University of Toronto
ADVANCED PHYSICS LABORATORY

MUON

Muon Lifetime

Interim Write-up

Revisions

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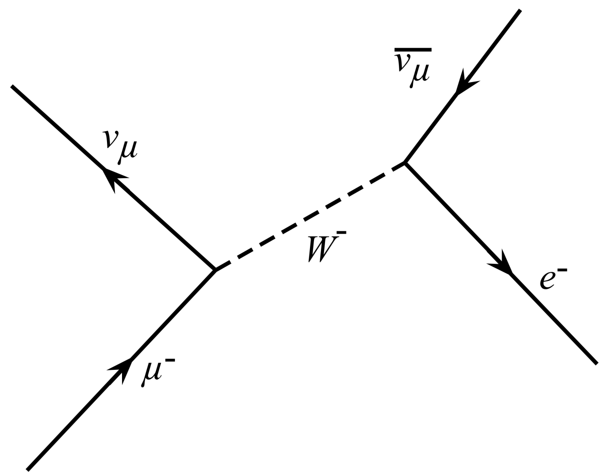


> In the 1930s, scientists thought they had matter figured out. Matter was atoms; atoms were protons, neutrons and electrons; and that was that. Then they discovered the muon—a surprisingly heavy cousin of the electron with no apparent purpose other than to baffle scientists. The muon was so unexpected that, regarding its discovery, Nobel laureate Isidor Isaac Rabi famously quipped, "Who ordered that?".
>
> - An excerpt from Symmetry Magazine's "Through a Muon's eyes"

1 Introduction

The goal of particle physics is to understand the basic building blocks of the universe and how they interact. We currently believe that the basic constituents are quarks and leptons, and these fundamental fermions interact via forces mediated by gauge bosons corresponding to fundamental symmetries of the universe. The goal of this experiment is to measure the lifetime, coincidence rates, and parity information of one of these fundamental fermions: the muon. This lifetime determines the value of the Fermi Constant G_F, which is the fundamental parameter describing the strength of low energy weak interactions. The mass of the W gauge boson can be calculated from G_F by using the standard electroweak unified theory.

A typical particle physics experiment consists of a beam, a detector, a data acquisition system, and an offline analysis system. In this experiment, cosmic rays provide us with a free muon beam.

The primary cosmic rays hitting the top of the earth's atmosphere are almost all protons or heavier atomic nuclei. These primary cosmic rays interact high in the earth's atmosphere producing copious quantities of secondary particles. The most common secondary particles are pions. Charged pions decay into muons and neutrinos, and these muons typically penetrate the atmosphere. Many of the muons reaching a ground-level laboratory are very penetrating, but a few may come to rest in a solid or liquid detector.

A muon coming to rest in a scintillation computer produces two pulses with a mean separation of approximately 2 microseconds. About five muons per minute are expected to stop in an individual scintillator in this experiment(depending on the size of the scintillator). A much lower rate of muons coincident on multiple scintillators is expected (~ 0.02 Hz). In this experiment, we measure and analyze the distribution of the muon decay time difference so as to infer the mean lifetime of muons and deduce whatever new information can be drawn from the result. Additionally, we will investigate muon coincidence and parity. Setting up and testing the necessary data-taking electronics is an important part of the experiment.

2 Cosmic Ray and Muon Physics

Cosmic rays, discovered in the 1930s as background radiation in laboratory experiments, provide us with a free source of muons. The flux of muons is not difficult to measure because the most penetrating ionizing particles in cosmic radiation at sea level are almost all muons. Gamma-ray showers, induced by the Doppler-shifted 70 MeV photons from π° decay in the upper atmosphere, also occur copiously at sea level, but they can be absorbed by a simple lead shield less than 20 cm thick. The cosmic ray muon flux can thus be isolated relatively easily. A brief history of the muon has been written by Wu and Hughes (1977).

Muons are known to decay, in their own frame of reference, with a vacuum mean life of $2.19703 \pm 0.00004 \mu s$ [Review of Particle Properties (1996) p. 21]. The primary decay mode

$$\mu^{+} \rightarrow e^{+} + \nu_e + \overline{\nu}_\mu \tag{1}$$

or

$$\mu^{-} \rightarrow e^{-} + \overline{\nu}_e + \nu_\mu \tag{2}$$

The only other known decay mode of the muon in free space is (Hughes and Kinoshita, 1977)

$$\mu^{+} \rightarrow e^{+} + \nu_e + \nu_\mu + \gamma \qquad or \qquad \mu^{-} \rightarrow e^{-} + \overline{\nu}_e + \nu_\mu + \gamma \tag{3}$$

which has a branching ratio of about one part in 1000. The decay of muons is a weak interaction process, and, apart from Coulomb interactions, the muon interacts only weakly with nucleons.

When positive muons stop in liquid scintillator or any other material, they may form muonium, a hydrogen-like atom ($\mu^{+}e^{-}$), by the reaction

$$\mu^{+} + X \rightarrow (\mu^{+}e^{-}) + X^{+} \tag{4}$$

where X is any available molecule. A possible additional decay mode of the μ^{+} bound to an electron in this way is

$$\mu^{+} + e^{-} \rightarrow \nu_e + \overline{\nu}_\mu \tag{5}$$

However, Pontecorvo has estimated that the branching ratio for decay mode (4) is only 1 part in 10^{10} (Hughes and Kinoshita, 1977), so that muonium formation should not affect the decay rate appreciably.

For negative muons, the alternative decays in the presence of matter are quite different. A negative muon stopped in a piece of matter forms a "muonic atom". (Hüfner, et al., 1977).

$$\mu^- + X \rightarrow (\mu^- X^+) + e^- \qquad (6)$$

The μ^-fall rapidly into hydrogen-like orbits around the nuclei of atoms. Since μ^- and e^- are not identical particles, the fact that an electronic orbit having particular quantum numbers is occupied does not prevent a μ^- from occupying an orbit having the same quantum numbers. Furthermore, the μ^- orbits have much smaller radii, $\sim \frac{1}{207}$ of the corresponding electron orbits. Thus, the Bohr radius of a C^{5-} ion is 8.8 x 10^{-10} cm whereas the orbit radius of μ in the lowest Bohr orbit of the muonic carbon atom is 4.3 x 10^{-12} cm. Thus, direct interaction is to be expected between μ^- and atomic nuclei, and in particular the decay mode within such nuclei

$$\mu^- + p \rightarrow (n^+ \nu_\mu) \qquad (7)$$

is proportional to Z^4 and so becomes significant for sufficiently high Z atoms. The rate is proportional to the number of protons in the nucleus and inversely proportional to the volume of the muon orbitals. An early measurement of the μ^- lifetime in carbon was made at Chalk River by Bell and Hincks (1952).

2.1 Non-conservation of Parity

A particle that has angular momentum and linear momentum in the same direction has helicity +1 and is called right-handed. A particle that has angular momentum and linear momentum in opposite directions has helicity -1 and is called left-handed.

Parity transformations create a mirror image of the coordinate system. Therefore, parity transformations flip the sign of helicity. Parity is conserved in strong and electromagnetic interactions, but not for weak interactions. The weak interaction couples only to left-handed particles and right-handed antiparticles. When a muon decays, the electron direction is most likely to be opposite to the muon spin direction; for anti-muons, the opposite is the case.

Safety Reminders

- Always ensure that the high voltage is off before connecting or disconnecting cables to avoid getting a nasty and possibly dangerous shock. Please be cautious when using these cables.
- Applying the wrong-sign high voltage to the detectors will destroy their photomultiplier tubes.
- Applying too high a voltage to the detectors will destroy their photomultiplier tubes.
- Be sure to carefully read the instructions (given later in this write-up) on how to turn on the high voltage supplies.
- If any sparking is seen or heard, or there is any burning smell, all power to the apparatus should be turned off and a Professor or Technologist consulted.
- Do not assemble, adjust, or disassemble the telescope by yourself - get help. The entire telescope is 100 lbs and expensive!
- Wear gloves whenever touching the threaded rods. The threaded rods have sharp edges and you will get painful metal splinters if you use your bare hands.
- Be very careful if you rotate the scintillator telescope. Rotate the telescope slowly under careful control, while making sure that cables and fingers are not pinched or cut.

NOTE: This is not a complete list of all possible hazards; we cannot warn against creative stupidities, e.g. juggling cryostats. Experimenters must use common sense to assess and avoid risks, e.g. never open plugged-in electrical equipment, watch for sharp edges, ... If you are unsure whether something is safe, ask the supervising professor, the lab technologist, or the lab coordinator. If an accident or incident happens, you must let us know. More safety information is available at http://www.ehs.utoronto.ca/resources.htm.

3 Apparatus

Up to five scintillator detectors are available for use in the experiment, but for normal muon lifetime measurements only one detector is used at a time.

- One large liquid scintillator
- One Sodium Iodine (NaI) crystal scintillator
- One plastic cylinder scintillator
- Two thick plastic (pancake) scintillator disks

The large liquid scintillator is used on its own for high statistics muon detection and decay measurements. The NaI and plastic cylinder scintillators can be used alone for similar muon measurements, or combined with the pancake scintillators into a muon telescope. More information on assembling the telescope can be found in 6.1.1.

Figure 1 shows the basic setup for the four detectors that can be used as a telescope Each detector is labelled by a letter in the diagram and in the lab.

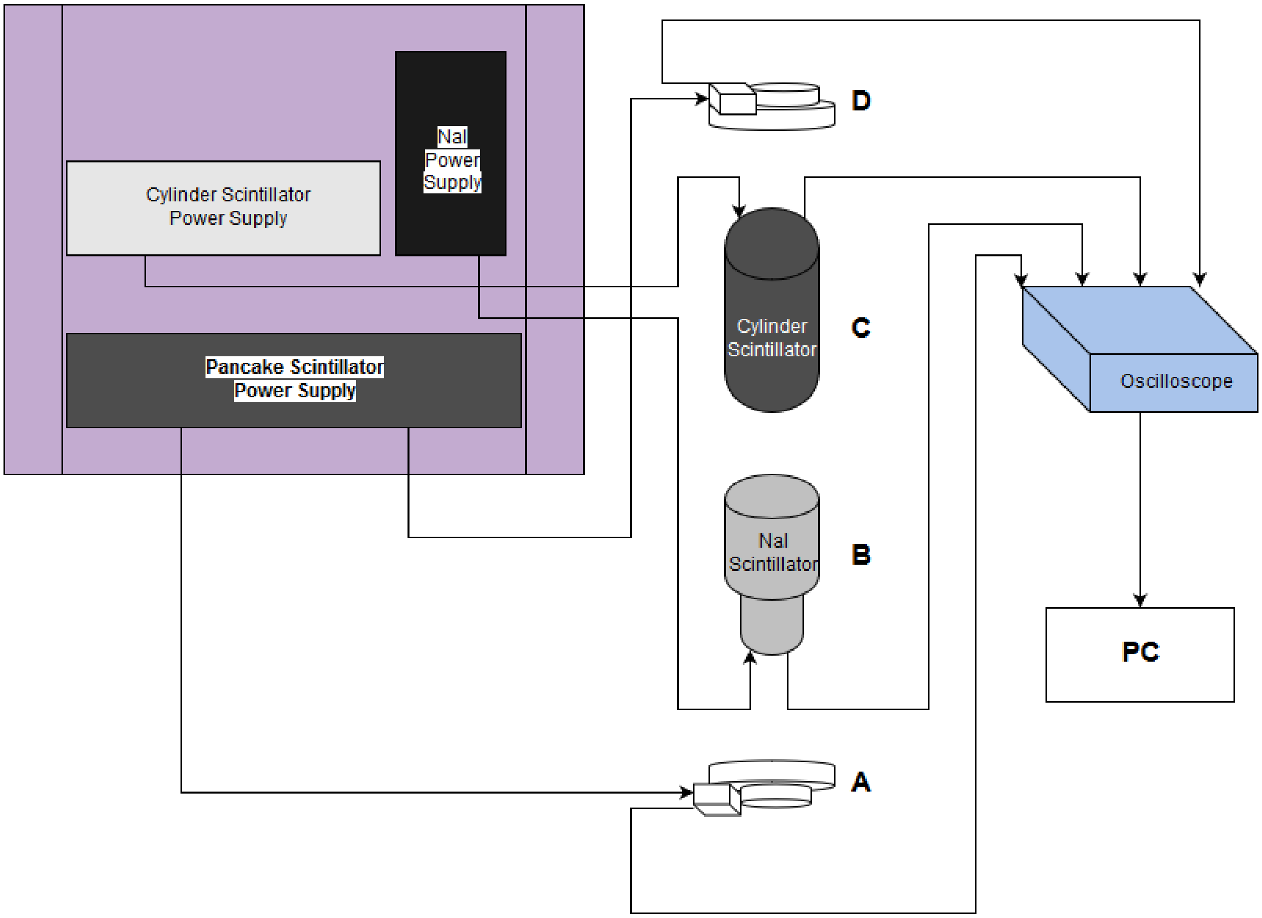


Figure 1: Illustration of how the power supplies, scintillators, and oscilloscope should be connected.

3.1 The Muon Detectors

Each muon detector has two main components: a scintillator and a photo-multiplier tube (PMT). A scintillator is a material that emits light when it absorbs ionizing radiation. This light is detected by the photo-multiplier tube which produces an amplified output current that is proportional to the amount of light. See Leo (1994) for more more information on the physics of scintillators and PMTs.

3.1.1 Detector Physics

Scintillators materials have electrons that can be easily excited by a passing muon. When this excited electron returns to the ground state, a photon may be emitted, often by a multi-step process involving several different kinds of molecules. When a charged particle passes through matter it loses energy by ionizing or exciting atoms or molecules. A scintillator is a material in which some of the lost energy is promptly emitted as visible light by the de-exciting atoms or molecules, often by a multi-step process involving several different kinds of molecules. The ionization energy loss for high energy particles varies from about 2 to 1 MeV per gm/cm^2 going from low to high atomic number materials. A muon decays into an electron/positron and two neutrinos. The neutrinos cannot be detected in this apparatus, but the electron/positron produces light all along its path. through the scintillator. Some of this light is detected by the PMT which produces an electronic pulse that is sent out to the oscilloscope.

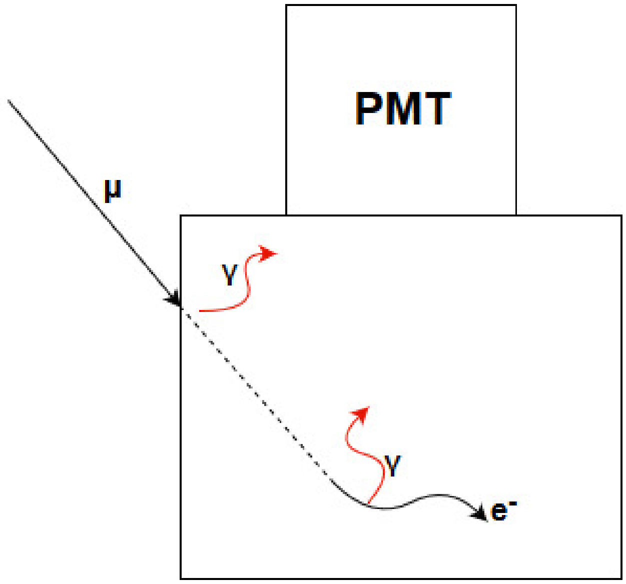


Figure 2: Schematic showing the generation of the two emissions of light used in determining the muon decay time. The first emission occurring when the muon enters the detector, the second when the muon decays within the detector.

Organic (plastic or liquid) scintillators produce only about a quarter as much light as NaI scintillators for the same amount of ionization energy deposited, but organic scintillators are usually much "faster" than NaI, i.e. their pulses are much narrower. (Compare Fig. 3 and 4.

3.1.2 Power Supplies

The five scintillators detectors are powered by four different power supplies, with the two pancake scintillator detectors sharing the same high voltage. Be careful that the right power supply and cable is used for each detector - **mixing them up could destroy the detectors.**

The liquid scintillator detector is powered by a **positive** high voltage HP6516A power supply. The NaI detector is powered by a **negative** high voltage HP6516A power supply. The cylinder scintillator is powered by DC low voltage via a unique three-pronged cable that is connected to a Teachspin Muon Physics box. The pancake scintillators are connected via MHV high voltage cables to ports on the front and back of the John Fluke Model 409A **negative** located at the bottom of the power supply shelf. Recommended voltages and maximum safe values are listed below.

Because the liquid scintillator is viewed by 3 PMTs whose outputs are summed, there are potentiometers that can be adjusted to equalize the gain of each tube.

3.2 Oscilloscope

The experiment uses a Siglent SDS 1104X-E Oscilloscope, which can receive signals from up to 4 detectors via BNC cables.

Detectors	Suggested Voltage (V)	(Voltage Limit)
Liquid Scintillator	+1600V	(+1800)
NaI	-1200V	(1400)
Pancake	-1360	-1500
Cylinder	Pre-set	

Table 1: Recommended voltages the different detectors; do not use voltages beyond the safe voltage limit.

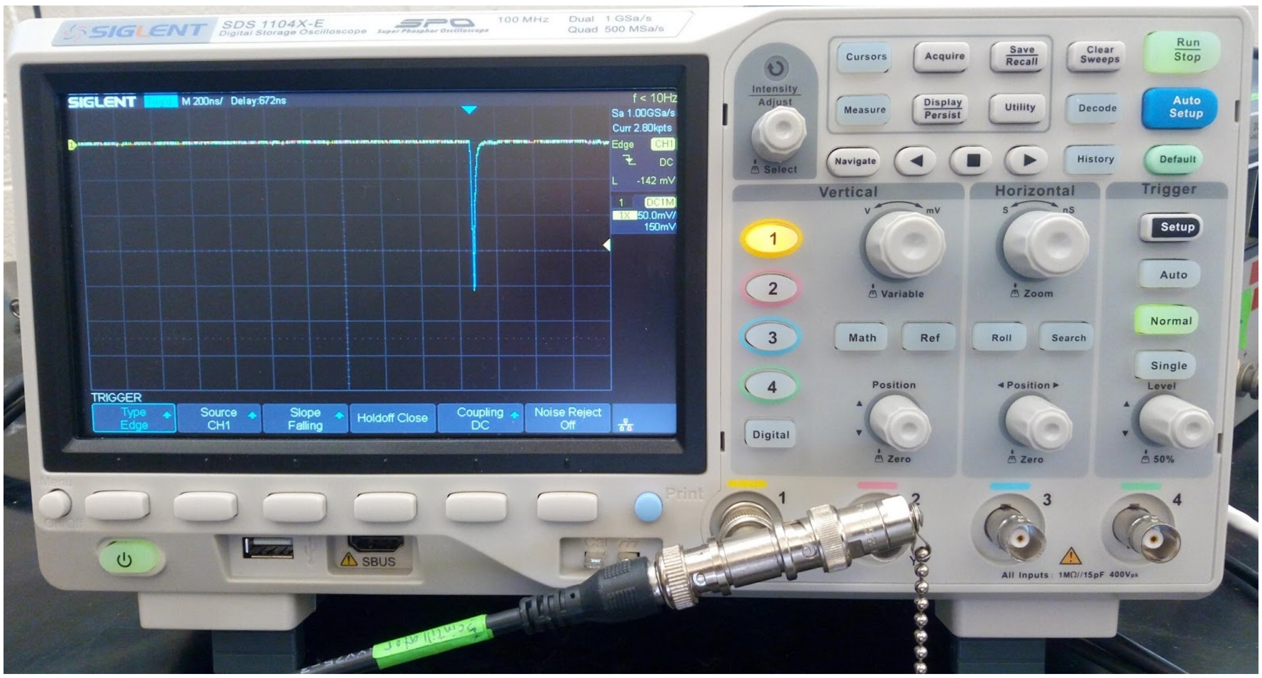


Figure 3: A single pulse from the liquid scintillator detector combined photomultiplier (PMT) output connected via BNC cable to Channel 1 of the oscilloscope. The horizontal scale is 200 ns per division.

These cables are interchangeable except that the signal from the cylinder scintillator must be terminated to ground through a 300Ω resistor. A cable-resistor combination is provided that enables this. The cables from the other detectors are best terminated with a 50Ω resistor.

All signal pulses in this experiment are negative, so the oscilloscope should be set to trigger on a falling edge. To look at single pulses, a simple edge trigger can be used as seen in Fig. 3. To observe muon decays, the *"Interval"* trigger should be used. This detects when two pulses arrive within a specified time interval, as shown in Fig. 4.

More complex triggers involving two or more scintillator signals can can be created with the *"Pattern And"* function, e.g. on muons passing though the telescope, or muons decays that span more than one scintillator.

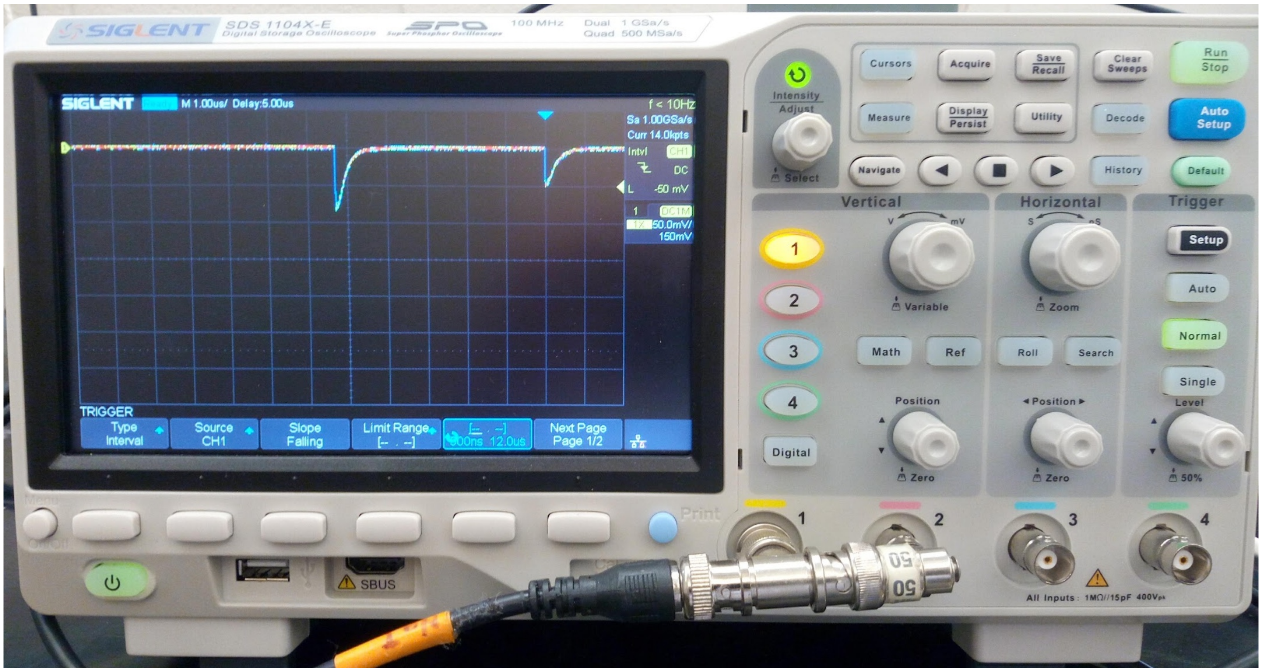


Figure 4: The two pulses from a muon first stopping and later decaying in the NaI scintillator. The horizontal scale is 1 μs per division.

3.3 Software

The interface for the oscilloscope is in a Python file titled muonScopeInterface.py on the local (T:) drive of the muon experiment computer. Refer to the TROUBLESHOOTING NOTES at the beginning of the .py file in case of common errors, which are listed.

To change the location to which the file is saved as well as the file name, adjust the two parameters of os.path.join, respectively. "w" refers to "write", as in writing to a file and should not be adjusted because this is how the data is pulled from the script and saved to a file.

The maximum runtime parameter is set in units of seconds. This parameter is varied to adjust how long the experiment is run. Typically, it is better to run for longer periods of time especially when measuring coincident muon events between scintillators since those events are more rare. The maximum number of events is usually set to be about a factor of ten of the maximum runtime when taking coincident muon events. The threshold count is set to be a constant at 50.

The scope timeout is set to be above the time between events (when the scope is triggered). Typically, it takes approximately 40 seconds between coincident events between two scintillators, thus the scope timeout is set here to be 60 seconds. Note: scope timeout is set in units of milliseconds.

The scope readouts per channel are set to pull data sequentially from channel 1 to channel 4. Similarly, for the timestamps. There is a readout delay of approximately 0.1 seconds between readouts which limits the timestamp value between channels. Thus, when coincident data is being recorded it can be assumed that events within this time limit are simultaneous.

```
#Set file saving to USB
channel1 = open(os.path.join('D:',"channel1.txt"), "w")
channel2 = open(os.path.join('D:',"channel2.txt"), "w")
channel3 = open(os.path.join('D:',"channel3.txt"), "w")
channel4 = open(os.path.join('D:',"channel4.txt"), "w")

# Set parameters for data taking
maximum_run_time         = 86400 #200 #57600 #60 #999999      # seconds
maximum_number_of_events = 8640 #280 #99999
threshold_count          = 50

# Default timeout is 2000 ms, which is too long, so make shorter
scope.timeout = 60000 #60000 #500 # in milliseconds
```

Figure 5: Settings for data saving including file name and location & Settings for runtime and number of events captured

4 Measurements

4.1 Muon Lifetime

Only one scintillator is needed to measure the muon lifetime, and it is recommended to start with the liquid scintillator since it is largest and hence has the highest rate of detected muon decays.

The oscilloscope traces can be recorded using the **interval** trigger on the scope, and a decay DAQ python file in the T:/ drive. Depending on the size of the scintillator and the muon count rates, different length trials will have to be recorded. After recording the scope traces, the decay analysis file can be used to investigate the muon lifetimes.

4.1.1 Liquid scintillator set up

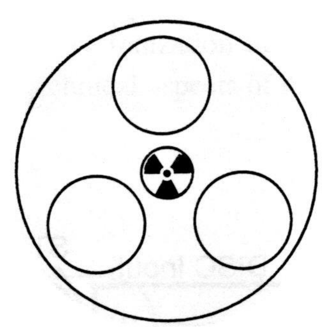
The principle of the experiment is to obtain a time distribution of consecutive pulse pairs coming from a large liquid (or solid) detector. Such a time distribution will contain a random component, indicating that some pulse pairs were unrelated in time, and an exponentially decaying component corresponding to muon decays. Only when the first pulse of a pair corresponds to a muon entering the detector, and the second to the decay of a muon which stopped in the detector, will we get an event contributing to the exponential decay.

The large liquid scintillator has about 9 litres volume and 12 cm vertical thickness. In this experiment, the scintillator is viewed by three XP1040 photomultiplier tubes that have been coupled so as to sum their output pulses. Ionization energy loss, scintillators, photomultipliers, discriminators, and almost all other technical aspects of this experiment are very well explained in Leo (1987).

Several additional measurements are necessary to complete this experiment. Generally, it will not be necessary to carry out all of these tasks, as there is continuity and experience accumulating in the use of the equipment.

```
while event_number < maximum_number_of_events :
    # Make one acquisition for channel 1
    try :
        scope.write("SAST?")
        status=scope.read()
        if status[5:9]!="Stop" :
            continue

        scope.write("C1:WF? DAT2")
        trace1               = scope.read_raw()
        event_absolute_time1 = time.time()

        scope.write("C2:WF? DAT2")
        trace2               = scope.read_raw()
        event_absolute_time2 = time.time()

        scope.write("C3:WF? DAT2")
        trace3               = scope.read_raw()
        event_absolute_time3 = time.time()

        scope.write("C4:WF? DAT2")
        trace4               = scope.read_raw()
        event_absolute_time4 = time.time()
```

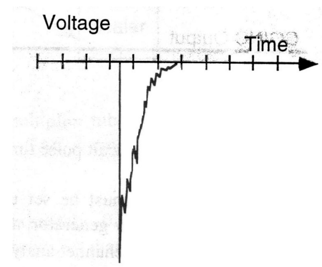
Figure 6: Code snippet highlighting the scope readout and time stamp commands.



Equalizing the photomultiplier gains If the gains of the three photomultipliers are equalized, then sensitivity to muons and their decay electrons is almost independent of where they decay in the scintillator. The photomultipliers view the scintillator from above as shown in the diagram. Gain equalization can be achieved by connecting the photomultiplier outputs one by one direct to the oscilloscope without going through the pulse adding network. If the threshold is set to its minimum and the voltage to the maximum allowed, then the detector system should be sensitive to nuclear gamma rays (^{60}Co or ^{208}Tl). The gain of each multiplier can be changed slightly by adjusting a potentiometer in series with the high voltage. If the gains are equalized, each multiplier will give the same count rate when a radioactive source is placed beneath the centre of the bottom of the tank, as in the figure.

If your photomultiplier high voltage is too low, some relevant pulses may not pass the trigger even at its lowest setting. If the voltage is too high, you may fry the PMT. The ideal choice of voltage and discriminator are those values which produce the spectrum which gives you the smallest errors on the muon lifetime.

Equalizing the photomultiplier delays The current pulses at the anodes of the photomultipliers are extremely fast rising and are not integrated on any input capacitance in this experiment. On a voltage-time scale, seen by passing this current signal through 50 ohms, a pulse might look like the sketch shown here, where the time marks are roughly at 10 ns intervals. When adding several pulses of this nature together, the leading edges of each need, for optimum effect, to be aligned with the others. This can be achieved by adjusting the relative cable length between each photomultiplier and the pulse-adding-circuit. When the cable delays are optimized, the average signal voltage peaks will be maximized (in the negative voltage direction).



Choosing the trigger level The energy loss of the initial stopping muon and the final decay electron pulse can be estimated from the kinematics of muon decays and the ionization energy loss in liquid scintillator of about 2 MeV/cm for muons or low energy electrons. Natural radioactivity will produce background pulses in the tank, with the highest energy common gamma rays being 2.6 MeV gamma rays from ^{208}Tl. A ^{60}Co source yields gamma rays of 1.17 and 1.33 MeV; when both are detected simultaneously, their Compton continua sum to a maximum-absorbed-energy of 2.5 MeV. The initial trigger setting should be based on the size of the observed ^{60}Co pulses and the energies of the background and signal pulses. An improved value can be achieved by observing the actual pulse size spectra.

4.1.2 Decay Rate

The background component of the observed time spectrum can include both random and non-random components. A random background event can occur, for example, when two independent muons randomly pass through a detector within the set trigger interval. Uncorrelated pulses from cosmic rays, gamma rays and electronic noise all contribute to this random background. Non-random background can occur from electronic pickup and glitches. For example, many photomultipliers, especially if old and somewhat gassy, have unwanted additional after-pulses, typically about half a microsecond after the normal pulse arising from an external event.

If there are no non-random backgrounds, the expected time spectrum is of the form

$$\frac{dn}{dt} = n_o e^{-\lambda t} + b \tag{8}$$

where dn/dt is the count rate of pulse pairs corresponding to time separation t, n_o is a constant, λ is the muon decay rate (The decay rate is simply the inverse of the mean lifetime, i.e. $\lambda = 1/\tau$), and b is the rate due to the random background component. Any part of the observed spectrum which has no non-random backgrounds can be fitted to equation 8 so as to obtain τ, the laboratory lifetime of the muon. An alternative to the use of equation 8 is the simple linear regression analysis

$$ln\Big(\frac{dn}{dt} - b\Big) = ln(n_o) - \lambda t \tag{9}$$

Use of 9 requires determination of b separately. The easiest way is to make the time window for your data long enough that all muons have decayed before the end of the time window, so b is simply measured from the final flat part of the time distribution. It is also recommended to use a scaler to count the total number of STARTS, including those without stops. If n is the START rate per second, and τ is the channel width, then for a random, low rate background we expect $b \approx n^2\tau$.

Although equation 9 correctly describes the vacuum decay of muons at rest, whether μ^+or μ^-, in matter negative muons can be captured by atomic nuclei forming "muonic atoms". The muon can then "disappear" via interactions with nuclear protons producing a neutron and a muon neutrino, i.e. $\mu^- p \to \nu_\mu n$. The total decay rate of negative muons in matter is hence:

$$\lambda_- = \lambda_0 + \lambda_c \tag{10}$$

where λ is the decay rate of negative muons in the scintillator, λ_o the vacuum decay rate and λ_c the capture rate. Positive muons cannot be captured by ncu

This means that a mixed μ^- and μ^+ beam would decay in the scintillator according to the expression

$$n = n_+ e^{-\lambda_o t} + n_- e^{-\lambda_- t} + b \tag{11}$$

where n_+ is the number of μ^+ decaying per second at time t = 0 and n_- is the observable number of μ^- decaying per second at t = 0.

In NaI, all the negative muons may disappear because of nuclear capture, so only μ^+ decays will be detected and the observed muon lifetime should be very close to the muon lifetime in vacuum. In organic scintillators (made primarily from light H and C atoms), some μ^- may decay before being captured and disappearing, so the observed decays will be a mixture of the μ^+ and shorter μ^- lifetime. With sufficient data, e.g. using long runs with the large liquid scintillator, two exponential components may be observed.

Comparing the average two rates λ_o and λ_- are too close. At best we can determine an average λ (using 8 or 9) and assume it to be a weighted average of λ_o and λ_-.

To determine the weighting, we make use of two facts: the approximately known ratio of μ^+ to μ^- in cosmic rays at sea level, and the fact that muons captured by nuclei in the scintillator will escape direct observation — even though these decays directly affect λ_- through equation 10.

Let the fractions of μ^+ and μ^- stopping in the scintillator be f_+ and f_-, and let the fraction of - that escape observation be f_c. Then the average λ corresponding to the weighted mean of λ_o (for +) and λ_- must be

$$\lambda = \frac{f_+\lambda_o + f_-(1-f_c)\lambda_-}{f_+ + f_-(1-f_c)} \tag{12}$$

Note that, while $f_+ + f_- = 1$, the denominator of 12 is not in general unity. The value of f_c follows directly from the decay channel widths for μ^-; hence

$$f_c = \frac{\lambda_c}{\lambda_o + \lambda_c} and \qquad 1 - f_c = \frac{\lambda_o}{\lambda_o + \lambda_c} \tag{13}$$

Eliminating f_c and λ_- from 12, using 13 and 10:

$$\lambda = \lambda_o \left\{ 1 + \frac{f_+ \lambda_c f_-}{(\lambda_o + \lambda_c) f_+ + \lambda_o f_-} \right\} \tag{14}$$

Solving for λ_c

$$\lambda_c = \frac{\lambda - \lambda_o}{1 - f_+ \lambda / \lambda_o} \tag{15}$$

In 15, we shall assume that λ is the single value given by fitting the summed exponentials in the experiment and that λ_o is the well-known vacuum value already cited. The lowest energy muon component in cosmic rays contains somewhat more μ^+ than μ^-. According to Thompson's article in Wolfendale (1973), the ratio is about 6:5. Assume this value is accurate to calculate the λ_c.

Note that equation 14 assumes we are able to view the entire muon decay spectrum, whereas the circuit logic of the present experiment forces us to blank out the first few channels of the muon spectrum. The omission of these few channels weights slightly the positive muon component which has the longer half-life, thus introducing a small systematic error in the use of equation 14.

4.2 Parity Violation Measurements

Use the two large scintillators (the cylindrical plastic and the NaI) to show that parity is violated in weak interactions by noticing where a muon decay occurs and detecting the direction of the decay products. Recall from (1) and (2) that the decay results in either an electron or a positron as one of the decay products. The non-conservation of parity suggests that these electrons and positrons only decay towards one side of the muon. There is a measurement that corresponds to parity violation in muon decay. For an extra challenge, try and repeat it.

After reading Appendix 6.1, place the cylndrical plastic scintillator and the NaI scintillator as close together as possible at the centre of the telescope. Set the trigger to capture on an interval similar to the decay measurement for one of the detectors. Simultaneously record any pulses from the other (cylindrical) scintillator that occur close to the time of the decay occurring in the first (NaI) scintillator. Then, repeat the experiment using the decays in the other detector. Finally, **after reading Appendix 6.1**, repeat the same experiment but with the telescope rotated 180 degrees. This data can be taken using the Parity DAQ python code in the T:/ drive. Then, by analyzing the trace of the scope for both channels, investigate the counts of parity violating muon decays for all orientations. This can be done using the parity analysis Python code in the T:/ drive.

4.3 Cosmic ray rates and directions

The full muon telescope consists of the cylinder and NaI scintillators as close together at the centre of the telescope, with the two pancake scintillators placed at each end of the telescope. If any adjustments to the positioning of the detectors is needed please see the Appendix Section 6.1

The trigger should be set to capture events across the two detectors using the ”Pattern And” function. The expected result on the oscilloscope should look like all four channels with a negative voltage spike simultaneously. There may be some delays between the each channel. This experiment requires a minimum of two detectors placed along the telescope. Vary the distances between the scintillators on the telescope and collect data. Then, data can be taken on average number of coincident muons per unit time, compared to muons incident on one detector. This information will be useful for parity measurements.

Find the rate of coincidence of muons entering all of the scintillators on the telescope at the same time. Changing the positions of the scintillators and the number of scintillators on the telescope should change the resolution of detection. Recall that cosmic ray muons travel down to ground level from various angles. What is their angular distribution? Do structures impede with this measurement?

5 Conclusions

By the end of the experiment you should have answered the following questions:

1. What is the average lifetime of the muons decaying in the liquid scintillator? Can you discern the mu+ and mu- lifetimes?
2. What is the lifetime of negative muons captured by nuclei in the scintillator?
3. Are the data consistent with a single lifetime and a random background? If not, what are the other features?

Optionally, you may also have answered some of the following questions

1. What is the angular distribution of the muons?
2. Can you "see" the Burton tower in the rate of coincident muons?
3. Could you demonstrate parity violation in muon decay?

From your average muon lifetime and the known muon mass, m_μ, you can calculate the lowest order value for the Fermi constant [Perkins (1987)]

$$G_F = \sqrt{\frac{192\pi^2}{\tau_\mu m_\mu^5}}$$

And you can make a lowest order calculation of the mass of the W boson from

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F sin^2\theta_W}}$$

where α is the fine structure constant, and $sin^2\theta_W$ is the weak mixing angle.

6 Appendix

6.1 Telescope Adjustments

The default position of the telescope has the cylindrical and NaI scintillators placed at the centre of the telescope as close as possible to one another and the two pancake scintillators at either far ends of the telescope. It is advised that students leave the telescope in this default position once they have finished their experiment.

6.1.1 Assembling the Telescope

WARNING: Use the provided gloves while assembling, adjusting, and handling the telescope. You will get metal splinters if you use your bare hands
Do not assemble, adjust, or disassemble the telescope by yourself - get help. The entire telescope is 100 lbs and expensive

1. Screw a flange nut flange-side-first onto each steel threaded rod a few inches down. Ensure that the nuts are the same distance away from the end of the steel rods
2. Insert the steel rods into a flat (pancake) scintillator such that the flanges of the screwed on nuts are all in contact with the pancake scintillator
3. Stand the rods up such that the pancake scintillator is on the bottom
4. Screw a flange nut flange-side-first onto each rod from the top. The flanges should hug the other side of the flat scintillator
5. Screw a flange nut flange-side-last onto each rod from the top. The flanges should each be 10 inches above the nuts below and be at equal heights
6. Slide aluminum plate #1 along the rods until it rests on the flanges of the nuts from step 5
7. Screw a flange nut flange-side-first onto each rod from the top. The flanges should hug the other side of aluminum plate 1. This nut-plate-nut system is called a unit
8. Screw a flange nut flange-side-last onto each rod from the top. The flanges should each be 7 inches above the nuts below and be at equal heights
9. **This step requires two people**: Insert the thin end of the NaI scintillator through the middle opening of aluminum plate 1 and hold it there. The other partner should slide aluminum plate 2 along the rods such that it goes around and hugs the fat end of the NaI scintillator. Once the scintillator is secure, the first partner may let go of the NaI scintillator
10. Screw a flange nut flange-side-first onto each rod from the top. The flanges should hug both sides of aluminum plate 2. Adjust aluminum plates 1 and 2 as needed to ensure that the NaI scintillator is held securely by the aluminum plates
11. Install another unit using aluminum plate 3 such that it is 30 inches from the bottom. This corresponds to the center of mass of the telescope

12. Install another unit using aluminum plate 4 such that it is right up against the unit below
13. Screw a flange nut flange-side-last onto each rod from the top. The flanges should each be 13 inches above the nuts below and be at equal heights
14. **This step requires two people**: Insert the end of the plastic cylindrical scintillator without the in/out into the middle opening of aluminum plate 4 such that it sits snug on the groove in the opening of the aluminum plate and hold it there. The other partner should slide aluminum plate 5 along the rods such that the grooves of aluminum plate hug and securely hold the plastic scintillator in place and the bolts on the circumference of the top of the plastic scintillator fit into the holes in the aluminum plate. Once the scintillator is secure, the first partner may let go of the plastic scintillator
15. Screw a flange nut flange-side-first onto each rod from the top. The flanges should hug the other side of aluminum plate 5. Adjust aluminum plates 4 and 5 as needed to ensure that the plastic scintillator is held securely by the aluminum plates
16. Screw a flange nut flange-side-last onto each steel threaded rod a few inches down. Ensure that the nuts are the same distance away from the end of the steel rods
17. Slide the other pancake scintillator along the rods until it rests on the flanges of the nuts from step 16
18. Screw a flange nut flange-side-first onto each rod from the top. The flanges should hug the other side of the flat scintillator
19. Using a wrench, tighten all bolts to ensure everything is secure, but do not over-tighten!

6.1.2 Adjusting the Telescope

When moving the scintillators to new locations on the telescope, please ensure that aluminum disk #3 is located around the new centre of mass of the telescope as to prevent a moment about the pivot which is attached to disk #3. For example, when both the NaI and plastic scintillators are right at the ends of the telescope right next to the pancake scintillators, the centre of mass will be 78 cm from the side that contains the plastic (cylindrical) scintillator. When both the NaI and plastic scintillators are close to the middle of the telescope, the centre of mass will be at 75 cm from the side that contains the plastic scintillator.

6.1.3 Disassembling the Telescope

When disassembling the telescope ensure that NaI and cylindrical scintillators have been removed prior to any unnecessary rotation or movement of the muon telescope.

6.2 Liquid Scintillator

The scintillation tank used in this experiment was originally purchased as a fast neutron detector for the 50-metre neutron time-of-flight vacuum beam in the McLennan sub-basement laboratory. Fast neutron detection in such a medium is though proton recoil. The equipment was first used in an experiment directed by Prof. K.G. McNeill and D.J.S. Hewitt – late professor of Nuclear Engineering. John Hewitt died prematurely in April 1995, while still in his fifties. Kenneth McNeill retired in 1992.

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Figure 7: The assembled full muon telescope before mounting on rotating stand. Scintillators from top to bottom are: pancake, plastic, NaI, pancake scintillator