

## **Positron Spectroscopy – Modern Laboratory**

### **Safety Information**

The power supply for this experiment outputs high voltages that are carried through cables to the detectors. The power supply produces only very low current, so it should not seriously harm you if you get shocked, but it would still be quite painful. The ends of the power cables are designed to be unable to shock you, so the only way to get shocked is if a cable is damaged. If you see a damaged cable, do not turn on the power supply.

\* If the voltage supply is not already on when you enter the lab, switch it on so that it can warm up while you acquaint yourself with the lab.

These experiments use lead for shielding purposes. Lead is a toxic metal. Either use gloves when handling the lead or wash your hands afterwards.

These experiments also use radioactive sources. The sources used are small enough that they are unlikely to hurt you even with very long exposure times. Nevertheless, you should keep your doses as low as reasonably achievable. Don't keep sources on your person for extended periods of time, and don't ingest sources.

### **Introduction**

In 1932, Carl Anderson observed particles in his cloud chamber that behaved as though they had the mass of an electron but with a positive charge. He interpreted these results (correctly) as a new particle he called the "positive electrons". Later renamed positrons, these particles would later be interpreted to explain Dirac's 1929 extension of the quantum mechanics to include special relativity and electron spin. Now called the Dirac Equation, this work found a counterpart solution to the electron. We now understand this solution to be antimatter. In the many years since this discovery, antimatter continues to play a critical role in areas as wide ranging as medical imaging to our fundamental understanding of the universe. In this lab you will perform a variety of experiments with positrons to explore a sampling of the positron's properties and applications.

### **Antimatter**

Antimatter is a counterpart to normal matter that is made of antiparticles which correspond to normal particles. As you can see in Table 1 below, these antiparticles have the same mass as their ordinary particle counterparts, but have some other quantities, like electric charge, reversed. The antiparticle of the electron is the most accessible of these antimatter particles as we can

obtain it simply from a radioactive source. It also has its own name, the positron, with the same mass but opposite charge.

Antiparticles will annihilate with their ordinary counterparts, turning their combined mass into energy in the form of annihilation photons (electrons/positrons) or mesons (protons/antiprotons and neutrons/antineutrons). This means that antiparticles tend to be quite short-lived, as they quickly find their corresponding ordinary particle counterparts and annihilate. The annihilation photons from electron/positron annihilation are high energy (100's of keV) and are thus classified as gamma rays.

Particle/Antiparticle	Mass	Charge
Electron/Antielectron (Positron)	511 keV/c <sup>2</sup>	-1/+1 e
Proton/Antiproton	938 MeV/c <sup>2</sup>	+1/-1 e
Neutron/Antineutron <sup>1</sup>	940 MeV/c <sup>2</sup>	0

**Table 1: Particle and Antiparticle Masses and Charges**

### Na-22 decay scheme

Our source of positrons for this lab is an isotope of sodium, Na-22. Na-22 has a half-life of about 2.6 years. When it decays (as shown in Figure 1), it does so mostly by  $\beta^+$  decay, ejecting a positron (and a neutrino that we can't detect) and converting a proton into a neutron. This leaves an excited state of neon which immediately (within a few picoseconds) emits a 1275 keV gamma ray.

The positron then interacts with the material eventually finding an electron and annihilating with it to form gamma rays. Often this happens simply by the positron finding itself in the proximity of an electron with the proper orientation for a short time. In this situation it can directly annihilate and form two back-to-back 511 keV gamma rays.

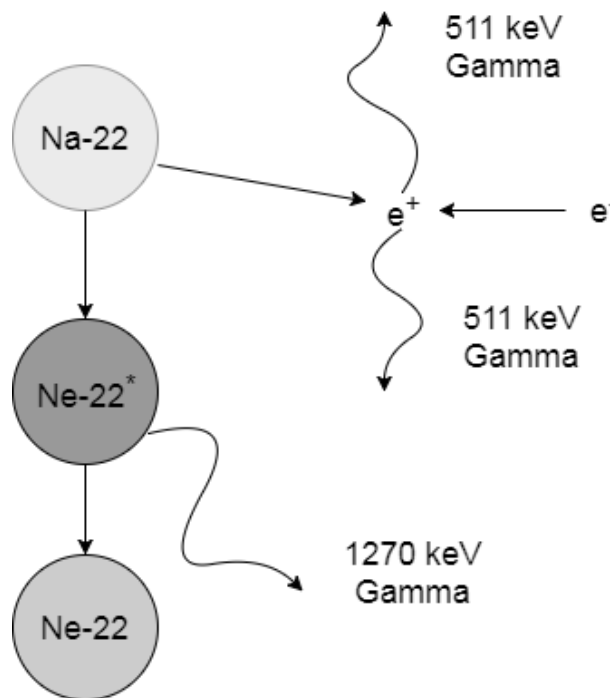
At other times, the positron finds itself in the proximity of an electron in a favorable position to bond with it. When a positron binds itself to an electron, it forms two types of positronium.

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<sup>1</sup> To see the difference between the neutron and the antineutron we need to look deeper than the charge of the particles. The neutron is NOT a fundamental particle (unlike the electron). It is fact made up of 3 quarks. The antineutron is thus made up of 3 antiquarks. While these 3 quarks add up to a total charge of zero, individually they do have a charge. The antiquarks that make up the antineutron have the opposite charge of the quarks that make up the neutron.

*Para-positronium* is a state where the electron and positron have a combined spin of 0. Para-positronium has a vacuum lifetime of about 124 picoseconds (which is far too brief for our detectors to resolve) and decays into two back-to-back 511 keV gamma rays.

*Ortho-positronium* is the other bound state, with parallel spins. It cannot decay via two gamma rays, and instead must produce three. This is because the spins of the electron and the positron line up to give a spin of 1, and the spins of two photons will add up to 0 or 2. Ortho-positronium's lifetime is more than one thousand times longer than that of para-positronium, at 142 nanoseconds. The details of why this is are beyond the scope of this lab, but it is in some sense "harder" to produce three gamma rays from para-positronium than to produce two.



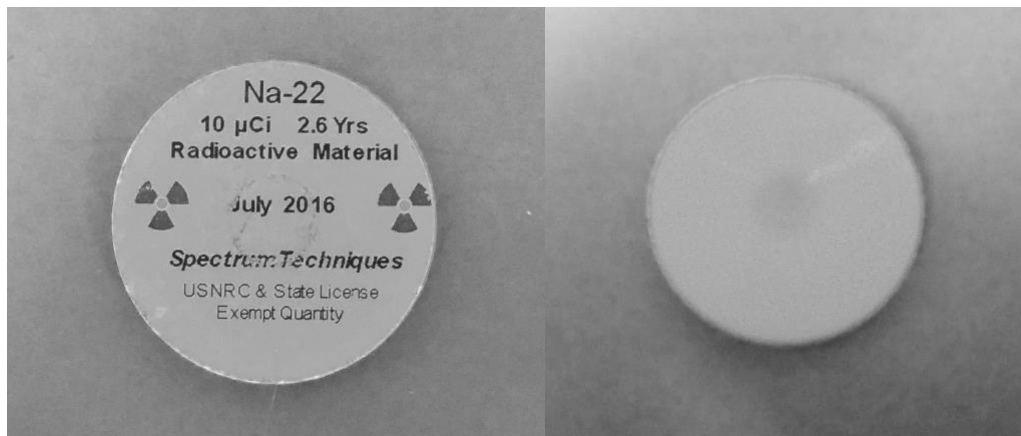
**Figure 1: Decay of Na-22 and Annihilation of Positrons.** Note that the time delay between the Na-22 emitting a positron and the Ne-22\* emitting a gamma (several picoseconds) is far less than the lifetime of a positron (100 picoseconds to 142 nanoseconds) and so the gamma can be used to indicate when the positron was emitted.

## **The Apparatus**

The main part of the apparatus consists of a Na-22 source, four detectors (the metal tubes), a lead collimator, an oscilloscope (the blue and silver box), and a computer running data acquisition software.

## The Source

The source (shown in Figure 2) is an orange plastic disk containing a small sample of Na-22. The sample is close to the surface of the orange side of the disk, meaning that positrons can easily escape from that side. In contrast, the yellow side of the disk (label side) has much thicker plastic, trapping the positrons and causing them to annihilate with electrons in the plastic. Because of this, only gamma rays leave the yellow side.



**Figure 2: Na-22 Source Top and Bottom Views**

Important Note: Make sure that only *one* source is out in the open at a time. Having extra radioactive samples out, whether it be lying around or close to the apparatus without sufficient lead shielding<sup>2</sup>, will interfere with whatever data you are taking with the detector(s).

## The Detectors

The cylindrical devices are *scintillation detectors*, and are designed to detect gamma rays. They do this by combining a *scintillator* with a *photomultiplier tube*.

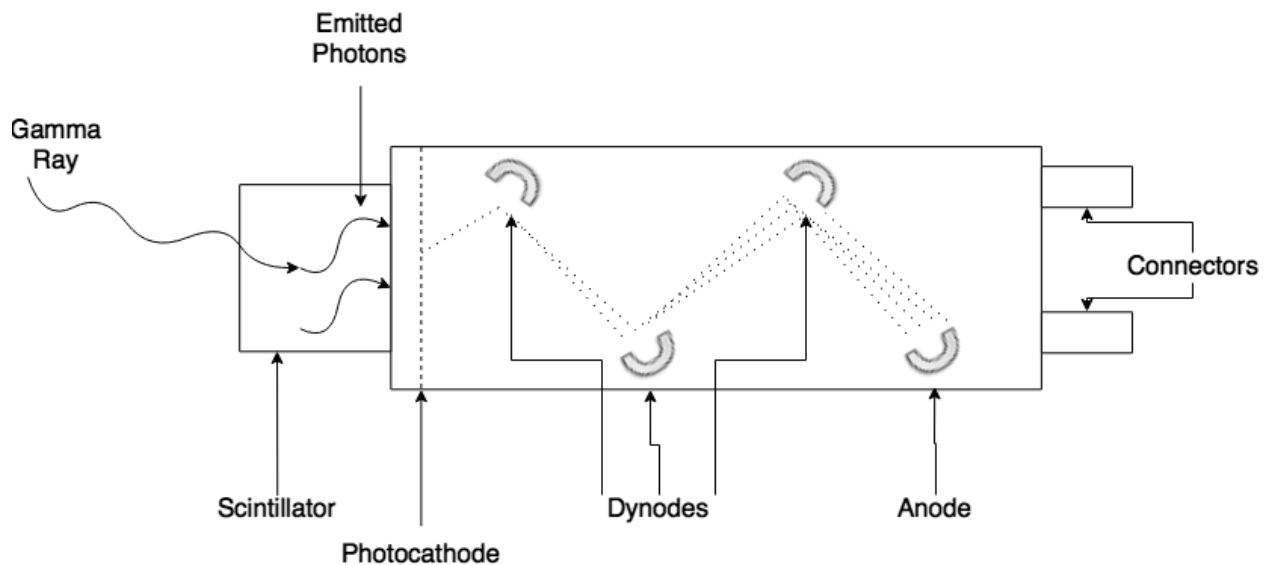
A scintillator is a material that absorbs ionizing radiation and responds by emitting light. The material we are using is sodium iodide (Na-I) doped with thallium. An incoming gamma ray deposits its energy in many electrons which causes the scintillator to emit light (in an amount proportional to the energy of the gamma ray). The gamma ray can deposit its energy in one of

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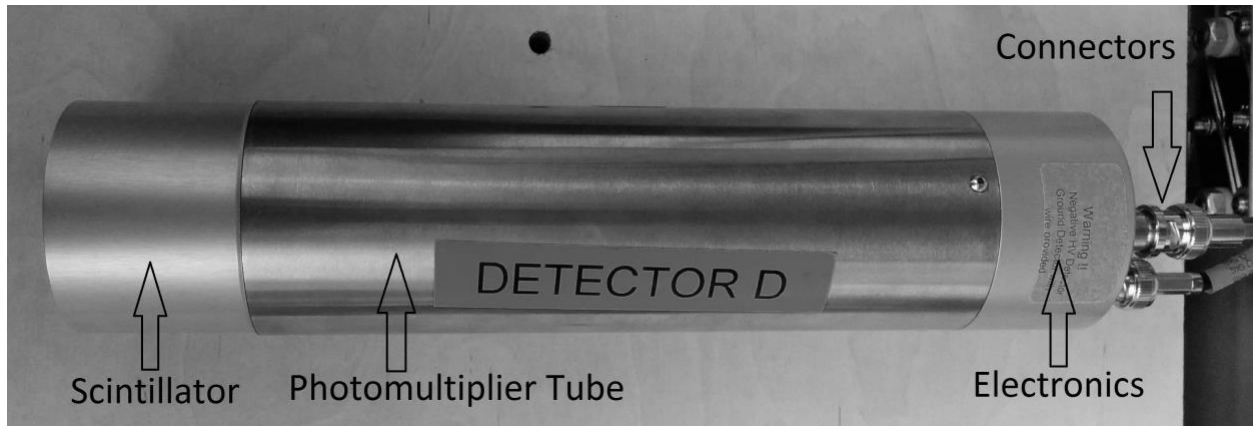
<sup>2</sup> Even though storing the radioactive samples in the lead pigs (lead cylindrical containers) keeps our bodies safe from unnecessary exposure, this is not enough to keep the detectors from picking up extraneous signals. Be sure to have them stored away behind layers of lead shielding (there is a designated area in the left corner by the lab printer). Also look around and make sure that no one else's experiment is running at the same time.

two ways: It can give all of its energy to an electron (and thus the detector) in a process known as *photoelectric absorption* or it can scatter off of an electron, leaving behind a portion of its energy in the electron as additional kinetic energy. In the latter process, the electron interacts heavily with surrounding atoms and excites the electrons in them. Those excited electrons emit light of appropriate energy in order to return to a more favorable, lower energy state. This process is known as scintillation and occurs in the part of the detector appropriately called the scintillator.

As shown in Figure 3, the light from the scintillator goes into the photomultiplier tube. These emitted photons cause the *photocathode* to emit electrons via the photoelectric effect. These are then accelerated by a strong electric field (thus the need for the high voltage power supply) to a *dynode*, where they release more electrons, which are accelerated to the next dynode and release more electrons which are accelerated to the next dynode and so on and so forth. The last stage accelerates the electrons onto an *anode* where they show up as electrical pulse carried away by the connected cables. Our detector (Figure 4) contains these components inside a light-proof housing to prevent signals from ambient light.



**Figure 3: Diagram of the workings of a Scintillation Detector**



**Figure 4: Our Scintillation Detector**

To prevent the delicate detectors from falling over when placed upright, please put them in the 3D printed detector bases, as shown in Figure 5:



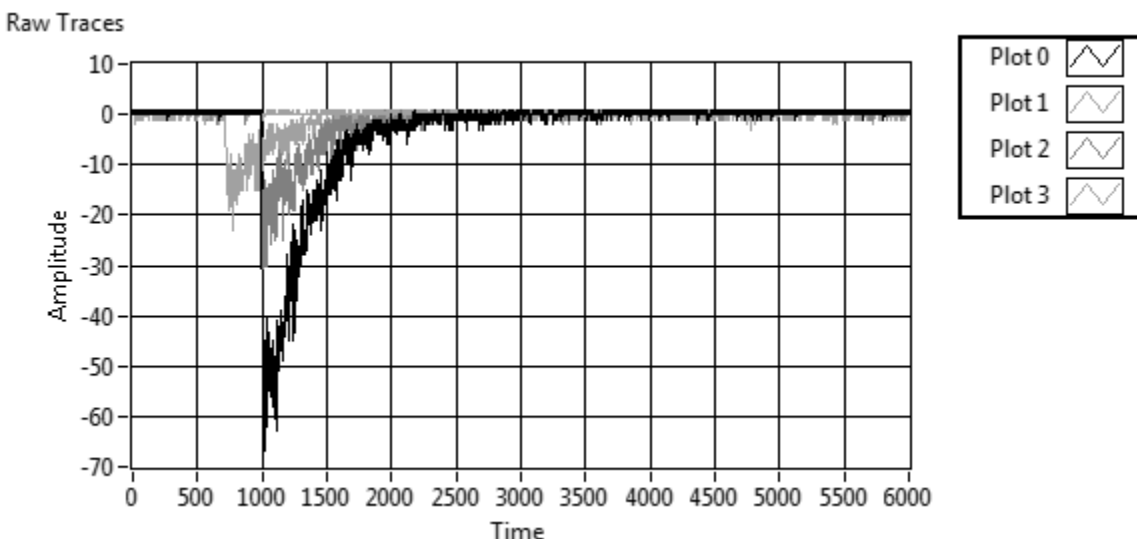
**Figure 5: Detector in a Detector Base**

## The Oscilloscope

The oscilloscope is much like standalone oscilloscopes you may be familiar with, with the exception that it does not have a display. Instead, it interfaces with a computer. The oscilloscope performs lower-level functions like digitizing the analog signal from the detectors and looking for signal coincidences. These signals can be analyzed by software to determine the timing and energy of the gamma rays we are studying.

## The Data Acquisition Software

The computer interfaces with the oscilloscope through a Labview program called Data Acquisition. This is located in a folder on the desktop labeled “Data Acquisition Project” in the location PicoSKD > PS6000 > Labview > “Data Acquisition.lvproj”. The oscilloscope sends the raw data it records (shown in the figure below) and the computer processes this data.



**Figure 6: Raw Data from the Oscilloscope**

The raw data consists of a recorded voltage as a function of time. To determine the energy of the gamma ray that produced the signal, the program finds the area of the electric pulse. The area is proportional to the energy of the gamma so this result is scaled in order to show the final results in the acquisition program. The parameters for this are determined experimentally and are discussed in the next section. The computer also determines the timing of the signal.

The Data Acquisition VI is very flexible. So long as you keep the LabVIEW program running (as in do not click the red stop sign button), the data from the current run can be accessed<sup>3</sup>, manipulated, and saved in either real time, while data acquisition is still on, or after stopping the acquisition of data. Note that exporting files will export all of and *only* the data displayed on the corresponding plots. If you need to export different data, change panel parameters as appropriate and wait for the plot display window to render and then export the revised data. Some of the

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<sup>3</sup> If clicking Start Data Acquisition or Calibration prompts an error message that the PicoScope is not found/connected, exit and cancel all error windows, unplug the PicoScope from the computer and plug back in again. If this doesn't work, unplugging the cords directly to the PicoScope may solve the problem. Seek instructor help if the error message persists.

data acquisition program's features are beyond the scope of this lab, but the experiments below will walk you through using the parts you need.

A note about the St. Olaf lab computers: Because of IT security, there is a default screensaver after 10 minutes of idling and you are required to login again to regain access to the desktop. The Data Acquisition program will still run if in the middle of taking data, however, if your computer settings have the computer going to *sleep* after a certain amount of idling, it could interfere with the acquisition of data. To verify this setting is off, go to Control Panel > Hardware and Sound > Power Options > Edit Plan Settings. Make sure that the "Never" option is selected next to "Put the computer to sleep".

If clicking Start Data Acquisition or Calibration prompts an error message that the PicoScope is not found/connected, exit and cancel all error windows, unplug the PicoScope from the computer and plug back in again. If this doesn't work, unplugging the cords directly to the PicoScope may solve the problem. Seek instructor help if the error message persists.

Extra materials needed for the modern labs are located on the right side of the high voltage source in the window sill.

## **Pre-Experiment Calibration**

Each day, before using the apparatus, you'll need to calibrate the detectors. To do this, place a 10  $\mu\text{Ci}$  Na-22 source into a source cup and place it on the table. Put each detector into a detector base and group these tightly around the source. After making sure that the Data Acquisition VI is running, open the Calibrate panel and click the Run Calibration button. This will begin an automatic calibration process that will take a few minutes. Do not touch the detectors or anything in the program while the calibration process is running. You'll know the calibration process has finished when the Run Calibration button stops blinking. When this happens, you can begin your experiments. Keep in mind that proper calibration is important for these experiments. If you have questions or think your calibration didn't work properly, ask your instructor for help.

## **Experiment 1: Na-22 Energy Spectra**

In this experiment you will explore the energy spectra of the sodium isotope, Na-22. We'll refer back to this data again in later experiments so be sure to keep track of your data. Begin by turning on the high voltage power supply and making sure that Data Acquisition.vi is open on the computer and running (by clicking the white arrow in the upper left corner if there is one). Calibrate the detectors as described above.



**Part one: Look at the spectra from a single detector.**

Take detector A and place it in a detector base and on the table. Take a sodium-22 source (orange disk) and place it yellow side up in a sample holder next to detector A.

On the computer, go to the Data Acquisition panel, set the Maximum Counts to 1 million, and enable the Use Maximum Counts button (it should light up green when enabled). On the Data Acquisition panel, in the trigger conditions box, make sure that only the first condition is enabled, and that the only channel enabled is Channel A. Go to the Energy Plots panel and make sure that only the button labeled Channel A is lit up.

Begin acquiring data (click the green Start Data Acquisition button in the Data Acquisition panel). In the Energy Plots panel you should see a histogram of measured gamma ray energies.

To stop the data acquisition, go to the Data Acquisition panel and press the red Stop Data Acquisition button. DO NOT press the stop sign button on the upper left of the window.

To save your histogram data, click the Export Energy Histogram To Excel button.

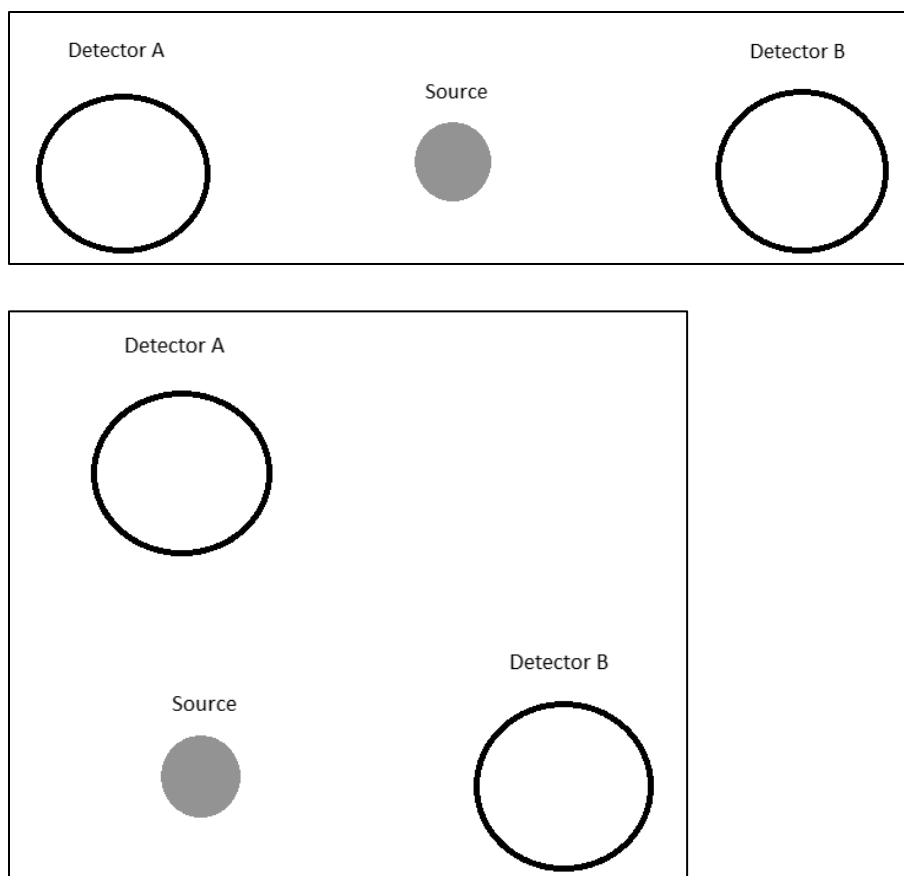
**Part two: Look at the spectra with coincidence at 0 degrees and 90 degrees.**

Place detectors A and B on the table. Place a source in a source holder yellow side up and directly between and equidistant to the detectors (as in the diagram below).

On the Data Acquisition panel, make sure that only the first trigger condition is enabled, and enable channels A and B. This means that data is recorded only if both detector A and detector B receive signals at the same time. Go to the Energy Plots panel and make sure that both the buttons labeled Channel A and Channel B are lit up.

Start data acquisition and look at the Energy Plots panel. You should see two plots, one for each detector. What differences do you see from the spectra with one detector?

Stop data acquisition. Change the placement of the detectors so that they are at 90 degrees to the source (as in the Figure 7).



**Figure 7: Setups for Experiment 1 Part 2: 0 Degrees (Top), 90 Degrees (Bottom)**

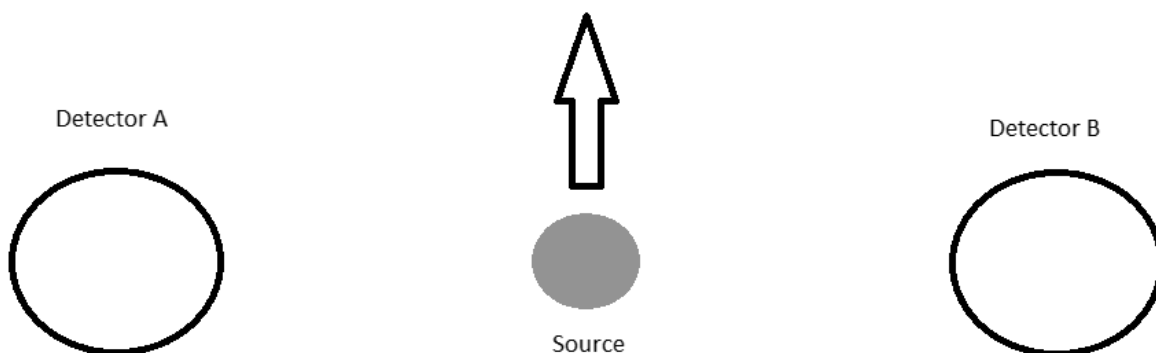
With this new arrangement, take another data run. How does the energy histogram look different? Make sure to stop data acquisition when you're done taking data.

**Part three: Look at detection rates as the source is moved off-axis.**

Place detectors A and B 50 cm apart. Place the source exactly in the middle of the detectors. Start data acquisition and take note of the energy plot and the peak(s) that are apparent from the energy spectrum. Record the number in the Rate (Hz) box. This number tells you how many gamma rays are being detected per second. Stop the data acquisition. Repeat this without demanding coincidence (enable trigger conditions 1 and 2, enable Channel A for the first condition and Channel B for the second condition; this will trigger for any signal from either detector A or detector B).

Move the source in the 0.5 cm increments perpendicular to the line between the detectors, as shown in the figure below. Start data acquisition while demanding coincidence, note the energy

spectrum peak(s), record the rate, and stop the data acquisition. Then do the same thing without demanding coincidence.



**Figure 8: Setup for Experiment 1, Part Three**

Repeat this process until you've moved the source far enough you are effectively only seeing background counts when demanding coincidence. Examine your data and explain what is happening.

This **collinearity** is used in medical PET scans, where a positron-emitting radioactive isotope is put in a patient's body. Pairs of scintillation detectors then look for signals. If two detectors directly opposite each other see signals at the same time, then we know that a decay happened somewhere along a line connecting the two detectors. By having many such pairs of detectors, we can build up a 3D image of where the positron annihilations are happening.

### Questions:

If you look at your data from part one, you'll see that there is no energy peak at 1022 keV. This means that the annihilation of a positron and an electron never produces just one gamma ray. Why is this? How would you know if the positron-electron pair was decaying into three gamma rays?

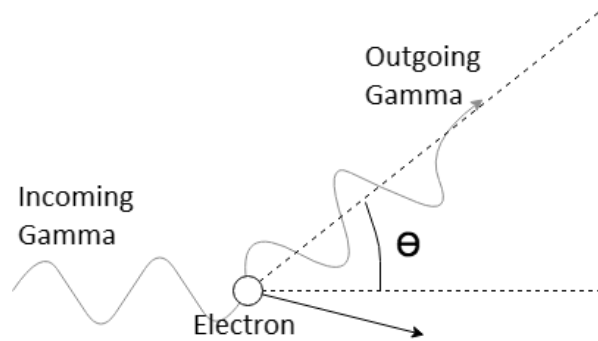
In your data from parts two and three, you'll see each energy plot has an energy peak at 511 keV, meaning that *both* gamma rays emitted were 511 keV. Why do they have equal energies instead of, say, 100 keV and 922 keV?

You'll also notice that the 511 keV gamma rays are always collinear (in exactly opposite directions). Why is this?

## Experiment 2: Compton Scattering

Compton scattering is a process where a photon interacts with an electron and transfers a portion of its energy to the electron. The equation for Compton scattering is:

$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{E_0}(1 - \cos \theta)$$

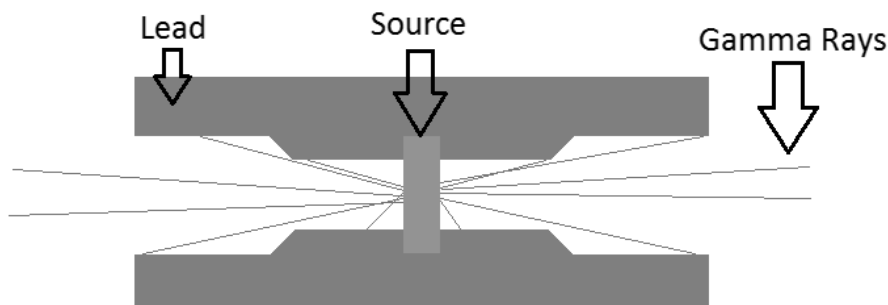


**Figure 9: Compton Scattering Process**

Where  $E'$  is the energy after scattering,  $E$  is the energy before scattering,  $E_0$  is the rest energy of the electron (511 keV), and  $\theta$  is the scattering angle. Conveniently, the gamma rays we're dealing with have the same energy as  $E_0$  so after some algebra we come up with:

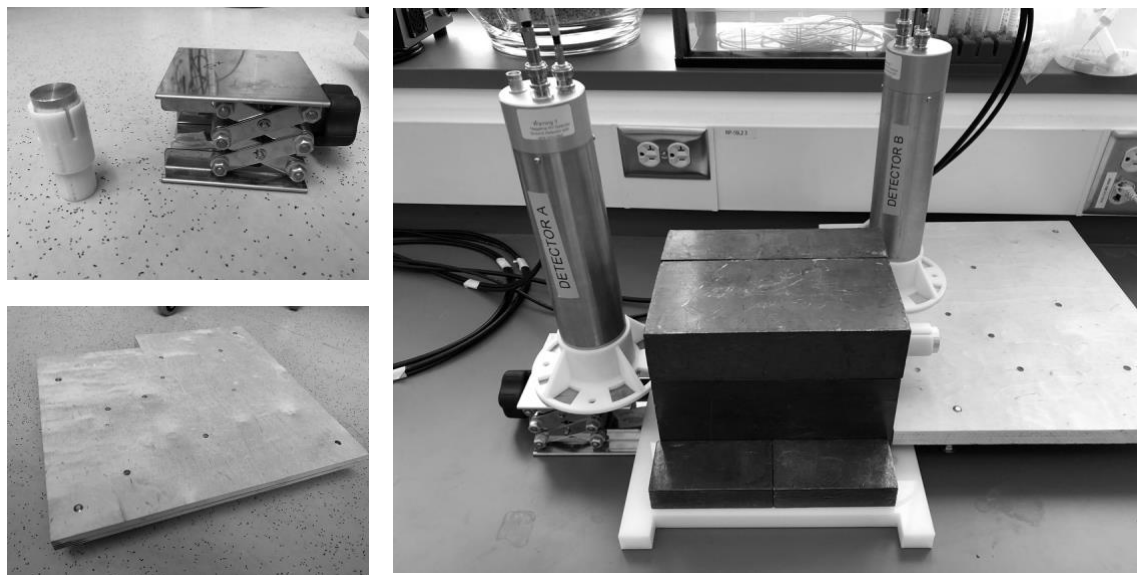
$$E' = \frac{E_0}{(2 - \cos \theta)} = \frac{511 \text{ keV}}{(2 - \cos \theta)}$$

To investigate Compton scattering, you'll be using the lead collimator. This has a Na-22 source at the center, and the lead shielding blocks all gamma rays that aren't travelling straight down the empty tube, as seen in the figure below.



**Figure 10: Cross Section of the Lead Collimator**

## Part one: Compton scattering without coincidence



**Figure 11:** Above are images of the *aluminum scattering target (cylinder) in a plastic target holder*, *metal adjustable platform* (top left), and the *wooden Compton scattering platform that fits on the right side of the collimator* (bottom left). The image on the right shows what the final setup should look like (from instructions below).

There should be a small lead block shielding each end of the collimator. Remove them and set them aside. Place the aluminum scattering target into the plastic target holder and insert on the right side of the lead collimator. Place detector A onto a detector base that sits onto a platform on the left side, up against the lead and in-line with the hole in the lead (this is setting up data-taking for part two). Place detector B onto a detector base and align the holes in the detector base with the holes in the Compton scattering platform so that detector B is at 90 degrees to the gamma ray axis. See Figure 11 to make sure your setup matches the image on the right.

On the Data Acquisition panel, make sure that only the first trigger condition is enabled, and that only Channel B is enabled for the first condition. Go to the Energy Plots panel and make sure that only the button labeled Channel B is lit up.

Start data acquisition. In the Energy Plots panel you should see a histogram of measured gamma ray energies. When you have enough counts<sup>4</sup>, stop the data acquisition and export your data.

Given you are measuring gamma rays scattered at 90 degrees, where would you expect to see an energy peak? Do you see one there?

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<sup>4</sup> This is usually indicated by a “smoothing” of the energy spectrum in the energy plots display. This ensures that you have high-resolution data.

## Part two: Compton scattering with coincidence

Repeat the same setup as in part one, but make sure that on the Data Acquisition panel both Channel A and Channel B are enabled in the first trigger condition. This makes it so that data is only recorded if both detectors A and B receive a signal at the same time.

Start data acquisition. What has changed for the energy section of Channel B?

## Part three: Find peaks at 0, 30, 60, 90 degrees

Set up the equipment as in part two. Record and export data at scattering angles of 0, 30, and 60 degrees in addition to the 90 degrees data from part two. Find the energy peaks of the scattered 511 keV gamma rays for each of these angles. How do these peaks compare to the values predicted by the Compton scattering equation?

Now, consider the energy that a gamma ray gives to an electron when it scatters. The minimum value is 0 when the scattering angle is 0. What is the maximum value, and at what angle does this occur?

Look back at your spectra from experiment 1 (part 1). In addition to both the 511 keV peaks and 1275 keV peaks there is structure in the spectra, as seen below. Below each peak is a valley that then rises again at what is called the Compton edge. At energies below this edge is a plateau. Given your knowledge of Compton scattering and photoelectric absorption, what might be the cause of these features? In particular, is the edge located at the energy you would expect, and what causes the plateau and valley features?

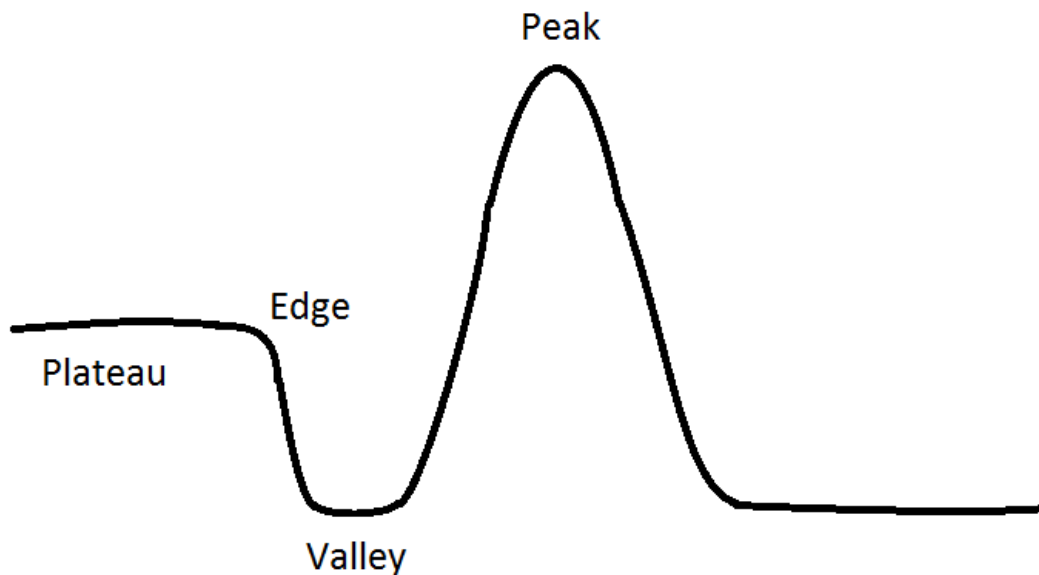


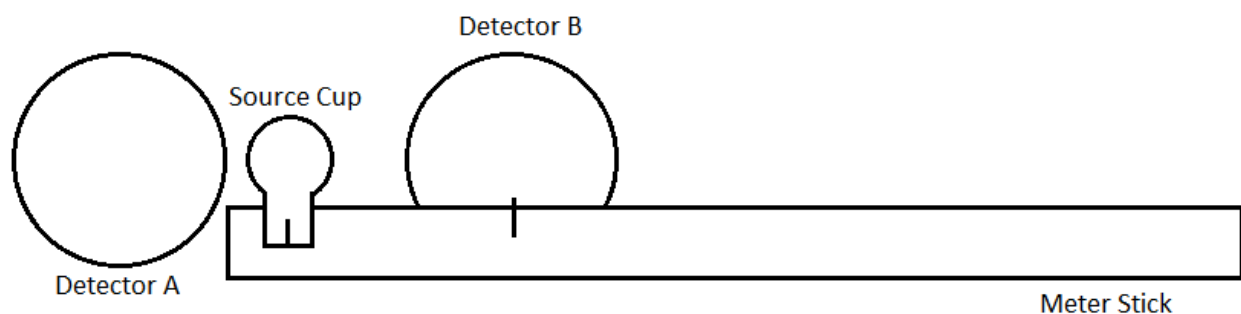
Figure 12: Simplified Gamma Ray Energy Spectrum

### **Experiment 3: Measuring the Speed of Light**

In the previous experiments, you only used the Data Acquisition and Energy Plots panels. Now you'll also be using the Timing Plots panel to look at the differences in time from when one detector receives signal to when another detector receives signal.

Place detector A at the left edge of the meter stick with the center of the detector in-line with the edge of the meter stick and clamp it to the table so that it will not move. Place a source yellow side up into the speed of light source cup (the one with an appendage that fits over the meter stick). Place the speed of light source cup against detector A and the edge of the meter stick so that you can see the markings on the meter stick through the small slit in the speed of light source cup. Record the position of the source cup and periodically check that it has not moved.

Place detector B in the speed of light detector base (the one with part of the base missing) and place the flat part of the base against the edge of the meter stick, as in the diagram below.



**Figure 13: Setup for Experiment 3**

In the Data Acquisition panel of the program make sure that only the first trigger condition is enabled, and that both Channel A and Channel B are enabled for the trigger condition.

In the Timing Plots panel of the program make sure that Enable Plot is pressed for the first row and not for any others. Set the Start Time Channel to Channel A and the Stop Time Channel to Channel B. This means that the program will start a timer when it receives a signal on detector A and stop the timer when it receives a signal on detector B.

You should also see boxes labeled Start Energy Range and Stop Energy Range. These values determine the gamma ray energies that will start and stop the timer. Determine appropriate values for these, given that you will be looking for 511 keV gamma rays in both detectors. Note that there is some uncertainty in the detected energy; you may wish to consult the spectra you recorded earlier in the first experiment.

Start data acquisition. In the Timing Plots panel, you should see a histogram of the timing differences<sup>5</sup>. You can double click on the axis min and max to set the histogram data to an appropriate domain, if it is not already. When you have a well-defined peak (about 6000 points of data as measured by the Total Counts box) stop data acquisition and click the Export Histogram Data to Excel button, making sure to record the position of detector B. Repeat this process for at least 10 different positions of detector B. Your results will have better accuracy with larger separations.

To process the data, fit at each dataset to find the peak of the histogram. Use this data to determine the speed of light. Compare your experimental value to the known value of the speed of light.

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<sup>5</sup> Note that the histogram detects negative time differences.

This means that for A Start → B Stop signal was detected in the B Detector *before* signal was detected in the A Detector.