Positron Spectroscopy – Advanced 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.

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

These experiments build upon material covered in the modern physics positron experiments dealing with positrons and the gamma rays they emit.

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. The annihilation of other antimatter such as Antiprotons or Antineutrons is more complex in nature and not relevant to our work here.

Particle/Antiparticle	Mass	Charge
Electron/Antielectron (Positron)	511 keV/c^2	-1/+1 e
Proton/Antiproton	938 MeV/c^2	+1/-1 e
Neutron/Antineutron[1]	940 MeV/c^2	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 β^+ 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.

[1] 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 the charge. The antiquarks that make up the antineutron have the opposite charge of the quarks that make up the neutron.

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. *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.

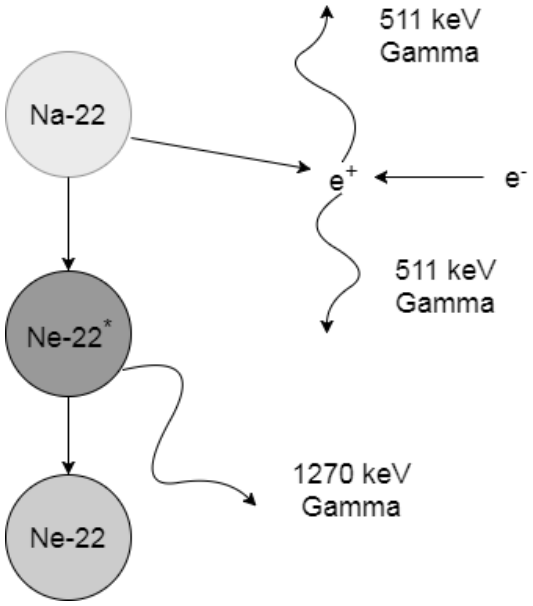


Figure 1: Decay of Na-22 and Annihilation of Positrons. Note that the time delay between the Na-22 emitting a positron and the Ne-22* emitting a gamma (several picoseconds) is far less than the lifetime of a positron (100 picoseconds to 142 nanoseconds) *so the gamma can be used to indicate when the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

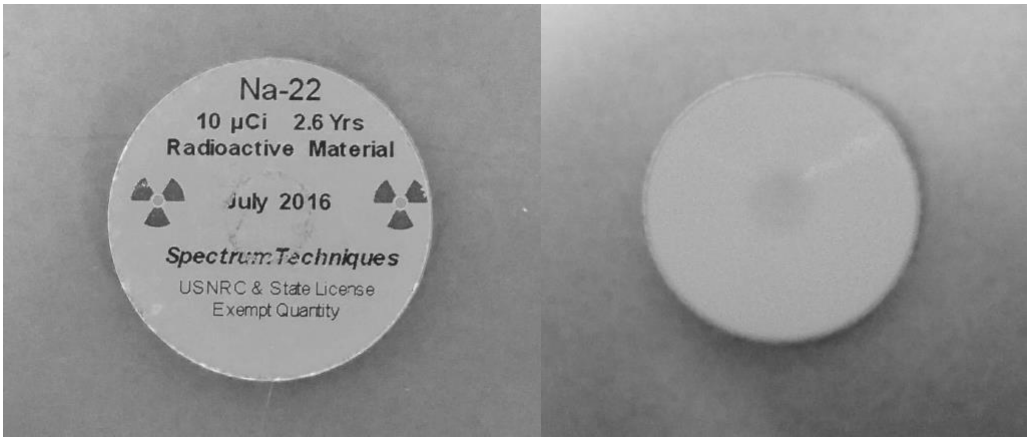


Figure 2: Na-22 Source Top and Bottom Views

In the first two experiments, you will still use a sample of Na-22 except in a thinner source, a thin plastic disk with a Mylar window that allows the positrons to escape the source. For both experiments use the thin source labeled 10 µCi. Take note of the date on the sample, as well, for it will help identify a more accurate activity level for the source. If a 10 µCi sample is about two and a half years old, then its activity will actually be 5 µCi.

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[2], will interfere with whatever data you are taking with the detector(s).

The Detectors

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

[2] 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 space for these samples 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.

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 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 gamma rays 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 detectors (Figure 4) contain these components inside a light-proof housing to prevent noise signals from ambient light.

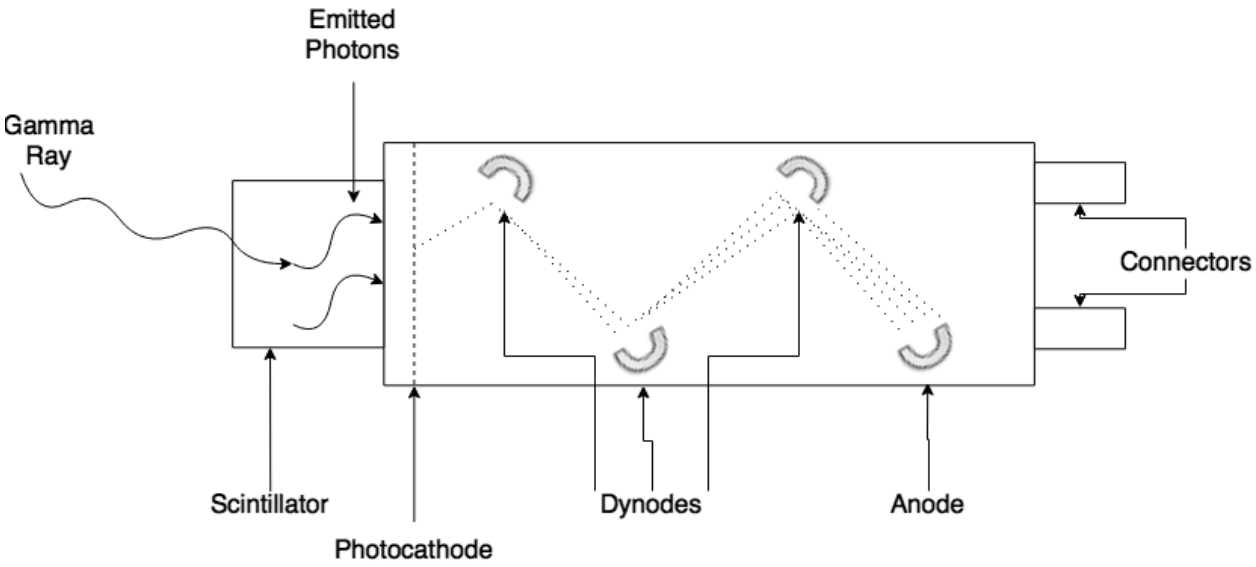


Figure 3: Diagram of the workings of a Scintillation Detector

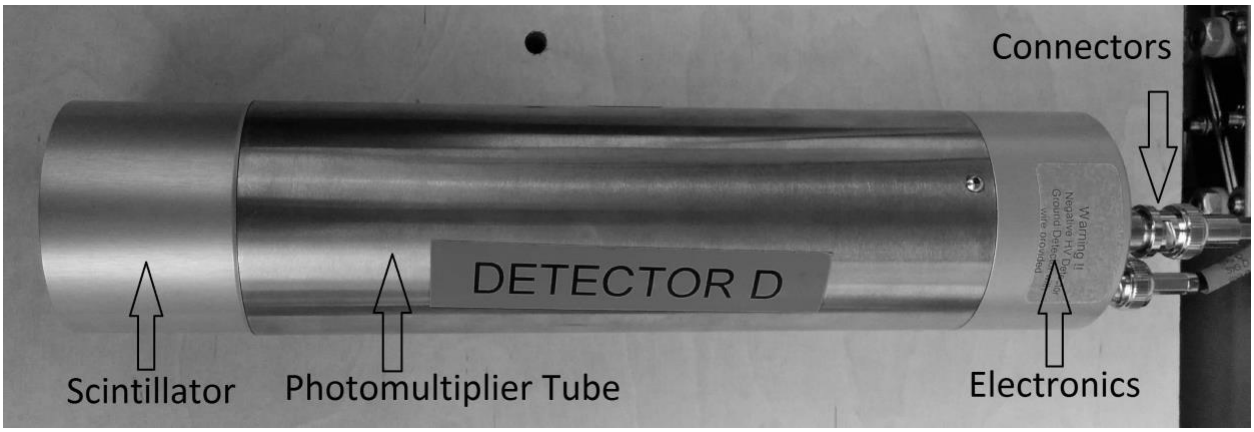


Figure 4: Our Scintillation Detector

To prevent the detectors from damage or from moving during acquisition of data, make sure that detectors in any apparatus are always securely fastened or situated in a holder or by secure structural barriers (e.g. lead shielding). To prevent the 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 Figure 6) and the computer processes this data.

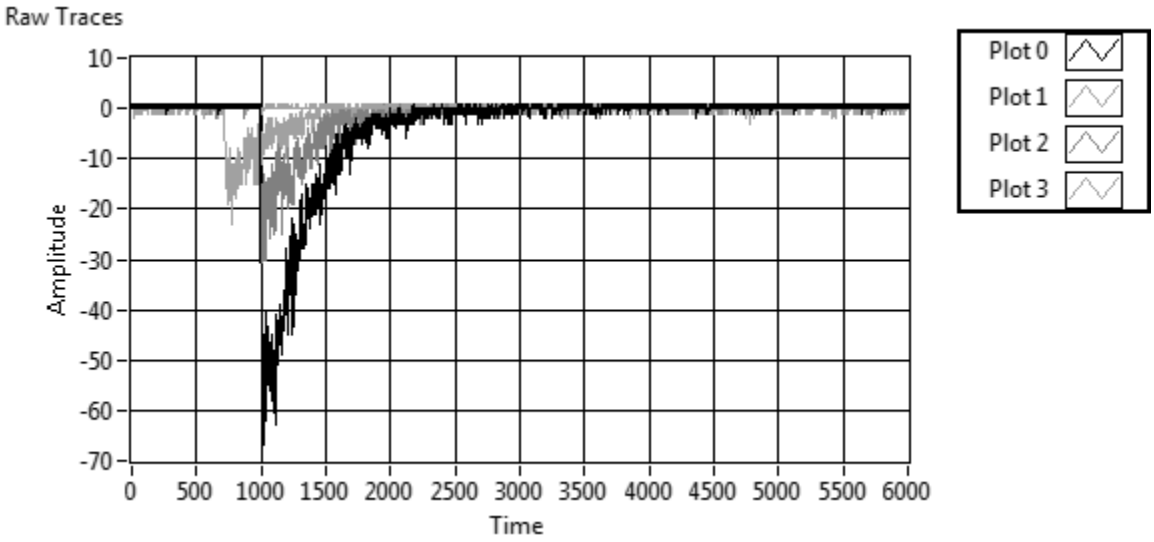


Figure 6: Raw Data from the Oscilloscope

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, 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 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. For reminders on the specifics of how each panel operates, you may refer to the Modern Lab Manual on Positron Spectroscopy.

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 advanced labs are located next to the lead shielding storing the radioactive sources.

Pre-Experiment Calibration

Each day, before using the apparatus, you'll need to calibrate the detectors. To do this, place a 10 µCi 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.

Modern Physics Lab Experiments

If you have not previously completed these experiments, take the time to familiarize yourself with the apparatus and its operation and quickly run through some of the modern physics lab experiments. Consult with your lab instructor about which experiments would be the most important. These will help you with the advanced lab experiments.

Long Data Acquisition Times

Experiment 2 and 3 require long acquisition times—much longer than that of the modern positron spectroscopy labs— because of the low detection rates of those events. Take into account that these runs will be about 2-3 hours long in order to acquire sufficient data to analyze. While you're waiting be sure to read through the lab manual and do any analysis that you are able to do in order to maximize productivity.

Experiment 1: Positron Lifetimes in Materials

When a positron enters a material, it may behave in a number of ways that can be categorized as having either a short lifetime or a long lifetime. (1) A positron can directly annihilate with an electron (both of which are spin-1/2 particles), emitting two back-to-back 511 keV gamma rays or (2) it can bond with an electron making para-positronium, which has a combined spin of 0 and then immediately decays into two back-to-back 511 keV gamma rays.

(3) Positrons can also bond with an electron making ortho-positronium, which has a combined spin of 1, but finds a nearby electron with appropriate spin such that the positron in the pair disregards the original electron and annihilates with the new electron, decaying into two 511 keV gammas. For denser materials, such as solid metals with lots of available electrons this process, called "pick-off", greatly reduces the lifetime of the ortho-positronium whereas other lifetimes may be less affected because electrons aren't as easily available in molecular materials.

Because of the conservation of angular momentum, there is no combination of spins of two gamma rays (spin-1 particles) that will also give way to a combined spin of 1. Thus, if the formed ortho-positronium never encounters a nearby electron of favorable spin, then (4) it will decay into 3 gamma rays on its own over a much longer period of time (~142 ns in a vacuum). When a positron enters a very diffuse material, the "pick-off" process reduces the lifetime of ortho-positronium in the material and can give us useful information about the material, such as the size of structural voids in the material, or how easily the positronium can pass through a material without annihilating. In this experiment we will be focusing on the timing plots and deciphering a lifetime decay parameter, τ. Figure 7 shows a simplified version of what your signal will look like (you will see a lot more noise) with varying lifetimes.

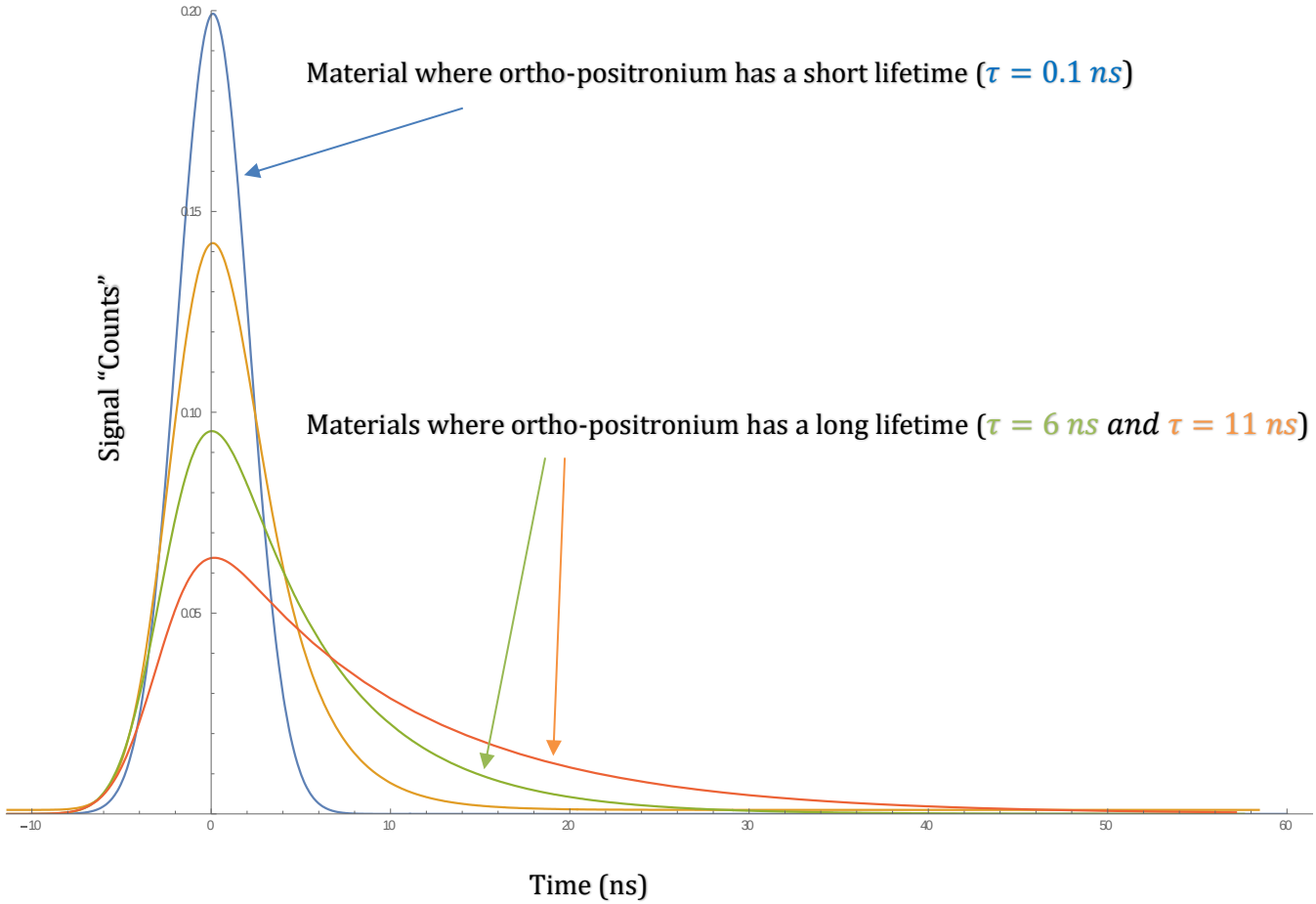


Figure 7: Timing Plot where the blue and yellow peaks "die out" more quickly, indicating a smaller average lifetime than the green and orange peaks.

You will be performing this experiment with three materials: Aluminum, silicone gel, and fumed silica powder[3][4]. What material do you expect to have the longest lifetime? The shortest?

[3] The Aluminum sample is a cylinder similar to the aluminum scatterers used in experiment 1, only shorter. The silicone gel sample looks like a blob of clear rubber that covers at least the Mylar window of the sample (need not cover the entire radius of the source cup). The fumed silica powder is in a plastic jar labeled "Cabosil Fumed Silica" and can be scooped into the source cup right over the thin source. There should be enough to make a stable pile on top of the source. The more there is on the source, the better signal you will detect.

[4] The Aluminum and silicone sample should stay in the lab. Do NOT dispose either of these. The loose silica powder pile can either be returned to the jar or be thrown away.

Setup

To perform this experiment, you'll be using the thinner Na-22 (the one labeled as 10 µCi) source disks. These let positrons out through a thin Mylar window (the shiny circle on one side of the disk). Place the thin source disk in the source holder with the Mylar side facing upwards, and place the sample material on top of the Mylar window. The positrons released will enter the material and annihilate. Place two detectors next to the source/sample and at 90 degrees, as shown in Figure 8. This will prevent the detectors from triggering from back-to-back 511 keV gamma-rays.

Figure 8: Positron Lifetime Setup

Using the Timing Plots panel for data acquisition and filter the timing data by energy by setting new energy ranges. The start signal comes from 1275 keV gamma rays while the stop signal for the lifetime comes from 511 keV. Thus, for the start signal use all signals with greater than 600 keV. For the stop signal, all energies under 600 keV can be used. This experiment runs with only the first Trigger Condition enabled with both A and B lit for coincidence acquisition. For two sets of timing data per run, enable two timing plots with opposite start and stop channels.

Recall that the timing plots panel in the data acquisition program logs the time *differences*. Thus, our data used for analyzing the decay of the "noise" signal. Even going out to 500 ns as the timing window maximum may not show apparent decay.

The decay of positrons follows the standard exponential decay equation: $N(t) = N_0 e^{-\lambda t}$ with λ the decay constant. The "lifetime" of the positron is often denoted as τ and is equal to $1/\lambda$. It is straightforward to show mathematically (try if you like) that τ is the average lifetime of

positronium with decay constant λ. You can compare the Aluminum and Silicone data. However, there are several issues with the equipment and methods used that make this data qualitative:

- First, the timing resolution of the detectors and oscilloscope are similar to the lifetime of positronium in these materials, convoluting the exponential with the resolution of the detector. (See Appendix if interested)
- Second, many of the positrons emitted by the source do not go into the materials and instead go into surrounding materials such as the protective disk for the source creating significant background signals.
- Third, direct annihilations (annihilations without forming positronium) can occur. This is observed as the 511 keV peak in the timing data.

When fitting the fumed silica data, you can get more quantitative results than with the aluminum and silicone gel because the lifetime of positrons within the fumed silica is much longer than the timing resolution of the equipment. Additionally, the long lifetime means that you can ignore all decays below 20 ns, since the all of the short lifetime components from annihilations in plastic are about 2-4 ns. However, there will be some roughly uniform background noise, so your analysis should take this into account.

Experiment 2: Three-Gamma Decays

In this experiment, you will attempt to demonstrate that the long lived decays from Ortho-Positronium are in fact due to decays from 3 gammas in fumed silica powder. To do so we will need to design an experiment that will provide an unmistakable 3-gamma signal. However, this is much more difficult than looking for 2-gamma decays. This is in large part because of the possibility of false signals from scattering and the possibility of multiple events occurring simultaneously. Figure 9 shows a number of these potential interfering signals.

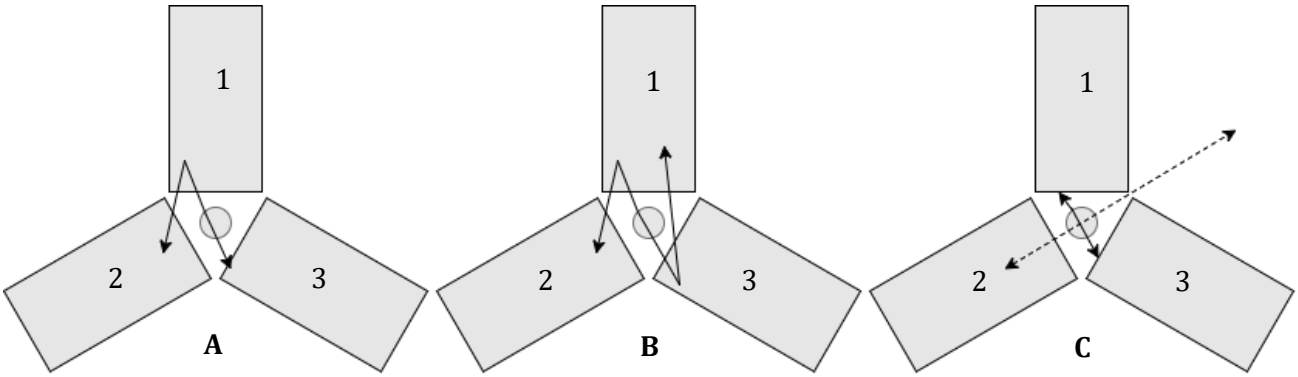


Figure 9: Three detectors receiving interfering 2-gamma signals from annihilating positrons in the form of:

A. **An annihilation occurs in the sample, emitting two gamma rays of 511 keV each in opposite directions. One of these 511 keV gammas deposits all of its energy into Detector 3 while the other 511 keV gamma deposits part of its energy into Detector 1 and then scatters with the remaining energy that is deposited in Detector 2. The sum energy detected by these three detectors is 1022 keV.**
B. **An annihilation emits two gamma rays where both 511 keV gammas deposit only part of their energy into detectors and scatters to another detector. In this particular figure, one 511 keV gamma deposits part of its energy to Detector 1 and scatters to Detector 2, depositing the rest of its energy, whereas the other 511 keV gamma does so in Detector 3 and Detector 1, respectively. The sum energy detected by these three detectors is also 1022 keV.**
C. **The first annihilation event emits two 511 keV gammas that deposit all of their energy into Detector 1 and Detector 3. A second annihilation event emits two 511 keV gammas, but only one is detected by Detector 2. The other 511 keV never reaches either of the other detectors (absorbed by the lead shielding). The sum energy detected by these three detectors is greater than 1022 keV, likely close to about 1533 keV.**

From the previous experiment, you found that the lifetime of ortho-positronium is much longer in silica powder than it is in either Aluminum or silicone gel.

To reduce these interfering signals you'll be using several techniques. First, you'll be using lead shielding between the detectors to reduce the chance that a gamma ray scattering off of one detector interacts with another detector (we will explore this more later on while you are waiting for the data to acquire).

Second, you'll be demanding a quadruple-coincidence (~600 ns window) by using a fourth detector to look for the 1275 keV gamma rays that accompany the emission of a positron from the sodium-22. This will reduce false positives from background radiation and from 1275 keV gamma rays scattering off of a detector and looking like an annihilation gamma ray.

Third, you'll be processing the data to see if the A, B, and C energies sum to about 1022 keV and the D energy is about 1275 keV, which is what we would expect for a 3-gamma event. Likewise, you'll ensure that the D signal occurs before the A, B, and C signals, and that the A, B, and C signals occur very close to each other in time (about a 10 ns window).

Last, you'll be using the same type of thin Na-22 source used in experiment 2. Verify that you are using the thin Na-22 source labeled as having 10 μCi.

Setup

The lower part of the three-gamma setup is shown in Figure 10 and 11 below. The detectors are positioned with their ends against lead shielding with a small window so that each detector has an easy path to the source but so that it is difficult for a gamma ray to scatter off of one detector and interact with a different detector. The lead shown in the figures is a stack of three small blocks. These are arranged symmetrically around a source cup[5] with a thin positron source in the middle, positioned so that the positron emitting end of the source is facing upwards and with some fumed silica powder generously piled over the source.

Above this are placed three more lead blocks, as shown on the right side of the figures. These support a fourth detector which is placed in a detector base. This leaves a window so that the fourth detector has a clear path to the sample, but no clear path to the other three detectors. When you've completed the setup it should look like the right side of Figure 11.

[5] Be sure to leave enough wiggle room so it is not too difficult to remove it to switch out samples. Otherwise, removing the lead blocks and detectors is tedious.

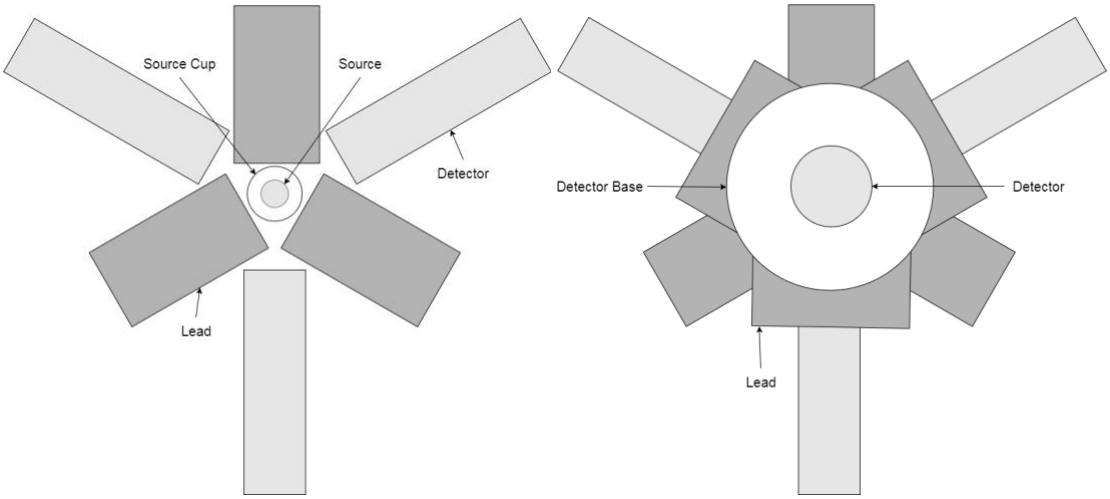


Figure 10: Lower Level of Three-Gamma Setup (Left), Completed Setup (Right)

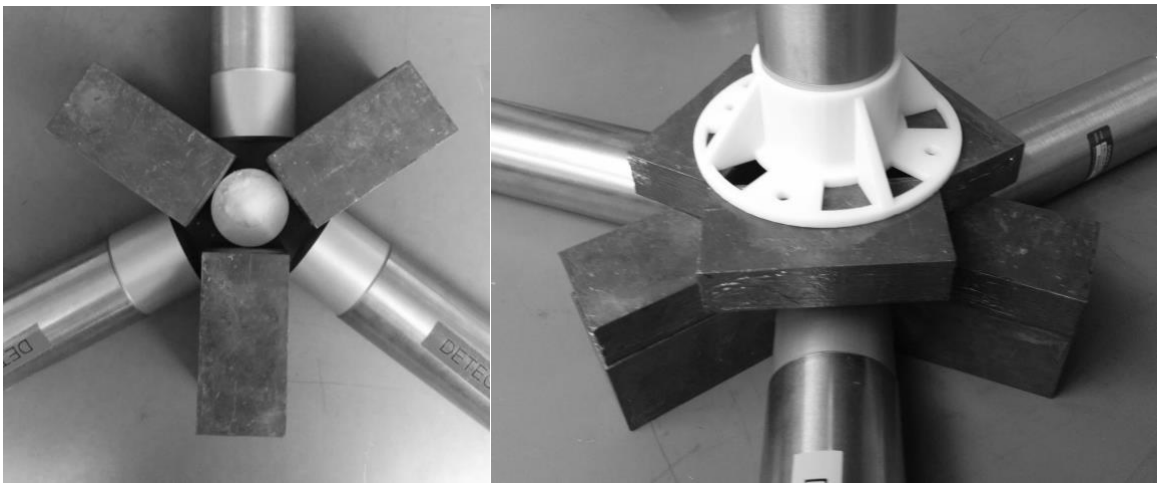


Figure 11: Photo of Lower Level of Three-Gamma Setup (Left), Completed Setup (Right)

To run the experiment, you'll need to demand a quadruple coincidence between the four detectors. To do this, enable only the first trigger condition and enable all four channels. This will make the oscilloscope trigger only when all four channels receive signals within the same time window. Because of the quadruple coincidence requirement and all the lead shielding, your data rate will be very low, so you will need to run this experiment over a couple of hours. Currently, the maximum counts allowed is 1,000,000, which if left unmonitored could leave you with an inordinate amount of data to analyze and process. Instead of constantly monitoring the data acquisition program to keep the data at a manageable size, change the value of maximum counts (should be at least 50,000) so it automatically stops after a certain number of detected coincidence counts. If at this point you are at the end of your lab session (and there are no other

lab sessions for the day) go ahead and start the data acquisition and come back in a couple hours to export the raw data for analysis.

Important Things to Consider for Analysis

While you are waiting for the data to acquire, consider the interfering signals from Figure 9. These are all two-gamma events that will still trigger a "simultaneous" event given the timing resolution of the detectors (600 ns window).

This particular setup is designed to ideally detect 3-gamma events where the emitted gammas have the same energy with coplanar momenta with a separation of 120 degrees with respect to each other.

Because not all gamma interactions result in the gamma ray depositing all of its energy into a detector, your data will also present events where there may be scattering within the detectors that either hits lead shielding or hits another detector. So long as scattered gammas are detected by detectors A, B, or C, the energy sum of those three detectors will remain 1022 keV. If the scattered gammas get absorbed by the lead shielding, then the data will present an event with an A, B, and C energy sum less than 1022 keV.

If you consider a single (A, B, or C) detector's energy versus the summation of detectors A, B, and C, your data will look like a bunch of scatter plot points. The location of the cluster formed from your data is significant in characterizing the primary events occurring in the annihilation of positrons in the fumed silica powder.

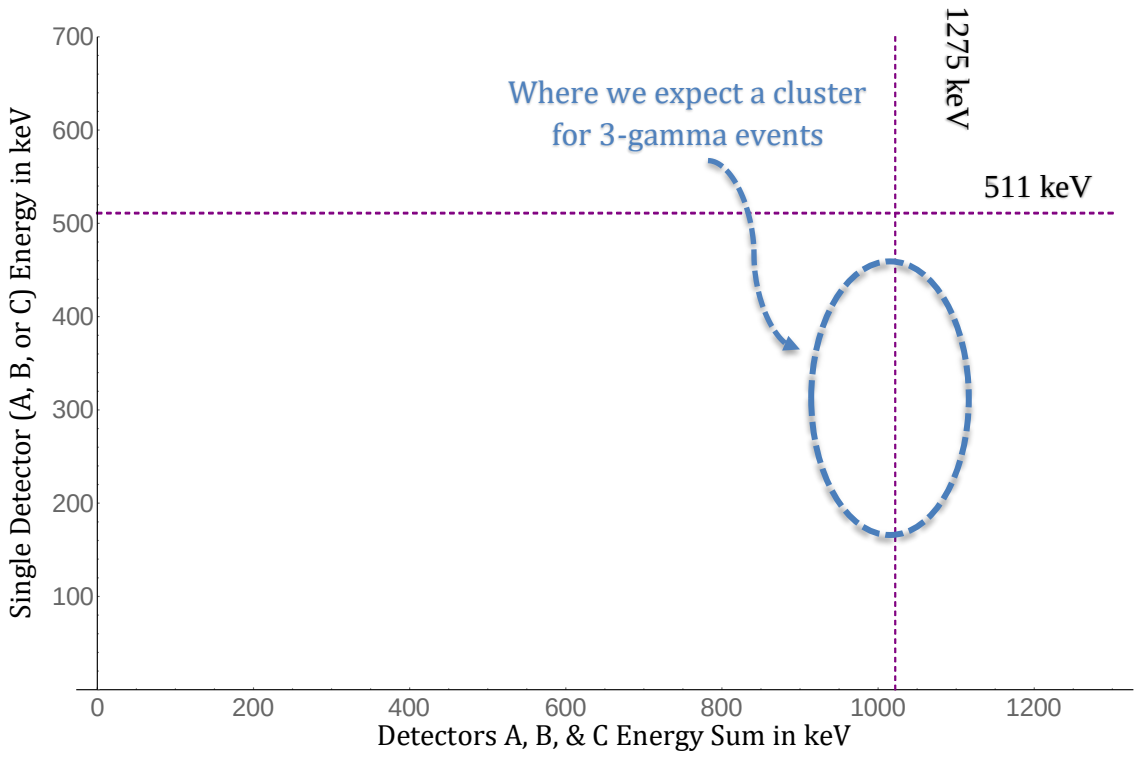


Figure 12: An empty plot of the energy of a single detector versus the energy sum of three detectors.

When you're done taking data, record the total time as indicated at the top of the interface and click the Export Event Time-Energy Data button in the Data Acquisition panel. This will output your data to an Excel spreadsheet in the format:

A Time, B Time, C Time, D Time, A Energy, B Energy, C Energy, D Energy

Energies are in keV and times are in ns. However, times are relative to some arbitrary zero for all of the detectors, so you'll need to calculate the time differences between channels at each coincidence. Because of the complexity of the data analysis for this experiment, you will use this exported data offline rather than in the Data Acquisition program.

Most of the data you get will be noise, not signal. You can improve this dramatically by filtering the data that you exported from Data Acquisition. The following are characteristic specifications for observing the 3-gamma decays that will guide the filtering of data points:

1. You can get rid of incomplete or nonsensical points (i.e. NaN or negative energy value entries) upfront so they don't get in the way as you go
2. You'll want to ensure that the A, B, and C timing signals are all close together, indicating that they probably came from the same event. A 10 ns time window works well for this.
3. You should check that the A, B, and C energies add up to near 1022 keV and that the D energy is near 1275 keV (plus or minus 100 keV works well or you may refer to appropriate energy ranges based off of previous experiments).

Take a glance at the Energy Plot Sum panel and note the energy of the prominent peak summing the energies of detectors A, B, and C. You can compare this to your calculated average energy sum. Plot the filtered data in your own "A Energy vs (A, B, C) Energy Sum" scatter plot. Based on Figure 12, what would you expect to see in this scatterplot? Does your data appear to provide evidence that the signals you see are indeed from 3-gamma events?

Now we want to replace the pile of silica powder with the aluminum sample. Instead of recording 50,000 total counts, enable the time stopping condition so that the program stops acquiring after the total time you recorded from the silica powder run. Any positron emitted from the source and into the aluminum should immediately annihilate with an electron in the aluminum instead of forming ortho-positronium. Because we know the lifetime of positronium in aluminum is far briefer than that of positronium in silica powder, we only expect to see 2-gamma events. Compare the total counts that the aluminum sample triggers in the detectors to the 50,000 counts acquired in the same amount of time with the silica powder. Filter your data Likewise, positrons emitted from the source and into the surrounding plastic should annihilate with a lifetime of a few nanoseconds. This should result in you seeing few to no three-gamma events. Does your data support this?

Note the number of filtered points that make it into your scatter plot with silica powder and with aluminum. Considering what you know about the lifetimes of positronium in both of these materials, what patterns in the data indicates a significant presence of 3-gamma events?

Experiment 3: Polarimetry

Recall from the modern physics lab experiment that Compton scattering is a process where a photon interacts with an electron and transfers a portion of its energy to the electron, as shown in Figure 13. The equation for Compton scattering energy is:

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

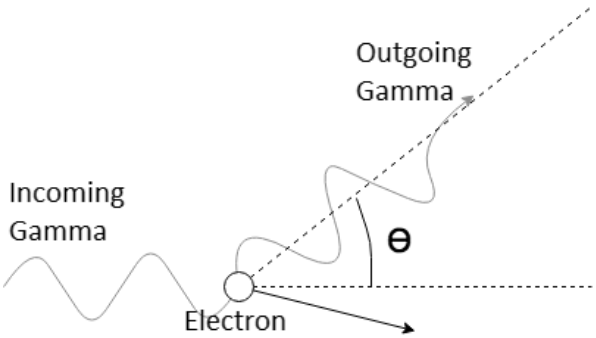


Figure 13: Compton Scattering Process

Where E' is the energy after scattering, E is the energy before scattering, E_0 is rest energy of the electron (511 keV), and θ 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 conserve angular momentum, the two gamma rays produced from an electron-positron annihilation must have opposite circular polarizations. However, the photons are an entangled pair and are in a superposition of the two circular polarization states. Circular polarization itself is a linear combination of horizontal and vertical linear polarizations. So the photons are in a superposition of linear polarization states and if we measure one as vertically polarized, the other will be horizontally polarized. We can investigate this property by exploiting the fact that linearly polarized gamma rays preferentially Compton gamma rays scatter at right angles to their polarization. To do this, you'll be using the lead collimator, shown in 14. This has a sodium-22 source at the center, and lead shielding blocks all gamma rays that aren't travelling straight down the empty tube. At the ends of the tube are aluminum cylinders. If they are not already in place, you can remove the small lead blocks covering the ends of the collimator and insert aluminum cylinders in their 3D printed holders and fit the plastic side in the holes at each end. The gamma rays will scatter off of these.

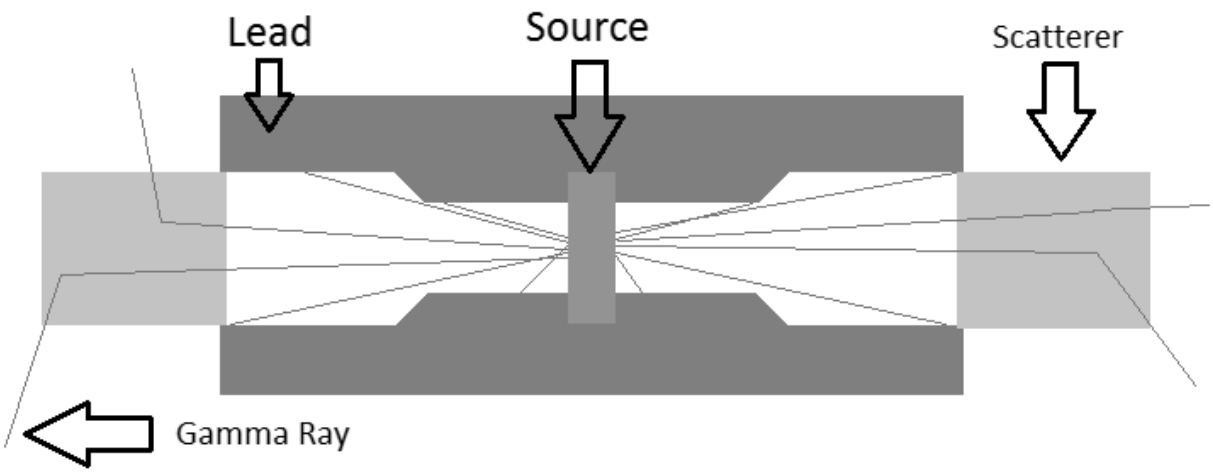


Figure 14: Lead Collimator and Aluminum Scatterers

Scintillation detectors are placed so that gamma rays can scatter at 90 degrees off of the scatterers and into the detectors. Two detectors are on each end of the setup so that one is above the scatterer and one is beside the scatterer.

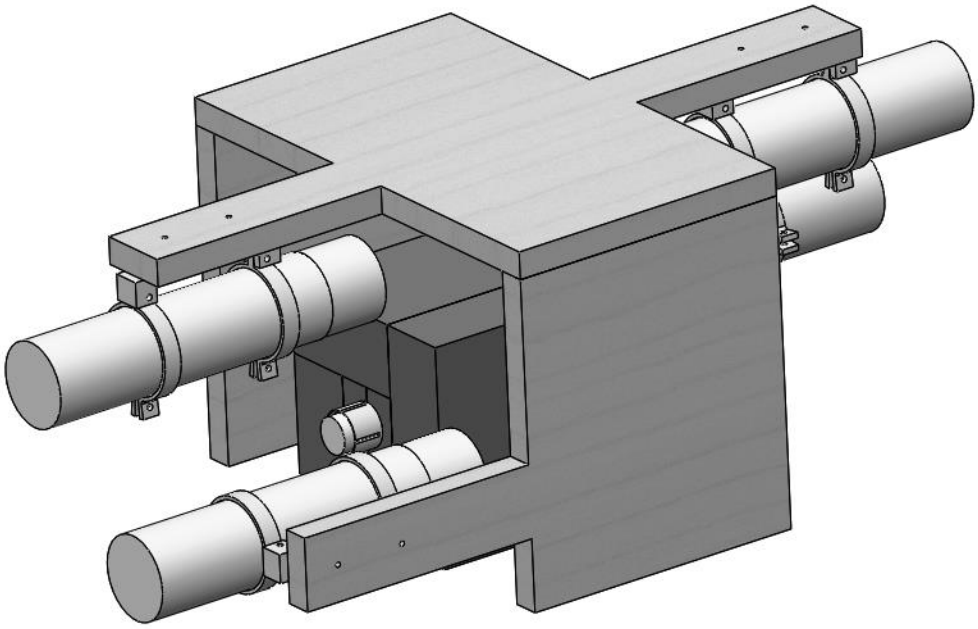


Figure 15: View of Polarimetry Setup

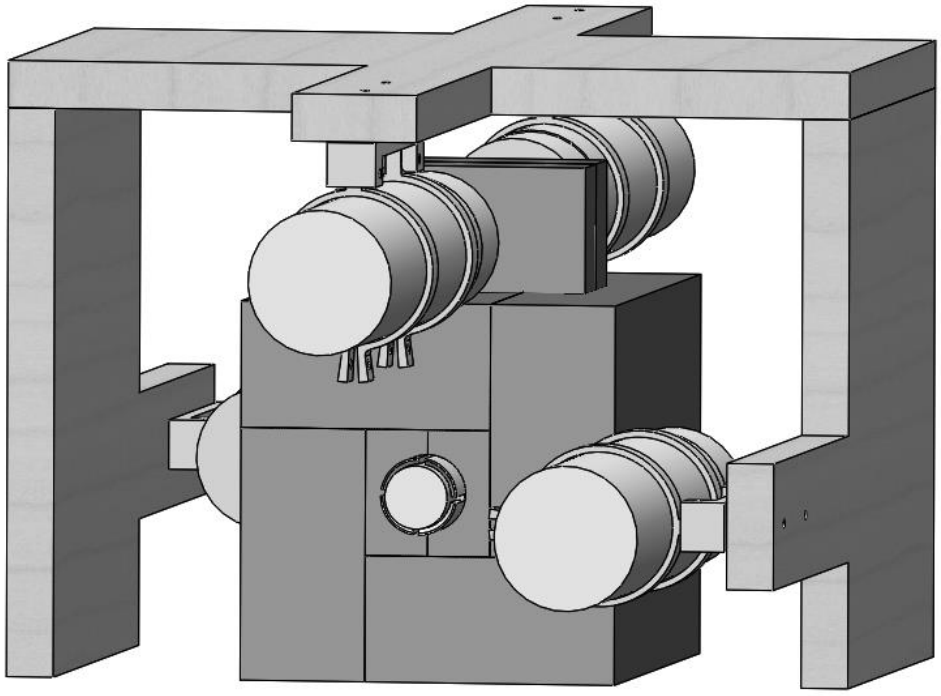


Figure 16: Front View of Polarimetry Setup

By counting coincidences between detectors on opposite ends of the setup, you can determine by how much the polarized gamma rays will preferentially scatter at 90 degrees to each other. If a top and a left detector both detect a gamma ray at the same time, this indicates that one gamma ray scattered upwards and the other scattered left (a 90 degree difference). If on the other hand a top detector and the other top detector both detect a gamma ray at the same time, this indicates that both gamma rays scattered upwards (a 0 degree difference). Likewise, if a left detector and the other left detector detect a gamma ray at the same time, this indicates that the gamma rays scattered in opposite directions (a 180 degree difference). So, by comparing how many of each type of coincidence you detect, you can figure out by how much pairs of polarized gamma rays prefer each scattering angle.

Setup

Set up one end of the polarimetry device with detector A in the side position and detector B in the top position. Set up the other end with detector C in the side position and detector D in the top position. Put two small lead blocks in between the two top detectors to block scattering between them. Place the polarimetry aluminum holders into the lead collimator and place the short (one inch long) aluminum scatterers into the holders so that they are as close to flush with the face of the lead collimator as possible. A part of the end of each detector should hit the top of a side wall of the lead collimator. Make sure that every detector is equidistant to the aluminum scatterer on its side of the lead collimator. When you've done this, the setup should look like Figure 15 and Figure 16 above.

To take data for this experiment, you can use the multiple trigger settings to simultaneously take data for each relevant pair of detectors (A-C, A-D, B-C, and B-D). To do this, enable all four trigger conditions and set each of them to one of the above pairs of detectors. This will ensure that the oscilloscope will trigger if any of those pairs of channels receive a channel simultaneously, but not if just one detector receives a signal or if the two irrelevant pairs (A-B and C-D) receive signals. NOTE: You will have to run this acquisition of data for at least two hours in order to acquire an appropriate resolution of results, so plan accordingly.

You can then analyze the data in the Counting panel. This allows you to set energy and timing ranges for each of the pairs of detectors given above. The timing range should be determined by looking at a timing plot and focusing on the timing peak. Refer to the Modern Lab Positron Spectroscopy Speed of Light manual or ask your instructor for reminders on the specifics of how to work with the Timing Plots panel.

What energy range do you expect to contain the signal for the scattered 511 keV gammas (accounting for the fact that the detectors have some uncertainty in the energies they report)? You can look at energy plots to guide you in this decision.

What energy ranges do you expect to contain noise? Make sure to think carefully about this, as the quality of your data will depend strongly on your choice of an energy range. Make sure to record multiple energy ranges for future reference in order to ensure appropriate records during data analysis.

If we denote the number of counts at 90 degrees as $N_{\pi/2}$ and the number of counts at 0 or 180 degrees as N_0, then we expect the proportional difference in counts, $\frac{N_{\pi/2}}{N_0}$ to be equal to:

$$1 + \frac{2\sin^4\theta}{\gamma^2 - 2\gamma\sin^2\theta}$$

Where θ is the scattering angle described in the Compton scattering section, and:

$$\gamma = 2 - \cos\theta + \frac{1}{2 - \cos\theta}$$

The derivation of this is complex and beyond the scope of this lab.

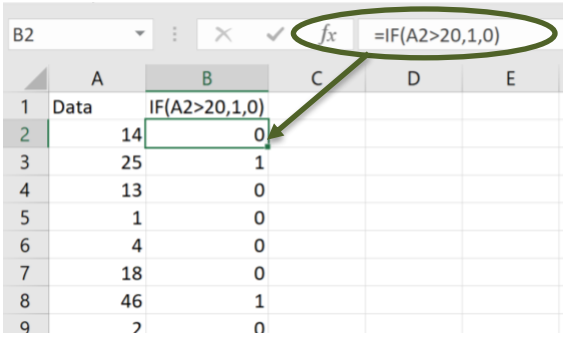
Detectors pick up signal along the metal "cap" on the bottom, which is not of infinitesimal size. This means that it is possible for the detector to pick up signals that are not from electrons scattered at exactly 90 degrees. With this in mind, compare your experimental calculation of $\frac{N_{\pi/2}}{N_0}$, which would be the proportional difference to be for ideal detectors with zero (infinitesimal) size, to the expected $\frac{N_{\pi/2}}{N_0}$ as given by the equations above. Is the predicted value a good estimate for these particular detectors?

Appendix

Here are some helpful excel functions that you may not have used before.

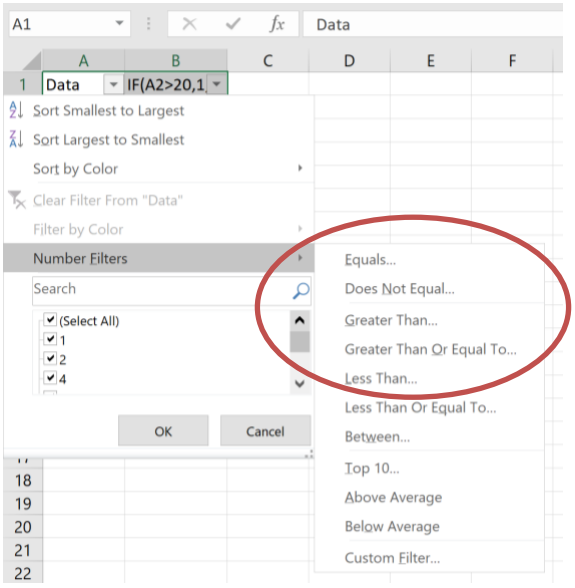
IF Conditional Statements

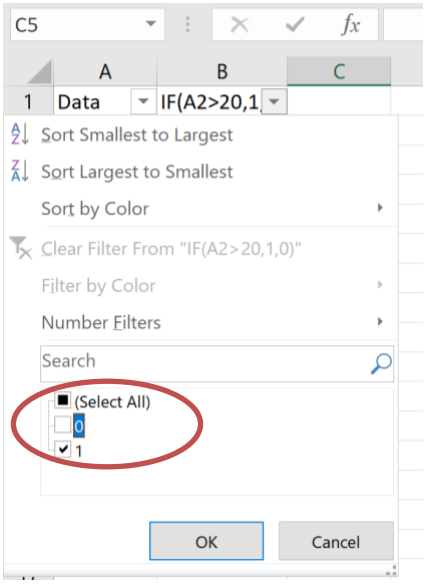
In equation mode, you can create “if” statements that will output a value for a true argument and another value for a false argument. This is useful for complex data with multiple simultaneous measurements. Like for all evaluations in Excel, click and drag down from the bottom right corner of a selected cell to apply the condition to the rest of the column. To apply the entered condition to a large data set, double click on the bottom right corner of a selected cell.



Filtering Function

Select the data you want to filter and under the Data tab, click the Filter button. Arrows will appear in each column. For the example data, we can sort using parameters in the left column or the right column.





Here are some suggestions for further investigation if time allows.

Positron Lifetimes in Materials: Convolution and Fitting

The timing resolution of our detector is comparable to some of the times we are trying to measure. Therefore, we need to know how the resolution of the detector modifies our lifetime measurements.

Imagine that we were only measuring instantaneous events; our detector-analysis setup would instead give us a Gaussian distribution centered at t_0 with some standard deviation σ so that the probability distribution is:

$$f(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(t-t_0)^2}{2\sigma^2}}$$

But when we're dealing with lifetime data, the data comes from an exponential distribution with lifetime parameter τ:

$$g(t) = \begin{cases} 0, & t < 0 \\ \frac{1}{\tau} e^{-\frac{t}{\tau}}, & t \geq 0 \end{cases}$$

We'll refer to this exponential probability distribution function as $g(t)$.

So if we see a signal at some time t we know that the probability that it came from between time t_0 and time $t_0 + dt_0$ is just:

$$\frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(t-t_0)^2}{2\sigma^2}} \cdot g(t_0) \cdot dt_0$$

So we can find our new probability distribution by integrating this:

$$h(t) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(t-t_0)^2}{2\sigma^2}} \cdot g(t_0) \cdot dt_0$$

This comes out to be:

$$h(t) = \frac{1}{2\tau} e^{\frac{1}{2\tau}\left(\frac{\sigma^2}{\tau} - 2t\right)} \cdot erfc\left(\frac{\frac{\sigma^2}{\tau} - t}{\sqrt{2}\sigma}\right)$$

Here, erfc is the complementary error function. It needs to be evaluated numerically. Most computation programs (such as Mathematica, Matlab, and Excel) have libraries of this function.

Note that the integral contains two terms and looks like:

$$\int_{-\infty}^{\infty} f(\tau) \cdot g(t-\tau) d\tau$$

This type of integral is known as a *convolution* which we denote as $(f * g)(t)$. This distribution, known as an exponentially modified Gaussian distribution, should help you fit short lifetime data better. However, you should note that there are likely multiple components that need to be fitted at the same time. For instance, when looking at positron lifetimes in silicone gel, some positrons will go into the silicone gel but others will go into the plastic surrounding the source. Other positrons form para-positronium with a lifetime of 125 ps or simply directly annihilate with an electron. Additionally, there will be some flat background noise. Each of these will add additional parameters to be fitted.

In addition to looking quantitatively at shorter lifetimes, try exploring other types of materials. See if you can come up with a model of what types of lifetimes to expect. If you are really enthusiastic, you can explore what happens to the lifetime of materials when you change their temperature. Polymers are particularly good for this type of investigation.

Ortho-Positronium Lifetime

The theoretical lifetime of Ortho-Positronium is 142 ns in a vacuum. Your results from looking at positronium in fumed silica are significantly lower than that. This is largely from positronium interacting with air molecules in the spaces between the silica. Try placing the fumed silica in a vacuum and see what lifetime you achieve.

To get more precise you can try one of the original techniques for measuring this lifetime. The technique consists of simply letting the positrons into a gas environment. Then vary the pressure of the gas and measure the positronium lifetime. Then extrapolate that to zero pressure to find the vacuum lifetime.