Introduction

In this experiment you will study the detection of $\gamma$ (gamma) radiation using a high-resolution liquid nitrogen cooled detector. $\gamma$ radiation is very high frequency electromagnetic radiation. Since $c = \lambda f$ for electromagnetic radiation, high frequency $f$ means the wavelength $\lambda$ is very short since the product of $\lambda$ and $f$ is the constant speed of light $c$. In addition, quantum mechanics tells us that electromagnetic radiation comes in quanta of energy $E = h f$ where $h$ is Planck’s constant. So, high-frequency $\gamma$ radiation means that the energy quanta are very large, large enough to ionize atoms. $\gamma$’s are emitted when unstable nuclei decay to other nuclei, sometimes by emitting electrons or positrons and sometimes by emitting alpha particles (helium nuclei). Typically $\gamma$ - radiation accompanies these modes of decay because the daughter nuclei are produced in excited states. When the excited states decay to the ground states of the nuclei, $\gamma$’s with well-defined energies are emitted. Have a quick look at the electromagnetic spectrum in the folder to see where $\gamma$’s fit into the range of electromagnetic radiation.

Using Radioactive Isotopes

Read the sheet that outlines the precautions about working with radioisotopes. We are using one-microcurie (1 $\mu$Ci where Ci is the abbreviation for Curie) sources. This level of radioactivity is well below that which requires licensing or the wearing of film badges. The sources we use are encased in plastic and are stored in small heavy lead canisters. These sources come through the regular mail. When the time comes, ask an instructor to show you how to handle the samples. Part of the purpose of this lab is to become familiar with radioactive samples and to put the level of radioactivity encountered in this lab into context, given the natural background levels of radioactivity and those commonly used in medicine.
There is a battery-operated, hand-held Geiger counter in the lab. Turn it on (and the sound) so you can measure the background radiation levels. This radioactivity comes from many sources in the Earth, from the sun, and from a variety of more distant sources both from within our own Milky Way galaxy and from beyond. On your own time you can investigate "background radiation" on the internet if you find this interesting. Later when you use your radioactive samples, measure them with the same Geiger counter at distances of one meter and one centimeter. Compare the one meter reading with background. There may be other experiments in the lab using radioactive samples. Measure the level of radioactivity in the surrounding area.

**The Apparatus: An Overview**

A γ that is incident on the detector is adsorbed and many electrons, whose number is proportional to the γ ray energy, are liberated and caused to flow as a pulse of current. These electrons are accumulated on a capacitor in a preamplifier, where the charge on the capacitor results in a voltage proportional to the amount of charge. This voltage is thus also proportional to the gamma ray energy. The circuits in the preamplifier then discharge the capacitor, creating a voltage pulse whose height is proportional to the gamma ray energy. An amplifier internal to the Multichannel Analyzer (MCA) then amplifies the pulse and shapes it to be a pulse that is about 1 µs long and 2-5 V high. The MCA measures this pulse height, digitizes it (matching the range of voltage to integers from 1 to 16k), counts the number of pulses with each integer value of the pulse height, and plots a histogram of the number of pulses with that height versus pulse height. The integers, representing pulse height and therefore γ - energy, are plotted on the horizontal axis of the display and are referred to as channel numbers. Thus, the channel number in the MCA is proportional to the energy of the original incident γ.

In this experiment, an electronic unit, the Canberra DSA-1000 acts as both a high voltage source for the detector and an MCA using the computer running the software Genie 2000 to display data.
The Detector: More Detail

The hyper-pure germanium detector is made of a very pure single crystal of the semiconductor material germanium. Electrons in a semiconductor are trapped in states whose energies correspond to the valence band. These electrons are localized in space, that is, they form part of a covalent bond between two germanium ions. Hence when a voltage is applied there is no current since these localized electrons cannot move. However, electrons, if given enough energy, are excited into a spatially delocalized conduction band in which they can move relatively freely. When a $\gamma$ enters the detector, it scatters from an electron, knocking it loose from the valence band into the conduction band and giving it a large kinetic energy in a process called Compton scattering. The $\gamma$ scatters with the remainder of the energy. The first electron can then collide with other electrons giving up its kinetic energy to the excitation of other electrons from the valence band to the conduction band. Meanwhile the scattered $\gamma$ may escape or it may collide with another electron, losing more of its energy to the excitation of electrons into the conduction band. If the $\gamma$ is fully "captured" all its energy is converted into excited electrons (and the $\gamma$ photon is destroyed). A high voltage is applied to the germanium crystal to "sweep up" the liberated electrons from the conduction band before they lose energy and fall back into the valence band. As this high voltage might lead to a high current of thermally activated electrons in the conduction band, the detector can only be operated when it has been cooled to the temperature of liquid nitrogen (77 K).

Your instructor will have arranged for cooling the detector in advance. A cable is connected from a temperature sensor mounted in the detector to the high voltage supply and this prevents application of the voltage if the temperature is not cold enough by inhibiting the functioning of the high voltage power supply.

Getting Started

Turn on the Canberra DSA-1000 power supply sitting on top of the oscilloscope. The switch is on the back. This does not turn on the high voltage discussed above. That comes later. This just allows communications between the power supply and the detector.
You need to check that that the detector is cold. To do this, note the blue "X" on the floor between the detector and the wall under the table. Put your head close to that X and look up at the detector. If you can see a small green light then the detector is cold and you can proceed. If you see a small red light, then you must ask an instructor to fill the dewar with liquid nitrogen.

Now, check that you are logged on with administrative privileges on the PC, which is a requirement of the Genie 2000 software. At the Novel login click workstation only and login as student: there is no password. Launch the Genie 2000 software, which emulates a Multichannel Analyzer (MCA) in Pulse Height Analysis (PHA) mode. The program name is "Gamma Acquisition & Analysis" and is in the Genie 2000 folder in the program menu of the computer. Click "File" and select "Open Datasource." Click the "Detector" button and select "HPGE" as the data source. (If you see no detectors or you receive an error message, you are either not logged in correctly or you haven't turned on the Canberra high voltage supply. Either way, seek assistance).

Click on the MCA menu. Under "Adjust" click on the Gain button. In this window set Course gain to X 10, and Fine gain to X 1.3. Later in the experiment you can adjust the Fine gain to change the energy scale on the x-axis. Use the "PREV" button to set "LLD" (Lower Level Discriminator) to 2% to eliminate large numbers of counts in the low energy channels due to noise.

Connect the cable from the detector preamplifier to an oscilloscope. It is labeled "ADC In." Turn on the oscilloscope set the controls to:

- **Vertical**: 200 mV/Div (calibrated)
- **Time/div**: 50 µs/Div (calibrated)
- **Trigger**: Automatic and Internal
- **Coupling**: AC
Place a cobalt-60 disk source in the source holder above the detector. Return to the software under the MCA menu and the "Adjust" selection. Click on the "HVPS" button and set the HV to 3000V. Click the "On" button under "status." You will see the green LED on the front of the Canberra DSA-1000 power supply light up when the HV is on. Check to make sure this is the case. The unit will slowly raise the voltage to 3000V.

Observe the pulses in the oscilloscope trace and note how they grow in height with increasing high voltage. Trigger the scope on the input channel so that a pattern of pulses appears as shown in Figure 1. This means going from "automatic" trigger to "normal" trigger. And in addition, the trigger should be set to "internal" and "channel two." Play with the trigger level. The pulses should look similar to those shown in Figure 1. This can be tricky. Get some assistance if needed.

Experiment with the scales, the intensity and the triggering. Note that when you lower the trigger level you get more pulses and when you raise the trigger level, you get fewer pulses. Why? Before you proceed make sure you are able to interpret what you see. Provide a description in your notebook. Have an instructor check the pattern before proceeding.

What is displayed are the charge pulses from the detector which have been integrated by the preamplifier and presented as exponentially decaying pulses. The "information" (that is, how much charge was generated) is given by the initial height of the pulse. Since the

![Figure 1](image-url)
pulse height is an indication of the energy deposited in the detector, this so-called Pulse Height Analysis of the MCA (multi-channel analyzer) results in a spectrum where energy is displayed along the horizontal axis and the frequency of occurrence of a pulse height (i.e., the number of times a γ of this energy was detected) is displayed along the vertical axis.

In the "Data Acquisition" window of the software click "Clear" and then "Acquire" to collect a spectrum. The MCA software displays a histogram, showing the number of pulses in each pulse-height bin. The energy calibration along the horizontal axis in terms of bins or N channel numbers will need to be established as part of this experiment. Note, the KeV values displayed by the software are not calibrated to your choice of gain so they are not meaningful. The vertical axis is the number of counts in each channel and can be increased by simply acquiring data for a longer time interval.

Under the "MCA ➔ Adjust" menu click on the Gain button. In this window set Course gain to X 10, and Fine gain to X 1.3. Adjust the Fine gain to change the energy scale on the x-axis. Use the "PREV" button to find the display that allows you to adjust the "LLD" (Lower Level Discriminator). Choose a setting (~ 2%) to eliminate the large numbers of counts in the low energy channels due to noise. When the LLD and the Gain are set to your liking, collect data for exactly five minutes. You can set the time of data acquisition by clicking on "Acquire Setup" under the MCA menu. Set the live time to 300 seconds. Learn to use the cursor and the "Expand On" window feature to look at the spectrum on an expanded horizontal scale. How many peaks do you see? Refer to the decay diagram for cobalt-60 to interpret the spectrum.

To save your spectrum data in a text format for further analysis using Kaleidagraph or Excel, select under the "Analyze" menu "F: Reporting, 1. Standard." Select "datalist.tpl" for the "template name," "channels and counts," and choose output to "screen." This will generate text output of your data in the "Report" window below the "Data Acquisition" window and in a file named <HPGE.rpt> in the "REPFILES" folder in the Genie 2000 folder. You can open this file in Kaleidagraph by clicking open and then selecting to
display files of all types. Select the file and in the import window that K-graph opens select "special" and specify a data format of w v w v. Read Titles should not be checked. This will place the data in a Kaleidagraph data file with two columns. Don’t forget to save any files generated this way with a different name before acquiring new spectra, since any new data will be saved to a file named <HPGE.rpt> overwriting the previous data.

Nomenclature
You will be observing γ rays from the decay of cobalt-60, cesium-137, sodium-22, and, maybe barium-133. The number following the element is the atomic number A: the number of protons Z plus the number of neutrons N in the nucleus. So, \( A = N + Z \). The name of the element tells you the number of protons Z in the nucleus: 29 for cobalt, 55 for cesium, 11 for sodium, and 56 for barium. So, the difference between these two numbers gives the number of neutrons \( N = A - Z \). Element with the same number of protons Z (and, therefore, the same name) but different numbers of neutrons N are called isotopes. Unstable isotopes decay and are called radioisotopes. So, for example, the common stable isotope of sodium found in common compounds is sodium-23. Data sheets on each of these nuclei are available for your reference as are sheets outlining the decay schemes. Review these and record the relevant decay equation for each element in your notebook. The nuclei are expressed as \(^{A}Z\)X. So sodium-23 is \(^{23}_{11}Na\) and so on.

Obtaining Nuclear Spectra and Calibrating the MCA
The high voltage supply should be on and set at 3000 V. The MCA software should be on and ready to go. Your cobalt-60 sample should be in place. Press "Acquire" in the "MCA" window to start acquiring a spectrum. While data is being collected, you can change the vertical range in the window by using the scroll bar. It’s like the vertical control on an oscilloscope: it affects the display only. The way in which the actual data is being collected is unaffected. Use the "Expand On" button to look at one of the two peaks in cobalt-60. You can watch it grow as you collect data.
The cobalt-60 source has the highest gamma ray energies of those emitted by the sources available to us. They are the two high-energy peaks at 1.173 and 1.332 MeV as indicated in a single large-print sheet in the folder. MeV means million electron volts. These two peaks are called "photo peaks" because of their correspondence to single $\gamma$'s. The continuous spectrum at lower energies is due to Compton scattering and is discussed later in this write-up.

If you haven’t already done so, adjust the amplifier "Fine gain" (whose control is found under the MCA $\rightarrow$ Adjust" menu and accessed by clicking on the Gain button) so that the highest photo peak is fully on the display but near the right-hand edge of the MCA display range. If your gain is too low, the spectrum will be scrunched up to the left and if your gain is too high, the high-energy photo peaks will be off scale. You will have to keep adjusting the gain, acquiring, clearing, acquiring some more and so on until you get it right.

Once you have selected the gain controls to get the highest photo peak just on scale, these gain settings must be kept fixed at those values for all the spectra you record so a consistent relation between gamma ray energy and pulse height (and thus also channel number) is maintained. Record these final settings. Since all other $\gamma$’s to be measured are of lower energy than the highest-energy cobalt-60 peak, if the entire cobalt-60 spectrum is on scale then so will all other spectra. You should check each day that you take data that your gain settings are the same.

You need to decide how long you should spend taking a spectrum. Notice that the longer you take a spectrum, the smoother it looks; there is less up-and-down scatter. This is because radioactive decay is a random process and is describable by Poisson statistics. If you have $N$ counts in a channel, then the uncertainty is $\sqrt{N}$. So, you would expect that the number of counts in a set of nearby channels to go up and down by about $\sqrt{N}$. (Check it out on your spectrum. If you have 100 counts in one channel, do neighboring channels range from near 90 to near 110?) Thus, the ratio of the noise ($\sqrt{N}$) to the signal ($N$) is $1 / \sqrt{N}$. What is this ratio for $N = 4, 16, 100$? So, the longer you
measure, the better the signal-to-noise gets, but it’s not linear, the signal-to-noise only goes as the square root of the number of counts (and, therefore, time).

Make a sketch of the cobalt-60 spectrum in your lab book. Record the channel numbers locating the two cobalt-60 photo peaks and their widths. To do this you need to zoom in on the area of interest using the "Expand On" feature of the software. To get the width interpolate where the number of counts has fallen to half its value at the peak. When you record a channel number, make sure you quote an uncertainty. Save the spectrum.

Now replace the cobalt-60 source with the cesium-137 source. Acquire a cesium-137 spectrum. Remember, you must not change any gain settings that affect the energy (horizontal) calibration. Sketch the spectrum in your lab book and note the channel numbers of the 0.662 MeV photo peak, the Compton Edge, and the Back scattered peak. Save the spectrum. Get some help in identifying these features and discuss in general their source in your notebook.

Now use the sodium-22 source. Record the channel numbers of the peaks, sketch the spectrum in your lab book, and save the spectrum. Sodium-22 has one photo peak at 1.277 MeV from its normal radioactive decay (the small, high-energy peak). Sodium-22 decays by emitting a positron, converting its nucleus into that of neon-22 in an excited state. The excited neon nucleus emits a single gamma to reach its ground state, so there is one photo peak. However, the positron (an antielectron) quickly finds an electron and both are annihilated in a process called electron capture. But in the annihilation, linear momentum and energy must be conserved so two gammas of identical energy are produced, each carrying away $mc^2 = 0.511$ MeV where $m$ is the electron (and positron) mass and $c$ is the speed of light. This is the large sharp peak in the spectrum at low energy. Can you see the Compton profiles for both the regular decay gamma and the electron-positron annihilation $\gamma$? Why don’t the spectra of Co-60 and Cs-137 have a peak at 0.511 MeV?
From the known energies of the single cesium-137 photo peak, the two cobalt-60 photo peaks, the single sodium-22 photo peak and the electron-position annihilation peak in the sodium-22 spectrum, make a calibration graph with channel number on the $x$-axis and energy in MeV on the $y$-axis using KaleidaGraph. Fit this to a straight line. Use a fitting routine that returns uncertainties in the slopes and the intercepts. If one is not in the KaleidaGraph library, then write one. See the notes on KaleidaGraph in the folder. Use the formulae entry in KaleidaGraph to make another column for energy. When you print out the spectra, they should be "counts" versus "energy."

You can choose from several things to do next. They are independent and all are discussed below. (1) You can use your calibration curve to sort out the complicated barium-133 spectrum. (2) You can move on to analyze the Compton profiles of the three spectra you have taken. In doing this, you can make a determination of the electron mass from the cesium-137 data. (3) You can engage in an environmental study of $\gamma$ emission from everyday sources. This involves doing a study of the effectiveness of our shielding, which is a combination of lead, tin, and copper. (4) You can do an absorption study with different amounts of lead or copper or whatever. (5) You can determine how the immediate surroundings of the sample and detector affect the Compton profile.

**Sorting out the Barium-133 Spectrum**

Look at barium-133. From your calibration curve, determine the energies of what you think are photo peaks and see if you can identify them. A complicated nuclear data sheet is available but you may have to do some additional internet research.

**Compton Scattering and the Compton Profile**

So far, we have investigated the energies associated with photo peaks. This is the case when the incoming $\gamma$ converts all its energy to a photoelectron and is destroyed in the process. Other incoming $\gamma$'s undergo scattering, after which they may either escape the crystal or convert their remaining energy to photoelectrons. This is called Compton scattering. Remember that the detector is measuring energy given to electrons. The incoming $\gamma$ can undergo a glancing collision with an electron and in this case the electron
will receive very little energy and appear at relatively low channel numbers. The most energy an electron can receive (without the incident γ being destroyed) is if the γ hits head on and "back scatters" through 180 degrees. These electron energies appear at the Compton edge. Now, the back-scattered γ can also be absorbed and the energy converted directly to a photoelectron (just like the original γ’s that gave rise to the original photo peak). This energy shows up in the "back scatter peak." γ’s can scatter many times so many energies between zero and the Compton Edge will be measured. It is not at all obvious why an actual peak appears at the backscattered peak. Understanding this requires an in-depth study of scattering theory. It should be clear why there is a cut-off at the Compton edge, however. This is the highest energy the original γ can give to an electron without being destroyed.

Record the channel numbers at which the three relevant features are located in the cesium-137 spectrum. Estimate uncertainties for these three values. Verify that the energy of the backscattered peak plus the energy of the Compton Edge equals the energy of the photo peak within experimental uncertainty. This must be so since the energy given to an electron from the head on collision with a γ plus the remaining energy in that γ must equal the original energy of the γ.

Now consider the cobalt-60 spectrum. The two photo peaks each have their Compton Edges and back scattered peaks but they overlap and this makes the analysis more difficult. See if you can make sense of the spectrum.

For the sodium-22 spectrum the Compton profiles for the annihilation peak should be clearly observable. See if the back-scatter and Compton peaks are where you expect them to be. Do the same for the high-energy photo peak.

You can, from the cesium-137 data, calculate the electron mass. To do this, you need to analyze the equations for the conservation of energy and momentum for the collision between a gamma (photon) and an electron. The interesting difference between this collision and the collisions involving two classical objects with mass is that the condition
$E = pc$ for gamma energy $E$ and momentum $p$ is very restrictive. A start on the algebra is available. You need the energies of the photo peak, the Compton edge and the back-scattered peaks. Compare your measured electron mass to the accepted value of $mc^2 = 0.511$ MeV.

**An Environmental Study**
The detector is sensitive enough to detect $\gamma$ emission from "everyday" samples like some dirt, tea, coffee, bananas, lantern lamps, and some nuts. You will need to do overnight runs to detect the weak emissions. You will need to make sure the detector has sufficient liquid nitrogen. An instructor will know when it was last filled and can determine this and refill the dewar if necessary.

**An Absorption Study**
You can put various materials between the source and the detector and measure the absorption of gammas. There are various pieces of metal that allow you to measure absorption as a function of thickness. You will need to investigate a range of acquiring times for this study. Do you have a hypothesis about which metal should absorb more? When you are looking at the spectra, the may be broadened (why) as well as at different energies, so to "count" detected $\gamma$'s, you must integrate over the whole line.

**The Effect of the Surrounding on the Compton Profile**
The Compton profile of the detector is constant but there might be Compton scattering before the gamma gets to the detector. You can try various housings in the vicinity of the sample to check this out.

hi res gamma 2008