E_{photoelectron} = E_{\gamma} - E_{binding}$

where *E*_{binding} represents the binding energy of the photoelectron in its original shell. Because the binding energy of the bound electron is much smaller than the incident energy of photon. (Usually, the gamma-ray energies of more than a few hundred keV). The photoelectron carries off the majority of the original photon energy. i.e.

 $E_{photoelectron} \approx E_{\gamma}$

The photoelectric process is the **predominant mode** of photon interaction at

• relatively low incident energy of photon.

For higher incident energy of photon, the bonding between the corresponding bound electron and nucleus is looser. The cross-section of photoelectric effect, $\sigma_{\text{photoelectric}}$ is inversely proportional to the E_{γ}^{3} .

• high atomic number Z.

For higher atomic number, the bonding between the bound electron and nucleus is stronger. The cross-section of photoelectric effect, $\sigma_{photoelectric}$ is directly proportional to Z^n . (where the exponent n varies between 3 and 4

over the gamma-ray energy region of interest.)

The probability of photoelectric absorption (or called photoelectric coefficient), symbolized τ (tau) and unit: m⁻¹, is roughly proportional to

$$\tau \propto \frac{Z^n}{\left(hf\right)^2}$$

where the exponent n varies between 3 and 4 over the gamma-ray energy region of interest.

2) Compton Scattering or Compton Effect

The Compton effect is a collision between a photon and a free electron. Of course, under normal circumstances, all the electrons in a medium are not free but bound. However, if the energy of the photon is of the order of keV or more, while the binding energy of the electron is of the order of eV, the electron may be considered free.

Compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material.

It is most often the predominant interaction mechanism for gamma-ray energies typical of radioisotope sources. i.e. energies of about 1 to 2 MeV.



Figure 8. Illustration of Compton Scattering

In Compton scattering, the incident gamma-ray photon is deflected through an angle θ with respect to its original incident direction.

The photon transfers a part of its energy to the free electron (assumed to be initially at rest), which is then known as a recoil electron, or a Compton electron.

- All angles of scattering are possible.
- The energy transferred to the electron can vary from zero to a large fraction of the gamma-ray energy.

• The Compton process is most important for energy absorption for soft living tissues in the range from 100 keV to 10MeV.

The Compton scattering probability is symbolized σ (sigma):

- almost independent of atomic number Z;
- decreases as the photon energy increases;
- directly proportional to the number of electrons per gram, which only varies by 20% from the lightest to the heaviest elements (except for hydrogen).

The energies of the incident photons (hf) and scattered photon (hf') and the Compton electron E_{comp} , are given by

$$hf' = hf \frac{1}{1 + \alpha(1 - \cos\theta)}$$

and

$$E_{comp} = hf \frac{\alpha(1 - \cos \theta)}{1 + \alpha(1 - \cos \theta)}$$

respectively.

The energy loss of the photon is related to

$$\frac{1}{hf'} - \frac{1}{hf} = \frac{1}{m_e c^2} (1 - \cos \theta)$$

where $= \alpha = \frac{hf}{m_e c^2}$, $m_e c^2$ is the electron rest energy, i.e. 0.511 MeV.

Limits of Energy Loss

Maximum energy transfers to recoil electron:

- angle of electron recoil is forward at 0° , $\varphi = 0^\circ$,
- the scattered photon will be scattered straight back, $\theta = 180^{\circ}$
- With $\theta = 180^\circ$, $\cos \theta = -1$ the expressions above simplify to:

$$E_{comp}(\max) = hf \frac{2\alpha}{1+2\alpha}$$

and

$$hf'(\min) = hf \frac{1}{1+2\alpha}$$

The Table below illustrates how the amount of energy transferred to the electron varies with photon energy. Energy transfer is not large until the incident photon is in excess of approximately 100 keV.

	Photon Energy, 5.11 keV	Photon Energy, 5.11 MeV
$\alpha = \frac{hf}{m_e c^2}$	0.01	10
$E_{comp}(\max) = hf \frac{2\alpha}{1+2\alpha}$	0.1keV	4.87keV
$hf'(\min) = hf \frac{1}{1+2\alpha}$	5.01keV	0.243MeV
Energy transferred to Compton electron, $E_{tr} = \frac{hf - hf'}{1 + e^{-hf'}}$	2%	95%
hf		

3) Pair Production



Figure 9. Illustrations of the Pair Production

If a photon enters matter with an energy in excess of $2m_ec^2$ (i.e. 1.022 MeV), it may interact by a process called pair production.

The gamma photon, passing near the nucleus of an atom, is affected to strong electric field effects from the nucleus and may disappear as a photon and reappear as a positron (e^+ , antimatter of electron) and electron e^- pair.

The two electrons produced, e^- and e^+ , are not scattered orbital electrons, but are created, de novo, in the energy/mass conversion of the disappearing photon.

Pair Production Energetics

The kinetic energy of the electrons produced through pair production will be the difference between the energy of the incoming photon and the energy equivalent of two electron masses (2×0.511 , or 1.022 MeV).

By conservation of energy: $E_{in} = E_{fin}$

Incident energy of photon = K.E. of e^- & e^+ + Rest energy of e^- & e^+

Pair production probability, symbolized κ (kappa),

- Increases with increasing photon energy
- Increases with atomic number approximately as Z^2





Figure by MIT OCW.

Figure 10. Comparison of the interactions of gamma ray and matter

- Photoelectric effect: produces a scattered photon and an electron, varies as ~ Z^4/f^3
- Compton effect: produces an electron, varies as ~ Z
- Pair production: produces an electron and a positron, varies as $\sim Z^2$

(c) The NaI(Tl) Detector



Figure 11. Illustrations of NaI(Tl) detector and its working principle

Overview of the detector system:

The structure of the NaI(Tl) detector is illustrated in Figure 10. It consists of a single crystal of thallium activated sodium iodide optically coupled to the photo cathode of a photomultiplier tube. When a gamma ray enters the detector, it interacts by causing ionization of the sodium iodide. This creates excited states in the crystal that decay by emitting visible light photons. This emission is called a scintillation, which is why this type of sensor is known as a scintillation detector. The thallium doping of the crystal is critical for shifting the wavelength of the light photons into the sensitive range of the photocathode. Fortunately, the number of visible-light photons is proportional to the energy deposited in the crystal by the gamma ray. After the on set of the flash of light, the intensity of the scintillation decays approximately exponentially in time, with a decay time constant of 250 ns. Surrounding the scintillation crystal is a thin aluminum enclosure, with a glass window at the interface with the photocathode, to provide a hermetic seal that protects the hygroscopic NaI against moisture absorption. The inside of the aluminum is lined with a coating that reflects light to improve the fraction of the light that reaches the photocathode.

At the photocathode, the scintillation photons release electrons via the photoelectric effect. The number of photoelectrons produced is proportional to the number of scintillation photons, which, in turn, is proportional to the energy deposited in the crystal by the gamma ray.

The remainder of the photomultiplier tube consists of a series of dynodes enclosed in the evacuated glass tube. Each dynode is biased to a higher voltage than the preceding dynode by a high voltage supply and resistive biasing ladder in the photomultiplier tube base. Because the first dynode is biased at a considerably more positive voltage than the photocathode, the photoelectrons are accelerated to the first dynode. As each electron strikes the first dynode the electron has acquired sufficient kinetic energy to knock out 2 to 5 secondary electrons. Thus, the dynode multiplies the number of electrons in the pulse of charge. The secondary electrons from each dynode are attracted to the next dynode by the more positive voltage on the next dynode. This multiplication process is repeated at each dynode, until the output of the last dynode is collected at the anode. By the time the avalanche of charge arrives at the anode, the

number of electrons has been multiplied by a factor ranging from 10^4 to 10^6 , with higher applied voltages yielding larger multiplication factors. For the selected bias voltage, the charge arriving at the anode is proportional to the energy deposited by the gamma ray in the scintillator.

The preamplifier collects the charge from the anode on a capacitor, turning the charge into a voltage pulse. Subsequently, it transmits the voltage pulse over the long distance to the supporting amplifier. At the output of the preamplifier and at the output of the linear amplifier, the pulse height is proportional to the energy deposited in the scintillator by the detected gamma ray. The Multichannel Analyzer (MCA) measures the pulse heights delivered by the amplifier, and sorts them into a histogram to record the energy spectrum produced by the NaI(Tl) detector. See Figure 13. for the modular electronics used with the NaI(Tl) detector.

- a. A good scintillation crystal should:
 - i) have a high stopping power for the incident gamma-ray. It also means high efficiency in detection of gamma-ray.
 - ii) have a high light output.

Light output (LO) is the coefficient of conversion of ionizing radiation into light energy. Having the high LO, NaI(Tl) crystal is the most popular scintillation material. LO (No. of photon/MeV) is the number of visible photons produced in the bulk of scintillator under gamma radiation.

 $\label{eq:LightOutput} LightOutput t = \frac{No.\,of \,\,Emitted \,\,Photons}{Obsorbed\,Energy}$

For the measurement of energy spectrum, the light output should be constant. Otherwise, the linearity of energy of incident gamma-ray and the amplitude of output pulse by the scintillation crystal is not obeyed.

- iii) have a short decay time to reduce detector dead-time and accommodate high event rates.
- iv) emit in a spectral range matching the spectral sensitivity of existing PMTs. This generates the maximum no. of photoelectrons in PMTs.

b. Photomultiplier Tube (PMT):



Figure 12. Illustrations of PMT

Photomultipliers are typically constructed with an evacuated glass housing, containing a photocathode, several dynodes, and an anode.

Incident photons strike the photocathode material, which is usually a thin vapordeposited conducting layer on the inside of the entry window of the device. Electrons are ejected from the surface as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission.

The electron multiplier consists of a number of electrodes called dynodes. Each dynode is held at a more positive potential, by ≈ 100 Volts, than the preceding one. A primary electron leaves the photocathode with the energy of the incoming photon, or about 3 eV for "blue" photons, minus the work function of the photocathode. A small group of primary electrons is created by the arrival of a group of initial photons. The number of primary electrons in the initial group is proportional to the energy of the incident high energy gamma ray.

The primary electrons move toward the first dynode because they are accelerated by the electric field. They each arrive with $\approx 100 \text{ eV}$ kinetic energy imparted by the potential difference. Upon striking the first dynode, more low energy electrons are emitted, and these electrons are in turn accelerated toward the second dynode.

The geometry of the dynode chain is such that a cascade occurs with an exponentially-increasing number of electrons being produced at each stage. For example, if at each stage an average of 5 new electrons are produced for each incoming electron, and if there are 12 dynode stages, then at the last stage one expects for each primary electron about $512 \approx 108$ electrons. This last stage is called the anode. This large number of electrons reaching the anode results in a sharp current pulse that is easily detectable, for example on an oscilloscope, signaling the arrival of the photon(s) at the photocathode \approx 50 nanoseconds earlier.

PMT - Combining two scientific discoveries:

The invention of the photomultiplier is predicated upon two prior achievements, the separate discoveries of the photoelectric effect and of secondary emission.

1. Photoelectric effect

The first demonstration of the photoelectric effect was carried out in 1887 by Heinrich Hertz using ultraviolet light. Significant for practical applications, Elster and Geitel two years later demonstrated the same effect using visible light striking alkali metals (potassium and sodium). The addition of cesium, another alkali metal, has permitted the range of sensitive wavelengths to be extended towards longer wavelengths in the red portion of the visible spectrum.

Historically, the photoelectric effect is associated with Albert Einstein, who relied upon the phenomenon to establish the fundamental principle of quantum mechanics in 1905, an accomplishment for which Einstein received the 1921 Nobel Prize. It is worthwhile to note that Heinrich Hertz, working 18 years earlier, had not recognized that the kinetic energy of the emitted electrons is proportional to the frequency but independent of the optical intensity. This fact implied a discrete nature of light, i.e. the existence of quanta, for the first time.

2. Secondary electron emission

The phenomenon of secondary electron emission (the ability of electrons in a vacuum tube to cause the emission of additional electrons by striking an electrode) was, at first, limited to purely electronic phenomena and devices (which lacked photosensitivity). In 1902, Austin and Starke reported that the metal surfaces impacted by electron beams emitted a larger number of electrons than were incident. The application of the newly discovered secondary emission to the amplification of signals was only proposed after World War I by Westinghouse scientist Joseph Slepian in a 1919 patent.

For an ideal detector and supporting pulse processing electronics, the spectrum of 662-keV gamma rays from a ¹³⁷Cs radioactive source would exhibit a peak in the spectrum whose width is determined only by the natural variation in the gamma-ray energy. The NaI(Tl) detector is far from ideal, and the width of the peak it generates is typically 7% to 10% of the 662-keV gamma-ray energy. The major source of this peak broadening is the number of photoelectrons emitted from the photocathode for a 662-keV gamma-ray. For a high-quality detector this is on the order of 1,000 photoelectrons.

Applying Poisson statistics (ref. 1 and 11), 1,000 photoelectrons limit the full width of the peak at half its maximum height (FWHM) to no less than 7.4%. Statistical fluctuations in the secondary electron yield at the first dynode and fluctuations in the light collected from the scintillator also make a small contribution to broadening the width of the peak in the energy spectrum.

The system necessary to observe and measure gamma rays consists of a **NaI scintillation crystal**, a **<u>photomultiplier tube</u>** (**PMT**) to detect and amplify the light pulses, **high voltage** to operate it, a **preamplifier**, a **linear amplifier**, an oscilloscope, and a <u>multichannel analyzer</u> (**MCA**). These are shown in Figure 13.

Experimental System and the MCA



Figure 13. Schematic diagram of the setup

Experimental arrangement

c. Multichannel Analyzer (MCA) The multichannel analyzer (MCA) records and stores pulses according to their height. Each storage unit is called a channel.

The MCA consists of a large number of "channels" - typically 1024. Each channel is simply a counter. The output display of the MCA, such as seen in Figure 15, shows the channels horizontally and the number of counts in each channel vertically. The height of the pulse has some known relation-ship — usually proportional — to the energy of the particle that enters into the detector.

For this experiment, the MCA is operated as a **pulse height analyzer**. In this mode, the MCA counts the number of pulses at each of 1024 possible voltages (actually small "bins" of voltage) and plots a histogram of the results.



Figure 14. Illustrations of relationship of channel and voltage of MCA

To do this, the MCA measures the height of each incoming voltage pulse and assigns that pulse to the corresponding channel. Roughly speaking, a pulse of height V is assigned to channel number 100 x V. For example, a 3.00 V pulse is assigned to channel 300 and a pulse of height 5.67 V is assigned to channel 567.

The number of discrete parts (channels) into which the input pulse range (0 to +10 V) is divided is called the *conversion gain*. The conversion gain is set by a stepwise control knob located on the front of the instrument (NIM). As an example, if the conversion gain is set at 2048 channels, it means that the maximum pulse height (10 V) is divided into that many parts. Therefore, the resolution of the MCA at this setting is

$$10 \text{ V}/2048 = 4.88 \text{ mV/channel}.$$

Once the voltage of an incoming pulse is measured, the accumulated count in the corresponding channel is incremented by 1. So if there are sixty-five 3.00 V pulses and twenty-two 5.67 V pulses, channel 300 will contain the value 65 and channel 567 will contain the value 22. This simple idea makes for a very powerful and versatile measuring instrument.



Figure 15. Illustrations of relationship of Pulse height and pass-through window



The horizontal axis is a channel number, or particle energy. The vertical axis is a number of particles recorded per channel.

Figure 15. showed a pulse height spectrum obtained with the MCA for a source such as ¹³⁷Cs that emits gammas of only a single energy. Note that the horizontal axis of the plot shows channel numbers, not energy values. We know, from the way the crystal, the PMT, and the MCA work, that the channel number is directly proportional to energy. But to have energy values on the horizontal axis, we will have to <u>calibrate</u> it by using photopeaks of <u>known energy</u>.



In looking at Figure 15., you should note the photopeak (the signal of interest), the broad continuum of lower energy peaks due to Compton scattering when the scattered gamma ray leaves the crystal, and the "Compton edge". At the very lowest energies there is a rising count rate due to "noise" – random voltage fluctuations that are an inevitable aspect of any experiment.

In addition to the photopeak, notice the smaller but distinct "mystery peak" at lower energy. Finally, note that the photopeak is not perfectly sharp, even though all the gammas that contributed to this peak had exactly the same energy. This "broadening" of the peak is an inherent part of the detection system. It is due to random fluctuations in the number of atoms excited, random fluctuations in the number of scintillation photons that reach the PMT, electronic fluctuations, and other factors.

Energy Resolution of a Detection System

We can measure the full width at half maximum (FWHM) of the photopeak, and this serves as a measurement of the **resolution** of the detection system. It is due to the following:

- 1. Statistical fluctuations in the number of charge carriers produced in the detector
- 2. Electronic noise in the detector itself, the preamplifier, and the amplifier
- 3. Incomplete collection of the charge produced in the detector

If we denote this width as ΔE , then the relative resolution at the energy E_0 is

Resolution =
$$\frac{\Delta E}{E_0}$$



A NaI detector has about 8% or 9% resolution for Gamma-rays of about 1 MeV, for example, while germanium detectors have resolutions on the order of 0.1%. It is worth repeating that in energy measurements it is the energy resolution of the counting system (detector– preamplifier– amplifier) that is the important quantity and not the energy resolution of just the detector.



Figure 18. Illustrations of resolution two signals by consider FWHM

Experimental Procedures

Experiment 1: Learn to use the MCA with a pulsed source.

Procedure

- 1. Amptek MCA 8000D multichannel analyzer is used. Follow the instructions to set the **mode** to <u>multi-channel analyzer</u> (MCA) and the number of channels to 1024. Also set the vertical scale initially to LOG.
- 2. In order to create pulses with which to test the MCA, we will use a signal generator which allows us to generate voltage signals. Set the waveform to pulse with a frequency of 10 kHz, low-level: 0V, high level: 2V, pulse width: 50 s, and make sure you can see this on the oscilloscope.

- 3. Connect the output of signal generator to the input of the Amptek MCA 8000D.
- 4. Start the MCA acquiring data by press the "Start" button. You should see one channel racing upward in counts and perhaps a few nearby channels gaining counts. This is the channel corresponding to 2 V.
- 5. Practice using the various MCA commands to acquire and erase data, change the vertical scale, move the cursor, expand the viewing region, and so on. Vary the pulse height (the high level) and watch how the MCA responds.
- 6. Stop acquiring and erase the MCA by pressing the "Stop" button.
- 7. Using the output from the oscilloscope, set the pulse height back to 2.00 V.
- 8. Acquire 5 s of data. (Use the preset time under MCA->Acq. Setup->MCA->Preset Real Time).
- 9. Find the total counts by setting a *region of interest* (ROI) to span all channels with counts. Since you recorded a 10 kHz pulse rate for 5 s, the total counts for all channels should be near 50,000. If not, check with your demonstrator.
- 10. You will notice in the information panel to the right of the spectrum that there is a "Live Time" and you will see that with the settings given above it is reading about 2.5 seconds. This is because the instrument records the time for which the pulse level is above some threshold (which the lab instructors have set to around 200 mV) and is unable to record another pulse during that time. So the time that the instrument is actually "live" is half of the real time of 5 seconds.
- 11. Change the pulse width to, say, 10s and record again for 5 seconds. You should get the same number of overall counts but now the live time should be 4.5 seconds. Does that make sense?
- 12. Since we have the signal generator plugged into the MCA we can do a quick check of the linearity of the MCA. Set the pulse height to 1 V and after clearing the MCA record for 5 seconds. The 10s pulse width you used before is fine. Use the ROI tool to find the centroid of the peak.
- 13. Repeat above process for pulse heights of 2 V, 3 V, 4 V, and 5 V. You should find that the difference in channels at which the centroids occur is pretty close to constant (and pretty close to 100). This means that the channel number is directly proportional to the size of the incoming pulse voltage. So if that voltage itself is proportional to the energy of the gamma rays, then we have an energy spectrometer!

Experiment 2: Measure the ¹³⁷Cs gamma ray spectrum.

Procedure

- 1. ¹³⁷Cs is a source we will use many times this year to set up the detector and MCA. Place the source on or under the detector, depending on how it's set up.
 - Turn the PMT high voltage to 500 V, and observe the PMT pulses on the scope.
 - Adjust the gain on the amplifier so that the pulses are $\approx 4 \text{ V}$ high. (You'll do a more precise adjustment in the next step.) The pulse widths should be $\approx 2 \mu s$.

Each pulse is from one gamma ray photon interacting with the NaI(TI) crystal. Most of the pulses are due to photoelectric absorption of the 662 keV gamma of the ¹³⁷Cs decay, although there will be some smaller pulses from Compton scattering.

Note: The amplifier gain is the <u>product</u> of the coarse gain setting and the fine gain setting. The numbers on the fine gain control range from 5 to 15, but these actually mean 0.5 to 1.5. So the fine gain changes the total gain from 50% to 150% of the coarse gain setting.

- 2. StarStart acquiring data with the MCA and set the vertical scale to 1000 counts max. Within just a few seconds you should begin to see an energy spectrum looking similar to Figure 17. Now adjust the amplifier gain to place the ¹³⁷Cs photopeak somewhere between channels 400 and 425. This will make all the peaks we look at later stay within the range of channels 1 to 1024. Then run the Cs source for long enough to record a smooth spectrum. Print out the spectrum (one for each lab partner). Record the following data right on your spectrum:
 - **a.** Find the *centroid* of the photopeak by setting the ROI *symmetrically* on the peak, down to near the baseline on both sides.
 - **b.** Determine, in channels, the FWHM of the photopeak.
 - **c.** Locate the channel number of the Compton edge. The edge isn't too well defined, but it makes most sense to measure the "half max," where the counts have dropped to about half their value on the relatively flat region of Compton-scattered pulses. Most of the width of the Compton edge can be attributed to the same mechanisms that are broadening the photopeak.
 - **d.** Determine the channel number corresponding to the center and the left and right end of the "mystery peak."

Important note: Now that you've measured the ¹³⁷Cs spectrum, <u>do not</u> change the PMT high voltage or the amplifier gain. If you do, you won't be able to analyze this spectrum with the energy calibration you're getting ready to do.

Experiment 3: Calibrate the MCA.

Procedure

- 1. The calibration is to determine as accurately as possible the energy corresponding to channel number *N*. We will do this with several sources that are gamma emitters, all of them known. Place one of the calibration sources on or under the NaI crystal. Do not adjust the amplifier gain or high voltage.
- 2. Run each calibration spectrum until it looks <u>very</u> smooth (i.e., has "good statistics" in each channel), and print one of these spectra for your report. The calibration sources are left at the side of the room.

a. Find the centroid of each peak by setting a *symmetrical* ROI around it.

3. Determine the FWHM for all the high energy peaks. You'll use this later to compare this resolution to that found earlier for the 137Cs + 60 Co photopeak.

Experiment 4: Measure the gamma spectrum of an unknown source.

Procedure

- 1. Move the ¹³⁷Cs and calibration sources <u>far away</u>. <u>Do not adjust the amplifier gain or high voltage</u>.
- 2. Place one of the unknowns under the detector and acquire a high quality gamma spectrum. Be sure to record the code letter that identifies your unknown. Print out the spectrum. Find the centroid and FWHM of each *notable* peak, and again record this information right on your spectrum.

Analysis:

1. The table below shows the gamma emitters in the calibration sources used in Experiment 3. Identify as many of these peaks as possible in your calibration spectra.

Energy (keV)	Gamma Emitters	<u>Haf Life</u>
122.1	57 _{Co}	272 days
136.0	57 _{Co}	272 days
661.7	137 _{Cs}	30 days
511.0	22 _{Na}	2.6 years
1275.0	22 _{Na}	2.6 years
1173.2	60 _{Co}	5.3 years
1332.5	60 _{Co}	5.3 years

Use Origin or other programs to plot the calibration data. Plot the energy of the photopeak (vertical) versus channel number (horizontal). Use Origin or other programs to fit a secondorder polynomial to your data. The result is your calibration equation in the form $E = a + bN + cN^2$. This equation converts channel numbers to the corresponding energies. Save your graph to submit with your report.

2. How good is your calibration? That is, if you measure a peak in channel *N*, what is the uncertainty ΔE in the energy that you calculate? To determine this, use the calibration

equation to calculate the energy E_{calc} for each of the peaks of your calibration spectrum. Since you know the actual energies, calculate the deviation $\Delta E = E_{calc} - E_{actual}$ for each peak. Finally, average the <u>absolute values</u> of all the deviations. The result is a reasonable estimate of the energy uncertainty ΔE that you'll obtain for any other channel number N.

Note: These calculations will be much easier if done in a spreadsheet than if done by hand.

3. Using your calibration equation, find the following for your 137 Cs spectrum:

a) The energy of the photopeak. Include an appropriate uncertainty. Compare your result to the known value.

b) The FWHM of the photopeak, in keV.

Caution: Plugging the FHWM in channels into your calibration equation will <u>not</u> give you the FWHM in keV. Think about it.

- c) The energy of the Compton edge.
- **d**) The energy of the "mystery peak."
- **4.** Calculate the expected energy of the Compton edge and compare your calculated value with your experimental measurement.
- **5.** Explain the source of the "mystery peak." (Hint: What angle of Compton scattering would produce this peak? Where could such photons be coming from?)
- 6. The <u>resolution</u> at energy *E* is defined as $R = \frac{FWHM}{E}$. That is, the resolution is the peak width expressed as a fraction of the peak energy. Smaller values of *R* are better! Calculate the resolution for all peaks. Plot *R* vs. *E*.
- 7. Determine the resolution R at 1332.5 keV, using the 60 Co line in the calibration spectrum.
- 8. A gamma of energy *E* creates a fast electron in the crystal that excites *N* atoms and creates *N* scintillation photons in a single event. The number *N* is directly proportional to *E*. Because *N* is a count, counting statistics tell us that the fluctuations in *N* from pulse to pulse should be roughly \sqrt{N} . It is these fluctuations in *N* that cause the photopeak to have a width.
 - a) Use this information to predict how the resolution R should vary with the photopeak energy E. That is, $R \propto E^x$ for some exponent x. Determine x.
 - **b**) Use your two experimental values of *R* to test your prediction. Do this by fitting the curve $R = aE^x$ through your *R* vs. *E* data using your predicted value for *x*.
- **9.** Identify your unknown. Look up the candidates of Table of Isotopes and select the one that most closely matches your spectrum.
 - a) All unknowns except one have only a single isotope. One unknown has ¹³⁷Cs plus a second isotope. You should now be able to recognize the ¹³⁷Cs spectrum, so your task would be to identify the other isotope.

- b) All our unknowns have half-lives in the range 200 days $< t_{1/2} < 100$ years. Shorter half-lives would have already decayed, whereas longer half lives make the source too weak for easy use.
- c) Some isotopes emit more than one gamma. If you have multiple lines in your spectrum, you need to find an isotope that emits <u>all</u> of them. Similarly, if an isotope is listed as having a weak line at 100 keV and a strong line at 200 keV, that can't be the source of a spectrum in which you have a line at 100 keV but no line at 200 keV.
- **d**) Some radioactive sources decay by e⁺ emission emitting a positron, or antielectron. The positron quickly annihilates by colliding with an electron, creating two 511 keV gammas. These really aren't gammas from the nucleus, so they are not shown in the table, but they are present for beta decays in which positron emission occurs.
- e) It's extremely unlikely that your photopeak energy, calculated from the calibration equation, is exactly correct. So you'll have to search over some range of energies. How big a range should you search?
- **f)** Even with these constraints, you may not be able to make a unique identification. If that's the case, list all the nuclei you think it could possibly be.

Note: In identifying the unknown (or possible unknowns), state the isotope, the known gamma energy or energies that you used to identify it, and its half life.

Reference:

- 1. ORTEC: Lab manual, Experiment 3: Gamma-Ray Spectroscopy Using NaI(Tl)
- 2. Measurement & Detection of Radiation fourth edition, Nicholas Tsoulfanidis and Shelodn Landsberger, CRC Press
- 3. Techniques for Nuclear and Particle Physics Experiments: A How-to Approach, W.R. Leo, Springer-Verlag
- 4. Instruction manual of Amptek MCA 8000D, <u>http://www.amptek.com/wp-content/uploads/2014/04/MCA-8000D-Option-PA-Digital-Multichannel-Analyzer-Instructions.pdf</u>