Introduction

There are many purposes underlying this experiment. First, we learn to do a fairly complicated nuclear physics experiment using several pieces of apparatus. They all have to be wired together in a complicated manner. Second, you want to determine the real decay rate of a radioactive sample. This means you have to correct for background radiation and several instrumental effects. Third, you investigate the angular dependence of gamma-gamma radiation, which is really another instrumental effect. Fourth, you want to investigate the physics of positron-electron annihilation. The major goal is to learn to use the fast electronics associated with nuclear instrumentation. The experiment is sufficiently complicated that you must understand what each piece of apparatus is doing. This will allow you to retrace your steps and to modify the procedures outlined in this write-up so you can do the experiment in a manner best suited to you.

Electron-positron annihilation

The two gamma rays (γ’s) that are emitted when a positron and an electron annihilate can be detected using temporal coincidence techniques. By successfully identifying the γ’s from the electron-positron annihilation, the angular correlation of their emission and the total activity of the source can be determined (despite the low efficiency of the detectors). A sodium-22 source, which decays by positron emission to neon-22 is used. Positrons interact strongly with matter. Each positron annihilates with an electron either in the plastic surrounding the source, in the source itself, or in the air in the vicinity of the plastic. The two steps are

\[
{^{22}_{11}}\text{Na} \rightarrow {^{22}_{10}}\text{Ne}^* + {^0_1}\text{e} + {^0_0}\nu_e \\
{^{22}_{10}}\text{Ne}^* \rightarrow {^{22}_{10}}\text{Ne} + \gamma \\
{^0_1}\text{e} + {^-1_0}\text{e} \rightarrow \gamma + \gamma
\]
where $^0_1\text{e} = \bar{e}$ is a positron and $^0_0\text{e} = e$ is an electron. The notation $\overset{A}{Z}\text{X}$ for the nuclei means that there are $Z$ protons and $N$ neutrons in the nucleus with the $A = N + Z$ being the number of nucleons. The asterisk means the nucleus is in an excited state. The name of a nucleus is uniquely defined by $Z$ so often $Z$ will be omitted. For leptons like electrons and positrons $Z$ is the charge and $A$ will always be zero. Using the complete notation will allow you to check the appropriate conservation laws in any Strong and Weak Interaction equation. The first and third interactions above are the Weak Interaction and the second is the Strong Interaction.

To conserve linear momentum in the third reaction above, the two $\gamma$’s each have to have the rest mass of an electron (or positron) in order to conserve energy. So, each $\gamma$ has an energy of 511 keV which is $m_e c^2$, the rest mass of the electron and the positron. In addition, the $\gamma$’s are emitted in opposite directions to conserve momentum. If the electron and positron are essentially at rest before they annihilate then the total momentum is zero. In this experiment you will single out these simultaneous 511 keV $\gamma$’s from all the other $\gamma$’s (like those coming from the second reaction, those from background, and those from secondary interactions inside the detectors. The experiment is technically a little complicated and requires many pieces of the equipment. Discuss questions, comments or reasonably phrased complaints with an instructor if and when problems arise.

**Using Radioactive Isotopes**

Read the sheet that outlines the precautions about working with radioisotopes. We are using one microcurie ($\mu$Ci) sodium-22 sources. This level of radioactivity is well below that which requires licensing or the wearing of film badges. The sources are encased in plastic and are stored in small heavy lead canisters. (Sources like this come through the regular mail.) When the time comes, ask an instructor to show you how to handle the sample if you have not done so before. 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 the Earth, from the stone used in the building, and from a variety of galactic and extra-galactic events. Later when you use your radioactive samples, measure them with the same Geiger counter at distances of one meter and one centimeter. There may be other experiments in the lab using radioactive samples. Measure the level of radioactivity in the surrounding area.

**Obtaining a Spectrum**

Figure 5 gives a schematic overview of the instrumentation involved in a simple $\gamma$ spectroscopy experiment. You will have two virtually identical setups like that discussed here. They are labeled One and Two on some of the equipment. Most of the connections are probably already made, but double check to make sure everything is connected correctly. It may help to refer back to Figure 6 later when you are in the midst of what may seem to be very complicated wiring. A $\gamma$ incident on the detector produces scintillation light in the NaI crystal, which in turn stimulates the liberation of photoelectrons in the PMT. The number of photoelectrons (i.e. the integrated photocurrent) is proportional to the energy of the original $\gamma$. The signal from the PMT goes to a Preamplifier (Ortec Model 113) and from there to a Delay Line Amplifier (DLA, the Ortec Model 460). The DLA amplifies and shapes the pulse. The output of the DLA is then input to the "Multi Channel Analyzer" (MCA) which measures the pulse height, digitizes it, counts the number of pulses with given pulse heights, and plots a histogram of the number of events versus pulse height, identified as channel number. The MCA for this experiment resides in the computer. An MCA card accepts the signals from the DLA and the program Genie 2000 displays the results for analysis.

Carefully examine, visually, the Bicron scintillation detector. (Again, your set-up has two complete detection systems.) These detectors are very fragile instruments and should be handled with extreme care. Each detector consists of a one-inch diameter crystal of NaI and a photomultiplier hermetically sealed in the chrome-plated metal case to exclude moisture and light. When a $\gamma$ is incident on the crystal, it ejects a number of photoelectrons. Note the two connectors on the back of the base socket attached to the photomultiplier/scintillation crystal unit. The connector marked HV is for the high
Electron-positron Annihilation

voltage cable (called an MHV cable). Check that the high voltage cable connects the high voltage power supply and the base connector of the detector. This voltage is divided among a series of dynodes in the photomultiplier, which cause multiplication of each photoelectron into a large pulse of electrons. (A dynode is just a photomultiplier tube and the physics is very similar to the tube used in the photoelectric effect experiment, except that many more electrons are produced.) This large pulse of electrons is collected at the anode and capacitatively coupled out through the base connector marked "S." (Capacitive coupling means that these electrons don't actually leave the device as a current. They just pile up on a capacitor to create a large voltage.) Check that the "S" output is connected to the input of the preamplifier (the Ortec Model 113). The preamplifier should be set to 100 pF (picofarad or $10^{-12}$ farad). The preamplifier integrates the electron pulse and provides an output pulse of its own where the output pulse height is proportional to the total integral of the input current pulse. The number of initial photoelectrons is proportional to the brightness of the flash of light in the scintillation crystal and, ideally, is proportional to the energy of the gamma ray. Thus, ideally, the output pulse height from the preamplifier will be proportional to the energy of the incident gamma ray.

Again, there are two preamplifiers labeled "preamp one" and "preamp two." The preamplifier power cords are connected to the power output connectors at the backs of the Delay Line Amplifiers in the NIM bin. It does not matter which Delay Line Amplifier powers which preamp. The "in-out" switch on the back of the Delay Line Amplifiers are set in the "in" position.

Many or all the connections you need to do this experiment may already be made. In this case, "connect" can be interpreted as "note the connection." The steps below are numbered just to help you keep track of where you are when you look away from these instructions. You may have to disconnect some leads here and there to connect others.

1. Connect the output of preamplifier One to channel one of oscilloscope One. (It may be the case that you are not familiar with the oscilloscope because of the order in which you are taking courses and the point in the semester you are doing this experiment.
That's fine. Just get some help.) Set the controls on the oscilloscope to:

- **Vertical**: 100 mV/Div (calibrated)
- **Time/div**: 50-200 µs/Div (calibrated)
- **Trig level**: AUTO and internal
- **Coupling**: AC

(2) Identify the CAEN 2-channel HV Supply in the NIM bin (the CAEN N1470AL). Hint, it’s the only one colored red (take a moment to appreciate the Italian style). Ensure that the voltages are both off – that is, verify that both toggle switches on the front panel are set to the OFF state (the middle position).

(3) Turn on the NIM bin which supplies power to all of the modular units plugged into it as well as units like the preamplifiers plugged into units in the NIM bin.

(4) Verify that the LCD display of the HV supply lights up. Verify that both HV channels are set to positive polarity. You should see a green LED with a “+” next to it for each channel. If you see the yellow LED with a “—” next to it, stop what you are doing and get your instructor before proceeding. The supply will need to be adjusted. Assuming that the HV polarity is correct for both channels, turn the plastic knob at the top (it’s illuminated by a blue light) until you see on the LCD display “ALL CH” and then the voltage readings for both channels. This will let you monitor the voltages as you ramp them up.

(5) Turn on Oscilloscope One and observe the usual horizontal line.

(6) Place a sodium-22 source up against detector One.

(7) Now power on the HV for the PMTs by flipping both toggle switches on the CAEN HV Supply up to the “HV EN/ON” position. You should see (on the LCD display) that the voltages ramp up slowly until they reach 700 V where they should stop. If this does
not happen, get your instructor.

Please take a moment to consider now how to turn off the high voltage power supply at the end of the day. You will simply return the two toggle switches to the “OFF” state and the supply will ramp down slowly. Do NOT turn off the NIM bin until the HV supply has fully ramped down.

(8) Observe the appearance of pulses in the oscilloscope trace and note how they grow in height with increasing HV voltage. Trigger the scope on the input channel so that a pattern of pulses shown in figure 1 appears. This means going from automatic trigger to normal trigger. In addition, the trigger should be set to "internal" and "channel one." You may have to play with the trigger level. On the oscilloscope, experiment with the horizontal and vertical scales, the intensity and the triggering. Before you proceed make sure you are able to interpret what you see. In particular, note that when the trigger that starts the sweep is set to a small voltage, you see many pulses. When you "increase" the trigger voltage, fewer and fewer pulses appear and eventually, it won’t trigger at all. What is going on here?

(9) Using a BNC "Tee" at channel one of oscilloscope One, connect the cable from the preamplifier output to another cable leading to the input of Delay Line Amplifier (DLA) One, on the right, as shown in figure 2. The DLA is used to shape the preamplifier pulses so that they can be easily sorted according to their pulse heights. This module has two outputs: unipolar and bipolar. The unipolar pulse is a µsec long pulse, which has a pulse height which corresponds to the input pulse height. In certain applications such a pulse, when fed into a dc-coupled device, will cause a temporary rise in the dc voltage level of the input. To avoid this, a bipolar pulse, which has a zero integral is also generated by the delay amplifier.
Set the Delay Line Amplifier as follows:

- Fine gain: 0.5
- Coarse gain: 10
- integ: 0.04
- pos/neg: neg

Connect the unipolar output of DLA One to channel two of oscilloscope One using a BNC TEE at the scope input. The other side of this TEE will be used later. Set the scope to 0.5 or 1.0 V/div, make sure it is on "calibrated," and trigger on this unipolar output (i.e., trigger the scope on channel two). Observe the very short unipolar pulses and their relative delay compared with the preamplifier pulses. You will need to select the "vertical mode" display of the scope to be on CH 2. The vertical mode setting is in a blue box on the front of the scope. Note that what you see on channel two is very sensitive to the
trigger level. (Why?) Since these pulses are very short, you will have to set the time/div on the oscilloscope to the 5 µsec/div scale to see the actual duration of the pulses. In the triggering section of the scope, note the "slope" button. You need to trigger on the leading edge (positive slope) of the square pulses when looking at channel two but you might want the long negative slope when looking at the long slowly decaying pulses on channel one. Get in the habit of adjusting the trigger level and pressing the slope button if needed in going back and forth between the two channels.

(11) Set up the scope on CH 2 so you clearly see the unipolar pulse (of which figure 3 is an ideal representation). Change the output cable on the DLA from unipolar to bipolar to look at the bipolar pulse (of which figure 4 is an ideal abstraction). Here, and at several steps in the setup, if there is another cable already connected to a connector you want to use, temporarily disconnect it. If you forget to put it back, that doesn't matter, that connection will be indicated at some later time in the setup. Change back to the unipolar output. Try to get a sense for the huge difference in time scales between what is happening in channel one (preamplifier output) as opposed to what is happening on CH 2 displaying the delay line amplifier output). A unipolar pulse is a signal which is shaped by an electric circuit to appear as shown in figure 3. Its height is proportional to the height of the pulse coming from the detector and its duration is fixed and short compared to the output pulse of the preamplifier. The bipolar pulse is shown in figure 4. The total area (considered positive above the line \( V = 0 \) and negative under it) is nearly zero for the bipolar pulse. This output is used with electronic circuits, which are sensitive to charge buildup. Why? (Hint: Think of the direction in which the current goes during the two portions of the signal, or equivalently, how the charge will move in the same time interval.)
To acquire a spectrum of the gamma emission from the Na-22 source you will be using a computer running Genie 2000 software to control an installed Canberra Multichannel Analyzer (MCA) card. Two BNC inputs into the card are visible at the back of the computer: "ADC IN" and "Gate." Two BNC cables are attached and labeled "MCA ADC" and "MCA Gate" respectively. Connect the "MCA ADC" cable to the other side of the TEE connected to channel two of the oscilloscope displaying the amplified unipolar pulse from the DLA. Again, if there is another cable already in the T on channel two, just disconnect it for the time being.

Your gamma spectrometer is now set up as shown in figure 5 and we can proceed to record a spectrum.

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 on the desktop of the computer. Click "File" and select "Open Datasource." Click the "Detector" button and select PAB-1001 in the source box.

The pulses sent to the MCA card are subdivided according to their voltage height into $N$ bins, where $N$ is determined by the "ADC gain" set with the software. Here ADC stands
for Analog to Digital Converter. Since the pulse height is an indication of the energy deposited in the detector, the so-called Pulse Height Analysis of the MCA results in a spectrum where energy is displayed along the horizontal axis and the frequency of occurrence of a pulse height is displayed along the vertical axis.

(14) Click on the "MCA" menu. Under "Adjust" set the "ADC LLD" to 1% to eliminate large numbers of counts in the low energy channels due to noise. Set the "Conv. Gain" to 2048. Close the "Adjust" window and click again on the "MCA" menu. Select "Acquire Set-up." Set the input size to 512 channels and the "Live Time" under "Time Preset" to 180 seconds. Close this window.
Electron-positron Annihilation

Detector

Preamp

Delay line amplifier

Unipolar Output

MCA

Preamp Output

DLA unipolar output

MCA display

# counts

counts

channel #

figure 5
(15) In the "Data Acquisition" window click "Clear" and then "start" just under "Acquire" to collect a spectrum. The MCA 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. The vertical axis is the number of counts in each channel and can be increased by simply acquiring data for a longer time interval. A gating signal may also be connected to the MCA card to filter those pulse heights that correspond to γ's with a particular energy. We will use this feature later.

(16) Observe the sodium-22 spectrum. Identify the relatively small photopeak (~ channel 350) from the high-energy gamma line, and the large electron-positron annihilation photopeak (~ channel 130). Compare the spectrum with the expected features by examining the decay scheme of the sodium-22 source provided at the back of the write-up. Carefully sketch the spectrum in your lab book, labeling the features according to energy.

(17) You can save your data in a text format for further analysis using KaleidaGraph or Excel. Select the "Analyze" menu and then click on "E Reporting." Select "datalist.tpl" for the "template name," "channels and counts" for the "section name," "1.000000" for the "Error Multiplier," and choose output to "screen." Then "Execute." This will generate a tab-delimited output of your data to the "Report" window below the "Data Acquisition" window and in a file which you can find as outlined below. Open KaleidaGraph and then "open" under "file." (KaleidaGraph on the HP Vectra pc is funky. Sometimes you have to try things twice.) This will bring up the "Open" dialog box. For "Files of type" at the bottom, choose "All Files" (not "Any File"). Then "Look in" the folders "Desktop," "Shortcut to Genie2k," and "Repfiles." In the folder "Repfiles" you will find a the file <Pab-1001.rpt>. Open it. This will bring up a "Text File Input Format Box." Under "delimiter" select "special" and this brings up a "Title Format" entry space which you can ignore and a "Data Format" entry space where you should specify the format as "w v w v." (Use just the four letters with spaces. No quotes and no period.) Under "Options" make sure "Read Titles" is not 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 <Pab-1001.rpt> and overwrite whatever is there.

Repeat the above Exercise for System Two

(18) Put a second source directly in front of detector Two and repeat whatever parts of the preceding exercise needed to achieve the same result for System Two. That is, you want to see the same spectrum. You don’t have to redo everything, just whatever is necessary to achieve the same result with system Two as you have with system One. Leave oscilloscope One for system One. Use oscilloscope Two for system Two. You now have two complete gamma spectroscopy apparatus.

When finished, disconnect the ‘MCA ADC’ cable from the TEE connected to channel two of the oscilloscope displaying the amplified unipolar pulse from the DLA. With a source in front of each detector you ought to be able to see pulses on both oscilloscopes One and Two.

(19) This is a good point to reconnoiter. Make sure your notebook is up to date and that you can give an instructor a mini-lecture on the physics and the instrumentation to this point.

Selecting the Electron-positron Peak

(20) The next piece of electronics to put in the system is a Timing Single Channel Analyzer (TSCA). The TSCAs filter pulses having a particular range of voltage heights using a window that is established with the upper and lower pulse height settings. For now set the upper level near its maximum value (10) and the lower level near its smallest value (0) on each TSCA. (Both settings should be a little bit from the endpoints because older TSCAs will sometimes behave oddly if these potentiometer are set at their limits.) The other important feature of a TSCA is that the time delay of the logic pulse it outputs
relative to its input pulse is variable. The time delay is varied by adjusting the delay setting on the TSCA. For now set the delay on each to about 5.0 which is near the middle of its range. Also, check that the appropriate switch on both TSCAs is in the 1-11 µs position and not the 0.1-1.1 µs position.

(21) Connect the bipolar output of each DLA to the DC INPUT of a TSCA. (There is a TSCA One and a TSCA Two.)

(22) Attach the POS OUT of TSCA One to channel 1 of a third scope (scope Three) via a BNC TEE at the oscilloscope. Attach the POS OUT of TSCA Two to channel 1 of a fourth scope (scope Four) via a BNC TEE. The other side of the TEE's at the scopes will be used later.

(23) Set the vertical mode to channel one. (There may already be a different signal on channel two but ignore that for now.) Trigger the scopes on the leading edge of the TSCA output pulses. It is assumed that by now you are an expert at triggering these scopes. You may have to make several adjustments. These pulses are constant voltage pulses (about 5 V) regardless of the height of the input pulses from the DLA. That is, they are simply counting pulses. The energy of the original $\gamma$ plays no role here. Make sure both systems are working.

(24) Make sure scopes One and Two are set to channel 2 and that scopes 3 and 4 are set to channel 1. Make sure you can see pulses on all four scopes. One of your two sources might be much older, and therefore weaker, than the other and one detector might be more efficient than the other so the two signals might have the same rate (which affects the brightness of the waveforms on the scope).

If you have lost sight of the forest for the trees, here is a physics refresher. So far, we are counting essentially all the pulses coming to each detector from each sample in front of it. The large 511 keV peak in the spectrum comes from the $\gamma$'s that have resulted from electron-positron annihilation. This annihilation event produces two $\gamma$'s going in opposite
directions. When we later put one sample in the middle, one $\gamma$ will go to one detector and the other $\gamma$ will go to the other detector. We want to count these, so we are going to get rid of all parts of the spectrum not corresponding to the 511 keV peak. And then, we must make sure that we only count pairs of $\gamma$'s that come to each detector at the same time. This way we ensure, with a high probability, that these two $\gamma$'s came from the same annihilation event. The experimental problem is to decide what we mean by "at the same time" since we can only count over a finite time interval. So that's the forest. We've "done" half the trees.

(25) We will want to adjust the time delay between the unipolar pulses from the DLA (on scopes 1 and 2) and the ~5V logic pulses from the TSCA (on scopes 3 and 4). To do this we delay the unipolar pulses from the DLA's with Delay Amplifiers (Ortec Model 427A). Set all five switches on the Delay Amplifiers (DA's) to the left (delay out). Connect the unipolar output of the DLA (using the TEE's on channel two of scopes One and Two) to the inputs of Delay Amplifiers (DA) One and Two.

(26) Connect the output of the DA's to channel 2 of Scopes Three and Four using BNC TEE's. The other side of the TEE's will be used later.

(27) Trigger the scope on the delayed unipolar pulses, channel 2, and view both channels by setting the appropriate vertical mode switch to "both." On the scopes, you should see a vertical range of pulses from the DLA's (via the DAs) on channel 2 and, a few microseconds later, the square ~ 5V pulses from the TSCAs on channel 1. The vertical mode section on the scopes should be set to "alt" (for alternate between channels), not to "add" or "chop" (meaning do a little bit of one then a little bit of the other). (Indeed, experiment with these three settings to see the difference.)

(28) Now, using first the delay switches on the DAs and, second, the delay knob on the TSCAs, adjust the delay between the two sets of pulses until they are superimposed. You may very well end up with all five switches on the TSCA to the right. You may find it
helpful to switch the triggering of the scopes (Three and Four) back and forth between 
channels 1 and 2.

(29) Switch the trigger on scopes Three and Four to channel 1 and readjust the trigger 
level. Now you are triggering on the logic output of the TSCA and so a trace is displayed 
only if the input unipolar pulse heights fall within the window of the TSCA. Adjust the 
delays on the TSCA’s (the third knob down) and note the effect.

(30) Do the following one system at a time. Starting with the "upper level" knob near 10 
and the "lower level" knob near 0, raise the setting for the lower level knob. Note that 
small pulses disappear from the unipolar trace in channel 2 (of scopes Three or Four). 
Why? Turn the lower level dial back to near 0 and now lower the upper level dial. Note 
that the large pulses disappear. Why? Turn the upper-level discriminator back to near 
10. All unipolar pulses should again appear.

(31) Now, adjust the TSCA window settings to select only the 0.511 MeV gamma-rays 
from electron-positron annihilation. If you are not sure which pulse heights correspond 
to 0.511 MeV gamma-rays, guess! Once you have a narrow energy range of peaks (i.e., a 
narrow range of heights) go back and forth from channel 1 triggering to channel 2 
triggering and make sure you understand what you see on the scope for both trigger 
settings.

(32) This is another good point to reconnoiter. Make sure your notebook is up to date 
and that you can give your instructor a mini-lecture of the physics and the 
instrumentation to this point. You can use the scopes and figure 6 in your mini-lecture.

(33) Make sure you can still obtain a spectrum. If you still have your spectrum 
showing, delete it. Using the TEE on the channel 2 input of scope Three, connect the 
output of DA One to the ADC BNC cable from the MCA. Acquire a spectrum.
We are going to use the MCA GATE to just acquire the 511 keV peak but GATE will blank out the part we want to acquire rather than blanking out everything else. So, first, from your newly acquired spectrum, note that channel numbers that correspond to the 511 keV peak. You want to go a little bit "up the slope" on both sides but your final width should not be less than 30 channels.

Using the TEE on the channel 1 input of scope Three, connect the POS OUT of TSCA One to the MCA GATE cable from the MCA. Acquire a spectrum on the MCA. In this configuration the gate should eliminate the 0.511 MeV peak from the spectrum.

Your set-up should look like Figure 6.
You can now further adjust the upper and lower window settings on TSCA One to pick out the 0.511 MeV peak more precisely. Try to have the edges of the peak visible in the scan, but don’t pinch the peak more than necessary. That is, the width should not be less than 30 channels. When you have completed this fine-tuning, record the upper and lower window settings on the TSCA One.

Repeat this procedure for System Two using scope Four.

At this point it is worth noting a few helpful hints. (A) When you turn everything on a day or so later you must wait about ten minutes for everything to warm up. (B) Don’t change cables once you have set up the various timing sequences. Why? (C) You must check the above procedure at the start of each day. Strange folk come in the night and change things.

**Coincidence Measurement: the Set Up**

Check that the two detectors on the angular correlation apparatus are 180° apart.

Before we can measure coincidence rates, we need to be sure that pulses originating simultaneously arrive simultaneously. For example, if the cables in one preamp’s circuit are one foot longer than the other’s, then the pulses produced at the same time by both detectors would arrive about 1.5 ns apart at the DLA (Q: why not 1 ns?). In order to adjust our two circuits so that each requires the same time interval to process signals, we will use a pulser (Ortec Model 480) to send identical signals simultaneously to both preamplifiers. If the detectors are equidistant from the source, and if the detector to preamp and preamp to electronics cables are of equal length for both preamps, then the signals reach the amplifiers just as if the detectors simultaneously detected γ’s.

Remove the sodium-22 sources from the vicinity of the detectors. Connect the pulser output to the TEST PULSE connector on one of the two preamps using a TEE at the preamp then using this TEE connect the two preamps together. (The TEE and the preamp-to-preamp connector may be in place.) On the pulser, set the pulse height to near
maximum (~8 on the dial) and all the switches to X1. Turn on the pulser, set its output to NEG, and open the TSCA discriminator levels fully (after making sure you have written down the original settings). Trigger scopes Three and Four on the DLA unipolar pulses in channel two. Using the appropriate TSCA, increase the lower-level discriminator to just below the pulser energy. Make sure the pulser signal gets through. You are doing this to eliminate pulses due to low energy noise.

Now we will adjust for the electronic delays inside the NIM modules to get the two TSCA pulses coincident. First look at the pulses on the scopes and see how the delay settings on the TSCA's affect the arrival time of the pulses (trigger on Channel 2).

Connect the positive outputs of the TSCA's to the A and B inputs of the Universal Coincidence unit (Ortec Model 418A) using the TEES at channel one of scopes Three and Four. You may have to disconnect the MCA gate cable. When the A pulse and the B pulse arrive within a resolving time, t, of one another the Universal Coincidence unit will produce a logic output pulse. The 871 Timer and Counter will be used to count the output pulses from the coincidence unit.

Connect the coincidence unit's output to the positive input on the 871. Most of the controls are self-explanatory. Set it to count for ten seconds which is \(M \times 10^N\) with the time base select on 0.1 second, \(M = 1\) and \(N = 2\). Turn the "DWELL" knob counterclockwise to "OFF" and use the top "SELECT" button to choose "COUNTER" (not TIMER).

On the coincidence unit set input A to COINC and the others to off. (These are pull, then set switches.) Set the Coincidence Requirements to 1. Check the counting rate by pressing STOP, RESET, COUNT on the 871. Repeat for B on COINC and the A (and the others) off. These numbers will be similar but different. Such is the effect of the two sets of electronics being different even though both preamps have the same pulser signal. Turn the pulser off then on again to make sure it is the pulser signal that you are observing on the counter. Now set Coincidence Requirements to 2, turn both A and B to
COINC. Choose one TSCA delay as the fixed delay. It should be near 5.0 Set the other TSCA delay (the variable delay) to this same value. Measure the coincidence rate. If it is zero, try lower and then higher values on the variable TSCA delay until you obtain a coincidence count. Measure the coincidence rate as a function of the variable TSCA delay. Plot this number of coincident pairs (in 10 s) of pulses vs. the delay. It should look something like the figure below. The TSCA delay is accurately calibrated. One full turn is one microsecond.

Hint: rather than searching blindly, you can look at the TSCA positive output for Channels 1 and 2 by using Scope 5, and then adjust the TSCA delay until the signals overlap on the scope. Then you can adjust the delay to map out the coincidence-vs-delay graph.

The width of the peak is twice the resolving time of the detection system. Set the delay you are varying for a maximum coincidence rate for pairs of pulses and lock them. If this is significantly far from its original setting then note this. Turn off the pulser.

Measure the rate of A only, then B only, then the coincidence rate with the pulser off and the source far from the detectors. Do this a few times and note the effect of the background. (Do you expect many coincidences? If there are any, where might they come from?)

Now insert the sodium-22 source half way between the detectors. Reset the window
settings on both TSCA’s for passing only the 511 keV pulses. Set the delay values on the TSCAs for a coincidence measurement. Observe the counts from one detector, then the other, then the coincidences. Make at least five measurements of each. Compute the averages and compare the differences between the individual entries for each average with the square roots of the averages. Random events are described by Poisson statistics and this predicts that each measurement will vary roughly by an amount equal to the square root of the measurement. This is a good point to ask an instructor if your observed numbers are reasonable.

This concludes the complicated setting up of the apparatus. There are two experiments that can be done now: measuring the real activity of the source and the angular distribution of the coincident gamma rays.

*Measuring the Real Activity of the Source*

When we measure a coincidence rate, there are two contributions. First, there are the real coincidences. These are produced at "exactly" the same time. (What fundamental physics determines the time duration that defines "exactly" here?) Because we allow two gammas that arrive at the two detectors within a time $2\tau$ to be called "coincident," there is a chance of counting coincidences that are not real. They may have been produced in two completely independent annihilation events up to a time $2\tau$ (or even longer! [how is that?]) apart. These chance coincidences are a second contribution to the measured rate. On top of this, we have the additional complication that the detectors are far from 100% efficient.

Let $R$ be the real production rate or "activity." Each disintegration produces two gammas 180 degrees apart. Independently, detectors One and Two measure count rates (counts per unit time) $R_1 = e_1 f R$ and $R_2 = e_2 f R$, where $e_1$ and $e_2$, both less than unity, are the efficiencies of the detectors and $f$ is the fraction of gammas being emitted by the source that go into the detector. If the detector radius is $r$ then it's area is $\pi r^2$. If the detector is a distance $L$ from the source then the area of a sphere at $L$ is $4\pi L^2$ and a fraction $f = \pi r^2 / (4\pi L^2) = (1/4)(r/L)^2$ of the gammas are heading into the detector. This is a purely
geometric parameter and it can be computed. We have assumed here that the sample is exactly half way between the detectors (which are 2L apart) and that the decays are isotropic. Also we’ve assumed that the detector area is much smaller than $4\pi L^2$ so that the solid angle subtended by the detector is approximately $\pi r^2 / 4\pi L^2$. If we measure for a time $T$, the numbers of counts $R_1T$ and $R_2T$ can both be measured.

Consider first the true coincidences. Of the $R_2 = e_2 f R$ counts (per unit time) observed by detector Two, detector One will get a fraction $e_1$ of these. So, if only true coincidences were observed, the observed count rate would be $e_1 e_2 f R$ and in the time $T$, $e_1 e_2 f R T$ counts would be observed. Second, the chance coincidences are uncorrelated so in a time $2\tau$, detector One will get $2\tau R_1$ counts and detector Two will get $2\tau R_2$ counts. If you think of these as probabilities (they would have to be normalized in some fashion), $2\tau R_1$ is the probability of getting a count in detector One in the time $2\tau$ and $2\tau R_2$ is the probability of getting a count in detector Two in the time $2\tau$. The probability of getting a count in detector One and a count in detector Two is then the joint probability which is $2\tau R_1 2\tau R_2$. (The probability of throwing a die and getting a one is $1/6$. The probability of two people each throwing a die and both getting a one is $(1/6)(1/6) = 1/36$.) The counting rate for these chance coincidences, then, is this joint probability or number of counts divided by the time interval $2\tau$. So, the chance count rate is $2\tau R_1 R_2$.

The actual observed count rate $C$ is the sum of these two contributions:

$$ C = e_1 e_2 f R + R_1 R_2(2\tau) $$

Dividing the measured coincidence rate by the predicted random rate, we get,

$$ C/[R_1 R_2(2\tau)] = e_1 e_2 f R / [R_1 R_2(2\tau)] + 1 $$

$$ = 1/(2\tau f R) + 1. $$
where we have used $R_1 = e_1 fR$ and $R_2 = e_2 fR$. From measurements of $\tau$, $R_1$, $R_2$ and $C$, and the calculated value of the geometric parameter $f$, you can predict the total rate of gammas entering the detector $fR$ and the total source strength or activity, $R$. You should find that $1/(2\tau R) >> 1$. From $f$ and $R$ you can predict the detector efficiencies $e_1$ and $e_2$. Convert $R$ to microCuries ($\mu$Ci) given that $1 \mu$Ci = $3.7 \times 10^4$ disintegrations s$^{-1}$. Compare your measured rate with the rate you would expect based on the original strength of the source and its age.

The Angular Distribution of Coincidence Counts

Once you are able to observe the electron-positron gamma-gamma coincidences, you can measure the coincidence rate as a function of the angle between the two detectors. How sharply peaked is this distribution? In degrees, what is the half-width at half-height. Surely the correlated gammas are coming out of the source exactly and only 180 degrees apart. Why? What then is giving this finite width? What would be the effect if you could repeat this experiment with the two detectors a kilometer apart rather than the current distance of 20 cm or so?

expt12_epluseminus_2013.docx