

### Equipment Required

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| <ul style="list-style-type: none"> <li>• Two <b>905-21</b> Fast Plastic Scintillators.</li> <li>• Two <b>265A</b> PMT Base.</li> <li>• Two <b>556</b> High-Voltage Power Supplies.</li> <li>• Two <b>583B</b> Constant-Fraction Differential Discriminator/SCAs.</li> <li>• One <b>DB463</b> Delay Box.</li> <li>• One <b>414A</b> Fast Coincidence.</li> <li>• One <b>480</b> Pulser.</li> <li>• One <b>567</b> Time-to-Amplitude Converter/SCA.</li> <li>• One <b>4001A/4002D</b> NIM Bin and Power Supply.</li> <li>• <b>EASY-MCA-8K</b> System including a USB cable, a suitable PC and MAESTRO software.</li> <li>• Two <b>C-25-15INCH-S</b> Special RG-58A/U 50-Ω coaxial cables with BNC plugs, 38-cm (15-inch) length (for the constant-fraction shaping delays on the 583B timing discriminators).</li> <li>• Three <b>C-25-1</b> RG-58A/U 50-Ω coaxial cables with BNC plugs, 30-cm (1-ft) length.</li> <li>• Six <b>C-25-2</b> RG-58A/U 50-Ω coaxial cables with BNC plugs, 0.61-m (2-ft) length.</li> </ul> | <ul style="list-style-type: none"> <li>• One <b>C-25-4</b> RG-58A/U 50-Ω coaxial cable with BNC plugs, 1.2-m (4-ft) length.</li> <li>• Two <b>C-25-12</b> RG-58A/U 50-Ω coaxial cables with BNC plugs, 3.7-m (12-ft) length.</li> <li>• Three <b>C-24-2</b> RG-62A/U 93-Ω coaxial cables with BNC plugs, 0.61-m (2-ft) length.</li> <li>• Two <b>C-24-4</b> RG-62A/U 93-Ω coaxial cables with BNC plugs, 1.2-m (4-ft) length.</li> <li>• Two <b>C-36-12</b> RG-59A/U 75-Ω coaxial cables with SHV Female Plugs, 3.7-m (12-ft) length.</li> <li>• One <b>MT050</b> 50-Ω Matched Tee Signal Splitter.</li> <li>• Two <b>C-28</b> Terminators, 50-Ω (male BNC plug).</li> <li>• Three <b>SA04544M</b> Ring Stand with Triangular Support.</li> <li>• Three <b>SB10760M</b> Right-Angle Clamp Holder.</li> <li>• Three <b>SB28602M</b> Extension Clamp (3-fingered).</li> <li>• <b>GF-022D-50*</b> <sup>22</sup>Na radioactive source, 50-μCi activity.</li> <li>• <b>TDS3032C</b> 300 MHz, 2-Channel Digital Oscilloscope.</li> <li>• Small, flat-blade screwdriver for tuning screwdriver-adjustable controls, or an equivalent potentiometer adjustment tool.</li> </ul> |
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\*Sources are available direct from supplier. See the ORTEC website at [www.ortec-online.com/Service-Support/Library/Experiments-Radioactive-Source-Suppliers.aspx](http://www.ortec-online.com/Service-Support/Library/Experiments-Radioactive-Source-Suppliers.aspx)

### Purpose

State-of-the-art, fast-timing techniques will be used to measure the flight time of a gamma-ray over a known distance. This will enable the calculation of the velocity of the gamma-ray, which will be compared to the accepted value for the speed of light.

## Gamma-Ray Time-of-Flight and the Speed of Light

### Introduction

The system illustrated in Figure 25.1 has been selected because it delivers excellent time resolution, while accommodating the high counting rates needed for coincidence experiments. See references 1, 6, 7, 8, 9 and 10 for more information.

The gamma-rays from the radioactive source are detected in BC418 plastic scintillators. The BC418 scintillator responds to each detected gamma-ray photon with a flash of light having a rise time of 0.5 ns and a 1.4-ns decay time. The photomultiplier converts the light flash into an amplified signal of electrons to produce an analog, electronic pulse at the anode output on the PMT

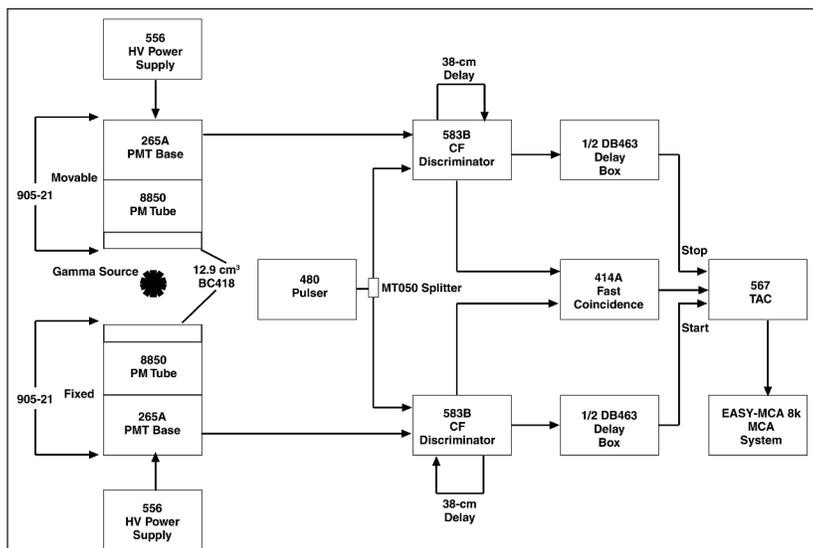


Fig. 25.1 Electronics Block Diagram for the Gamma-Ray Time-of-Flight Measurement.

\*The charged-particle time-of-flight measurement in the original experiment has been omitted because of unavailable apparatus.

## Experiment 25

# Gamma-Ray Time-of-Flight Spectroscopy

base. The pulse rise time is about 2 ns and the width is approximately 8 ns. The amplitude of this negative pulse is proportional to the energy deposited in the scintillator by the gamma ray.

The 583B Constant-Fraction Differential Discriminators are responsible for marking the exact arrival time of the pulses from the Scintillator/PMT assembly. By generating a timing logic pulse when the analog anode pulse reaches 20% of its maximum amplitude, the 583B ensures that all pulses are timed from the same phase point, independent of the pulse amplitude. In addition to the timing function, the 583B has upper- and lower-level discriminators that are used to select the range of pulse heights (energies) that will be accepted to generate the timing logic pulses. These constant-fraction and discriminator features enable narrow peaks to be accumulated in the time spectrum, with symmetric, Gaussian profiles.

The timing logic pulses from the 583B timing discriminators are passed through a DB463 Delay Box with selectable coaxial cable delays to compensate for the transmission delay of the 414A Fast Coincidence. The Delay Box also serves to retard the Stop signal so that it arrives a convenient time after the Start pulse at the inputs to the 567 Time-to-Amplitude Converter. The Time-to-Amplitude Converter (TAC) transforms the difference in arrival times between the Start and Stop pulses into an analog pulse height. Subsequently, the EASY-MCA 8k digitizes the analog pulse amplitude, and stores the event as one count in the channel corresponding to the pulse height. As multiple Start-Stop pairs are processed during a data acquisition period, the EASY-MCA builds up a histogram that represents the number of pairs versus their difference in arrival times. The result is a time spectrum.

In this experiment the annihilation radiation from a  $^{22}\text{Na}$  source will be used. When the positron from the decaying  $^{22}\text{Na}$  nucleus encounters a free electron, the positron and electron annihilate each other, and convert their mass into two 511-keV gamma rays emitted in opposite directions. Because the two gamma-rays are emitted at the same time, the time spectrum will display a narrow peak. The position of the peak in the spectrum will be determined by relative transmission delays through the two electronic paths, and the differences in the distances from the source to each detector. By moving one of the detectors a known distance, the shift in the peak position will enable calculating the velocity of the gamma-ray photon.

In symmetric coincidence experiments, the TAC can be flooded with a lot of Start pulses for which there are no corresponding Stop events. This causes a lot of useless dead time in the TAC. The addition of the 414A Fast Coincidence overcomes this situation by opening the Start Gate on the TAC only when it detects a pair of Start and Stop events within 110 ns of each other.

After the initial installation and connection of all the modules, the time scale of the TAC and MCA combination will be calibrated using the 480 Pulser and the selectable delays on the DB463 Delay Box. Next, the pairs of 511-keV gamma rays from  $^{22}\text{Na}$  will be utilized. The detector driving the START input of the TAC will be left in a fixed position, with the  $^{22}\text{Na}$  source located a constant distance in front of this Start detector. The detector that drives the STOP input on the TAC will be moved different distances from the source to cause a peak shift in the time spectrum. The change in distance divided by the time shift will yield the velocity of the gamma-ray, and this should match the known speed of light ( $2.9979 \times 10^8$  m/s).

Before proceeding with Experiment 25, the information in Experiment 13 should be reviewed. In particular, the decay scheme for  $^{22}\text{Na}$  in Figure 13.1, and the angular correlation between the two 511 keV annihilation gamma rays in Figure 13.5 should be examined. Keep in mind how tightly the directions of the two gamma rays are aligned at  $180^\circ$  to each other. This dictates that the source and two detectors must be located along a common center line.

As illustrated in Figure 13.1 of Experiment 13,  $^{22}\text{Na}$  decays 0.05% of the time by positron ( $\beta^+$ ) emission to the ground state of  $^{22}\text{Ne}$ . Approximately 90% of the time  $^{22}\text{Na}$  decays to the 1.274-MeV excited state of  $^{22}\text{Ne}$  by positron emission. The lifetime of the 1.274-MeV state is 3 ps. Consequently, there is a prompt decay to the ground state via the emission of a 1.274-MeV gamma ray. For analysis of materials by positron lifetime spectrometry, the 1.274-MeV gamma ray is detected to signal the creation of the positron. In many materials, the positron wanders around for a few nanoseconds losing energy before it encounters a free electron and annihilates. Thus, the pair of 511-keV annihilation gamma rays can be delayed by a few nanoseconds relative to the emission of the 1.274-MeV gamma ray.

## Experiment 25

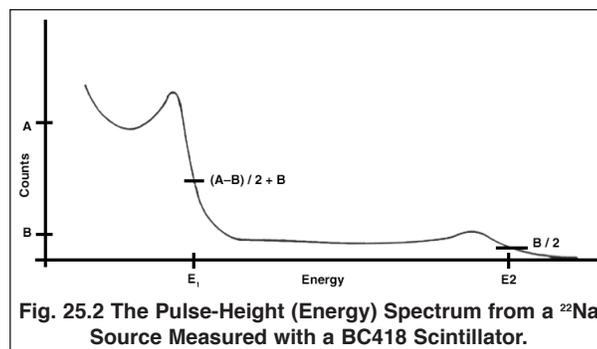
# Gamma-Ray Time-of-Flight Spectroscopy

In this experiment, only the two 511-keV annihilation gamma rays will be employed, because they are in prompt coincidence. Compared to a source with an essentially isotropic angular correlation, such as  $^{60}\text{Co}$  (Experiment 19), the fact that the annihilation gamma rays are emitted at  $180^\circ$  to each other improves the efficiency of detecting a coincidence in scintillators arranged on opposite sides of the source.

For our purposes, the 1.274-MeV gamma ray from  $^{22}\text{Na}$  will be ignored, although it adds a minor complication to the measurement. Figure 25.2 shows the typical pulse-height (energy) spectrum delivered by a BC418 scintillator on a photomultiplier tube. Because BC418 is composed entirely of hydrocarbon compounds, gamma-ray

detection in the scintillator is dominated by the Compton scattering interaction. The photopeak is absent, because the cross section for the photoelectric interaction is proportional to  $Z^5$ , and the average atomic number is low, i.e., about half way between  $Z = 1$  and  $Z = 12$ . High-atomic-number scintillators, such as  $\text{NaI}(\text{Tl})$ , generate photopeaks with excellent energy resolution, but lack the sub-nanosecond timing properties offered by fast plastic scintillators.

The 1.274-MeV gamma ray causes a rather flat Compton distribution in the energy spectrum, with a Compton edge at 1.06 MeV, ( $E_2$  in Fig. 25.2). Offering noticeably greater intensity, the 511-keV annihilation gamma rays produce a Compton edge at 341 keV ( $E_1$  in Fig. 25.2), with a broad Compton distribution extending towards zero energy. (For details on the Compton edge and Compton distribution, see Experiment 3.) In this experiment, the upper- and lower-level discriminators on the 583B timing modules will be set to include the upper 90% of the Compton distribution from the 511-keV gamma rays, which will exclude most of the interference from the 1.274-keV gamma ray.



## Procedure

### A. Basic Connections

**NOTE:** 50- $\Omega$  RG-58A/U coaxial cables must be used for all the fast, negative timing signals. For the slow, positive logic pulses, 93- $\Omega$  RG-62A/U cables can be used.

1. Use the retort stands and clamps to mount the two 905-21 Scintillator/PMT/PMT-Base assemblies facing each other, about 50 cm apart. Take advantage of the 3.7-m cables to locate the detectors as far away from the supporting electronics and personnel as possible. Plan the appropriate space to permit the movable detector to be backed off from the source by 4 meters while still staying on the center line passing through the stationary detector and the  $^{22}\text{Na}$  source. Set up the mount for the source half-way between the two detectors with the third retort stand. But, do not install the 50- $\mu\text{Ci}$   $^{22}\text{Na}$  source until absolutely needed, in order to minimize radiation exposure.
2. Place a C-28 50- $\Omega$  terminator on the DYNODE output of each 265A PMT Base.
3. Insert the modules in the NIM Bin, but leave the Bin power and HV power turned off. To avoid confusion, it may be advantageous to install a 556 HV Power Supply at each end of the Bin, and locate a 583B timing discriminator next to each HV supply. This organizes the controls specific to each detector at opposite ends of the bin. The rest of the modules can be located anywhere in the remaining bin space. Note that the DB463 Delay Box and the EASY-MCA 8k do not go in the bin.
4. Using a 3.7-m C-36-12 cable, connect the HV OUTPUT on the rear of the 556 at the right end of the bin to the HIGH VOLTAGE input on the movable 265A PMT Base. Make sure that the POLARITY switch on the rear panel of the 556 is turned to NEGative. Using a 3.7-m C-25-12 cable connect the ANODE output on that same PMT Base to the INPUT of the 583B located at the right end of the bin. Connect one of the 38-cm-long C-25-15INCH-S Special RG-58A/U 50- $\Omega$  coaxial cables between the two DELAY connectors on this 583B front panel.
5. Repeat the connections in step 4, but with the stationary detector and the 556 and 583B modules at the left end of the bin.

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## Gamma-Ray Time-of-Flight Spectroscopy

- Using 0.61-m C-25-2 RG-58A/U 50- $\Omega$  coaxial cables, connect the TIMING OUTPUT of the left-end 583B to the top left INPUT on the DB463 Delay Box. Connect the OUTPUT of this delay section to the INPUT of the top right delay section of the DB463. Connect the OUTPUT of this latter delay section to the START INPUT of the 567 TAC.
- Repeat the connections in step 6 for the right-end 583B, the lower delay sections on the 463B, and the STOP INPUT of the 567 TAC.
- Using a 0.61-m C-24-2 RG-62A/U 93- $\Omega$  coaxial cable, connect the BK OUT (blocking output) of the left-end 583B to the A COINCidence input on the 414A.
- Repeat step 8 for the right-end 583B and the B COINCidence input of the 414A.
- On the 414A set the INPUT CONTROL switches to IN for inputs A and B, and OUT for inputs C and D. Set the RESOLVING TIME dial to its maximum (clockwise) value (110 ns) and lock the dial.
- Using a 0.61-m C-24-2 RG-62A/U 93- $\Omega$  coaxial cable, connect the 414A OUTPUT to the START GATE input on the 567 TAC.
- Using a 1.2-m C-24-4 RG-62A/U 93- $\Omega$  coaxial cable, connect the TAC OUTPUT on the 567 to the analog INPUT on the EASY-MCA 8k analyzer.
- Make sure the EASY-MCA is connected to the supporting computer via a USB cable and that the MAESTRO software is running on the computer.

### B. Initial Settings

- On both 583B timing modules, set the UPPER LEVEL dial to its maximum clockwise value. Set the LOWER LEVEL dial to 100 mV. Set the DIFF/INT switch to DIFFerential, and place the CF/SRT switch in the CF position. Turn the BK OUT WIDTH to its maximum value (1  $\mu$ s). Using a voltmeter on the front-panel test point, turn the WALK screwdriver adjustment to achieve a reading of  $-0.5$  mV on the voltmeter.
- For the sections of the DB463 supporting the Start signal, select a total delay of 100 ns. On the sections supporting the Stop signal, set the total delay to 120 ns.
- On the 567 TAC set the STROBE switch to INTernal, the START GATE switch to COINCidence, the STOP GATE switch to ANTIcoincidence, and the TAC INHIBIT switch to the OUT position. Select the 50-ns RANGE and the X1 MULTIPLIER.
- With the MAESTRO software operating the EASY-MCA, select a conversion gain of approximately 8000 channels full scale. Set the ADC ULD to 100% of full scale and the ADC LLD to 2% of full scale. Turn the ADC Gate OFF. Set all preset counting and time limits to OFF.
- Turn on the 4001A/4002D NIM Bin power.
- Choose an initial High Voltage setting of  $-2000$  V on both 556 High Voltage Power Supplies, and turn the two power supplies on.
- Place the 50- $\mu$ Ci  $^{22}\text{Na}$  source half way between the two detectors. To avoid unnecessary exposure to the radiation from this source, maximize your distance from the source, and minimize the time spent in close proximity to the source. Do not handle the source with your fingers. Use tongs or forceps to move and position the source.
- For the detector providing the Start signals, disconnect the ANODE output from the 583B, and connect it instead to the oscilloscope signal input. Set the input impedance of the oscilloscope to 50  $\Omega$  to properly terminate the 50  $\Omega$ , C-25-12 coaxial cable. With a horizontal scale of 5 ns/cm, and a vertical scale of 1 Volt/cm, trigger the oscilloscope on the negative anode signals to display the pulses. The pulse-height distribution observed on the oscilloscope should correspond to the distribution illustrated in Fig. 25.2.
- Adjust the High Voltage applied to this detector until the maximum pulse height observed on the oscilloscope is approximately 2 Volts. To avoid distorting the pulse amplitude, the oscilloscope must add a rise time that is less than 1.5 ns. A 300-MHz oscilloscope bandwidth (corresponding to a 1.2-ns rise time) should be adequate.

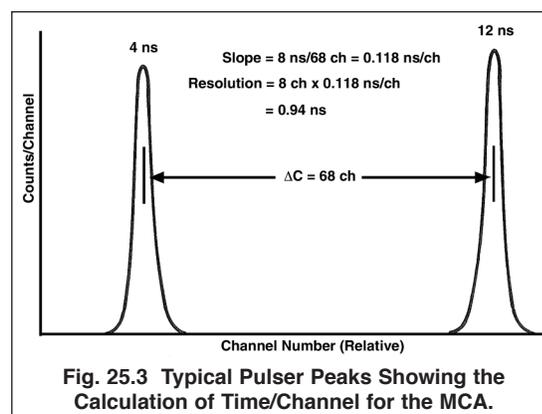
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# Gamma-Ray Time-of-Flight Spectroscopy

- Record the amplitude of the pulses corresponding to the 1.06 MeV Compton edge from the 1.274 MeV gamma ray ( $E_2$  in Fig. 25.2). Label this recorded voltage  $V_{1060}$ . Observe and record the amplitude where the intensity increases for pulses at and below the 341 keV Compton edge from the 511 keV gamma rays. Denote this voltage as  $V_{341}$ . Calculate the ratio,  $V_{341}/V_{1060}$ . How closely does the voltage ratio match  $0.341/1.06$ ? If there is a significant discrepancy, what is causing that deviation?
- Reconnect the ANODE output to the INPUT of the 583B. Set the 583B UPPER LEVEL to a dial reading corresponding to  $1.1V_{341}$  (Volts). Set the 583B LOWER LEVEL dial to  $0.1V_{341}$  (Volts). This selection ensures that the 583B will be accepting at least 90% of the pulses from the 511 keV gamma rays and rejecting most of the pulses from the 1.274 MeV gamma rays.
- Repeat steps 8 through 11 for the detector and 583B that deliver the Stop pulses to the TAC.
- Remove the  $^{22}\text{Na}$  source and return it to its shielded container.

### C. Delay Alignment and Time Calibration with a Pulser

- Using a 30 cm C-25-1 RG-58A/U 50- $\Omega$  coaxial cable, connect the middle connector on the MT050 50  $\Omega$  Matched Tee Signal Splitter to the ATTENUATED OUTPUT on the 480 Pulser. Set the Pulser polarity to NEGATIVE.
- Disconnect the coaxial cables from the two detector ANODE outputs and connect them instead to the remaining two connectors on the MT050 Signal Splitter. Turn the Pulser ON. This arrangement will supply synchronized electronic pulses to both 583B INPUTs.
- With the oscilloscope set for a 1-M $\Omega$  input impedance, observe the BK (blocking) OUTPUT of one of the 583B modules. Adjust the ATTENUATOR switches and the PULSE HEIGHT dial to find the lowest and highest pulse heights that generate a BK OUTPUT. Record these two limits.
- Repeat step 3 with the other 583B.
- Set the 480 Pulser to a pulse height that is approximately in the middle of the lowest to highest acceptable range for both 583B timing modules. Lock the dial.
- With the BK OUTPUTs reconnected to the 414A, acquire a spectrum on the EASY-MCA. A narrow peak should be observed growing at approximately 60 counts/second near mid-scale in the spectrum. Stop the acquisition when enough counts have been accumulated to form a well-defined peak.
- To calibrate the time scale for the spectrum on the EASY-MCA change the DB463 Stop delay by 4 ns and continue the spectrum acquisition to obtain a second, well-defined peak. Repeat this process enough times to produce time calibration peaks distributed over the entire time spectrum spanned by the EASY-MCA. Figure 25.3 illustrates a segment of that spectrum containing two pulser calibration peaks. Your calibration may differ because of the number of channels selected for the MCA range. You may wish to save a copy of your time calibration spectrum for future reference.
- Plot the peak positions (x-axis) versus time delay (y-axis) to establish a time calibration for the spectrometer. Calculate the slope of the calibration curve (ns per channel).
- Measure the FWHM (full width at half maximum height) of one of the peaks near mid scale. Using the slope of the calibration curve, calculate the FWHM time resolution of the peak. This is the timing uncertainty contributed by the electronics, exclusive of the detectors. This pulser time resolution should be small compared to the time resolution obtained with the detectors connected and responding to the  $^{22}\text{Na}$  source.
- Disconnect the 583B INPUTs from the Pulser and Signal Splitter. Reconnect the 583B INPUTs to their appropriate detector ANODE outputs.



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## Gamma-Ray Time-of-Flight Spectroscopy

### D. Gamma-Ray Time-of-Flight Measurements

1. Return the 50  $\mu\text{Ci}$   $^{22}\text{Na}$  source to its position mid-way between the two detectors.
2. Acquire a new spectrum on the EASY-MCA.
3. Adjust the DB463 delays in the Stop circuit to place the peak at 30 to 40% of full scale on the EASY-MCA. Once that position is achieved, take a spectrum long enough to accumulate a well-defined peak.
4. Optional Adjustment: If sufficient time is available, it may be worthwhile to adjust the WALK setting on each of the 583B modules to achieve the most symmetric and narrowest peak possible in the timing spectrum. Basically, this adjustment ensures that the small pulse heights do not trigger early or late compared to the large pulse heights. The effect of this adjustment will be most noticeable in the lower skirts of the time peak. See the 583B instruction manual for the procedure.
5. Measure the FWHM of the peak, and calculate the time resolution using the previously plotted time calibration curve. The result should be between 150 ps and 400 ps.

QUESTIONS: How does this resolution compare to the time resolution achieved with the pulser? Does the dominant contribution to time resolution come from the detectors or from the supporting electronics? Why?

6. Move the detector supplying the Stop signal exactly 1 meter further away from the  $^{22}\text{Na}$  source. Make sure that the center line between the detectors passes directly through the  $^{22}\text{Na}$  source.
7. Acquire a new spectrum, and measure the peak position. It should take approximately 25 times as long to acquire the same counts in the peak as it took for the previous spectrum. The peak should have moved approximately 3.3 ns. Use your time calibration curve to calculate the peak shift in nanoseconds. For the 1-meter change in distance, and from the time shift, calculate the velocity of the gamma rays.
8. Repeat steps 6 and 7 for 2, 3 and 4 meters, instead of the 1-meter. The 4-m acquisition may take a few hours. But it will yield the most accurate measurement of the velocity. Because the relative error reduces linearly with increasing distance.
9. Remove the  $^{22}\text{Na}$  source from the experiment, and return it to its shielded storage container.
10. Compare the velocity measurements for the four distances to the accepted value for the speed of light.

QUESTION: How does this measured value compare to the accepted value for the speed of light?

QUESTION: What are the two major sources of uncertainty in your measurements? Estimate their magnitudes.

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