

Muon Lifetime Experiment

Purpose

To detect cosmic ray muons using a setup with three plastic scintillators, and to determine their lifetime. To learn about coincidence methods and electronics used in high-energy physics.

Introduction¹

In 1912, Austrian physicist Victor Hess discovered cosmic rays, which are very high energy charged particles, including ionized atomic nuclei, protons, electrons, positrons, and some antiprotons, from space. Those particles receive their energy from “cosmic accelerators” including magnetic fields and shockwaves. Intense magnetic fields are formed in space by white dwarfs, radio galaxy lobes, galactic clusters and compact objects, such as neutron stars and active galactic nuclei. Charged particles or nuclei traveling through these fields can be accelerated to great speeds. Shockwaves from supernovae, galaxy collisions and high-speed jets in some powerful radio galaxies also impart energy to particles and nuclei, accelerating them and forming cosmic rays. Each cosmic accelerator is characterized by a total power and a maximum energy per particle; each also produces a mix of different kinds of particles that reflects its environment. Therefore, by studying cosmic rays, we can learn about the area in space from which they came and the properties of particles at speeds higher than we can produce on Earth.

Cosmic rays hit the top of the Earth’s atmosphere at a rate of roughly 1,000 particles per square meter per second, where they generate cascades of lower-energy particles. Figure 1 [please see the web site in footnote 1] shows a simplified development of an air shower. The majority of the particles that reach the ground are electrons and muons (+ or -). The muon was first discovered by American physicist Carl D. Anderson in 1936 and has a mass that is 206.8 times larger than that of the electron. Previous measurements of the muon lifetime yield $t_0 = 2.1970 \pm 0.00004 \mu\text{s}$ (from the Particle Physics Data Book). Despite its short lifetime, the muon is able to travel the 10 km from where it is formed in the atmosphere to the ground below. This is a result of relativistic time dilation / length contraction. The broad distribution of muon energy peaks at around 3000 MeV which means they are traveling at about 0.9989 times the speed of light. Thus, in the frame of a stationary observer, the muon seems to have a longer lifetime, $t = 46.2 \mu\text{s}$, as described by the equation for time dilation:

$$t \equiv \gamma t_0$$

$$\text{where } \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}.$$

Equivalently, one can consider the lifetime of the muon in its own rest frame, which is the accepted value of 2.2 μs . In this frame, the distance between the atmosphere and the detector is length contracted to $L = 0.476 \text{ km}$ using the expression:

¹ Introduction is from the site <http://mxp.physics.umn.edu/s01/Projects/Muon/muonfinal1c.pdf>

$$L = L_0 / \gamma$$

A fraction of the muons created in the atmosphere can cover this distance before decaying.

Muons decay by the processes:



The μ^- can also be captured by a nucleus with the emission of a neutrino and a neutron, and the probability of this occurring increases rapidly with the increasing Z of the surrounding matter. Therefore, the measured mean lifetime in matter of the μ^- decreases slightly in the presence of other matter.

Outside at ground level, muons arrive at roughly 110 per square meter per second per steradian. Inside with about 2 floors of shielding overhead, that number decreases to about $80/\text{m}^2/\text{s}/\text{sr}$ at our detector. Only 10 – 25% of those muons decay, so we expect a count rate of about 8 – 20 muons per second.

How can these particles be detected? Particles with a reasonable mass (unlike the neutrino, with an implied very small mass) will interact with plastic materials known as scintillators, deposit their energy and give off a flash of light. The flashes of light are subsequently detected by photomultiplier tubes (PMT) that transform the flashes of light into electrical pulses with nanosecond duration and sub-volt amplitude. Thus the signature of a high-energy particle will ultimately be an electrical pulse that can be processed by commercial counting electronics.

Basic Principle of the Experiment

Figure 1 shows the three scintillators and four photomultiplier tubes, A, B, C, and D. Assume that a cosmic ray muon enters the apparatus from above, and it happens to come to rest in the large scintillator block. That means we will detect a pulse in PMT A, and either PMT B or C (or both), but not in PMT D. This combination of pulses, ((B OR C) AND A AND (NOT D)), will be our “start” signal. It will trigger a timer (the **time-to-amplitude converter**) to begin timing.

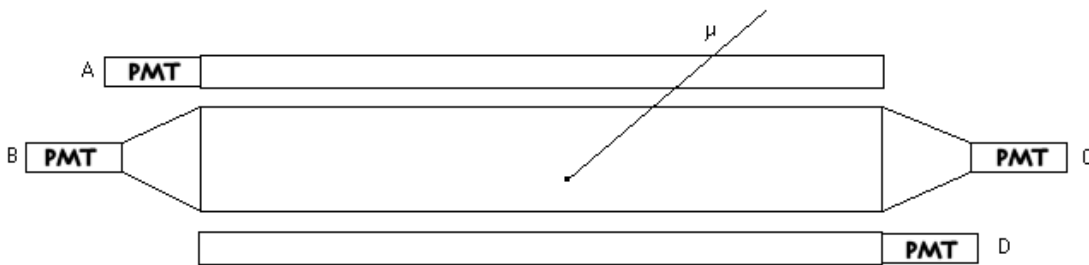


Figure 1. Start signal in the scintillators.

As mentioned in the introduction, a muon decays to either an electron or a positron, plus neutrinos. Electrons and positrons have a very short range in matter, so they cannot travel outside the large scintillator block. Therefore, when a muon decays, we will see a signal in PMT B or C (or both), but definitely not in A or D. So our stop signal will be ((B OR C) AND (NOT A AND NOT D)). This signal will turn off the timer, and the time interval between the start and stop pulses will be stored in the computer. [We are not able to detect the ν 's with our equipment.]

Equipment List

Set of three scintillators with four PMTs
Oscilloscopes: Tektronix 2246A and/or HP 54501A
Power Supplies: Fluke model 412B High Voltage Power Supply and Power Designs 3K-40
LeCroy model 222/222N Dual Gate Generator
LeCroy model 365AL Dual 4-Fold Majority Logic Gate with Veto
LeCroy model 465/466 Triple 4-Fold Coincidence Units
LeCroy model 429 Fan-out
LeCroy model 623 Series Quad Discriminators
Ortec model 430 Scaler or 773 Timer/Counter
Ortec model 567 Time-to-Amplitude Converter
Ortec model 462 Time Calibrator
Ortec 427A Delay box and OSU delay boxes
Computer with National Instruments PCI-6220 data acquisition card
and LabView program Muon Lifetime 2010.vi
Stopwatch

Important note about radiation safety:

You may have noticed several radiation warning signs and stickers around the lab (room 2087). Please follow the rule that no food or drink may be brought into the room. Do not eat or drink anything while in 3018; do not even chew gum. This is a federal law and an OSU policy.

Experimental Tasks

1. Find appropriate operating voltages for the photomultiplier tubes (PMTs).
2. Adjust the time delays for the signals coming from the discriminators.
3. Set up the logic for “start” and “stop” inputs.
4. Connect the start and stop signals to the TAC, and hook up the computer
5. Use the Time Calibrator to check the calibration of the TAC and computer.
6. Accumulate a short run of data to check that everything is working.
7. Accumulate a long (overnight) run to get data with good statistics.

Procedures and further info

1. Finding voltage plateaus for the PMTs:

Connect the PMTs to the high voltage (HV) supply if they are not connected already (**make sure power is off before you do this!**).

For some range of voltages, the number of counts recorded in a given time interval will vary with voltage. Then, in an ideal operating range, this curve should reach a plateau. Above a certain voltage, the accelerated electrons will cause unwanted discharges in the PMT, and so the number of counts will once again rise as a function of voltage.

To allow the experiment to be completed in two weeks, we will tell you the voltages to use, rather than have you make your own plots of counts/min vs. voltage.

PMT A, D: $V = -1.52$ V on monitor. (actual voltage = -1520 V)

PMT B, C: $V = +1.25$ kV on power supply panel meter.

Notice that the monitor voltages are scaled down by a factor of 1000 from the true voltages.

Use **negative** high voltage for these PMTs A and D. Use **positive** high voltage for these PMTs B and C.

How to turn on the Fluke power supply:

1. Be sure the "High Voltage" switch is in the off position. Be sure all the voltage knobs are at zero.
2. Turn on the "A.C. On" switch. This just supplies A.C. power to the unit.
3. Wait for about 30 seconds. The "High Voltage" ready light should come on. Then flip the "High Voltage" switch to the "ON" position. The red light should come on.

Connect the output of the PMT to the oscilloscope. As you learned in the experiment on pulses and coax cables, it is valuable to know the characteristics of pulses you will be manipulating and recording. Continue using the scope throughout the experiment. Make sketches of the pulses in your notebook, noting any important values such as amplitude and time scale.

2. To adjust the delays:

Imagine a particle passes through the stack of scintillators, depositing energy in each of them. Ideally, all the PMTs' signals from this **event** would arrive at the electronics rack at the same time. Why is this desirable? (When doing this experiment, should we worry about the time it takes the muon to travel from Scintillator A to Scintillator block B/C? Why or why not?)

Some possible reasons that the signals don't all arrive together:

Different model PMTs with different time constants

Different cable lengths connecting PMTs to the rack

Different scintillator geometries (such as big block vs. thin slab) cause more or less spread in the time it takes light from the event to reach the photocathode.

If your signals are not arriving together, you will need to add delays to the faster ones to compensate. For more information, see the 2nd reference below. You will need to make graphs like figure 9.13 in the second reference. See also fig. 2 below.

Note that you will have to put the outputs from the PMTs through discriminators before using them as input to any of our other modules. The purpose of a discriminator is to take the variable-amplitude "tail pulses" produced by the PMTs and create uniformly sized, square logic pulses from them. For comparing arrival times of two (or more) signals, pulses with

vertical rising and falling edges are ideal. The logic pulses in this experiment mostly follow the NIM (Nuclear Instrumentation Module) standard, which specifies amplitude ~ -0.85 V for “true” and 0 V for “false”.

View the discriminator output pulses on the scope to see which arrives first. Use the LeCroy 465 coincidence unit. Use the Ortec 430 scaler to find the count rate. Plot count rate vs. delay in nsec.

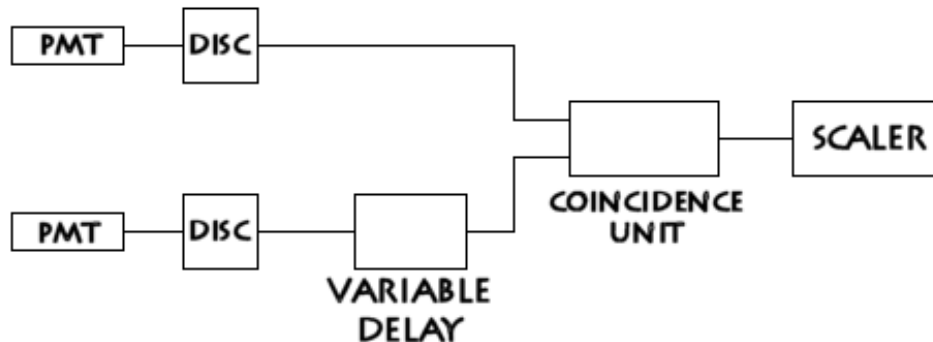


Figure 2. Setup for adjusting time delays. Adapted from fig. 9.8, Melissinos, *Experiments in Modern Physics*.

3. Setting up the logic:

See the first reference for some hints and info on what the various modules do. See fig 3 (note: delays found in part 2 are not shown in the figure). Note that a model 222 Gate Generator is used after the start signal. Think of this gate as the opening a “window of opportunity” during which a stop pulse can occur. What is an appropriate length for this gate?

Also, there is a delay between the start signal and the gate generator. This ensures that a start signal cannot inadvertently trigger a stop, which could happen if signal A turns off a few ns early (due to random fluctuations in the arrival time of signals).

4. Connect the start and stop signals to the TAC, and hook up the computer:

The TAC works by charging a capacitor during the interval between the start pulse and the stop pulse. The voltage on the capacitor is then proportional to the time interval. The model 567 puts out a signal between 0 and 10 volts. This voltage range represents the time range you select on the front panel. For example, if you select a range of $20 \mu\text{sec}$, then 5 V represents $10 \mu\text{sec}$, 2.5 V represents $5 \mu\text{sec}$, etc. However, you should check these numbers using the time calibrator (see below).

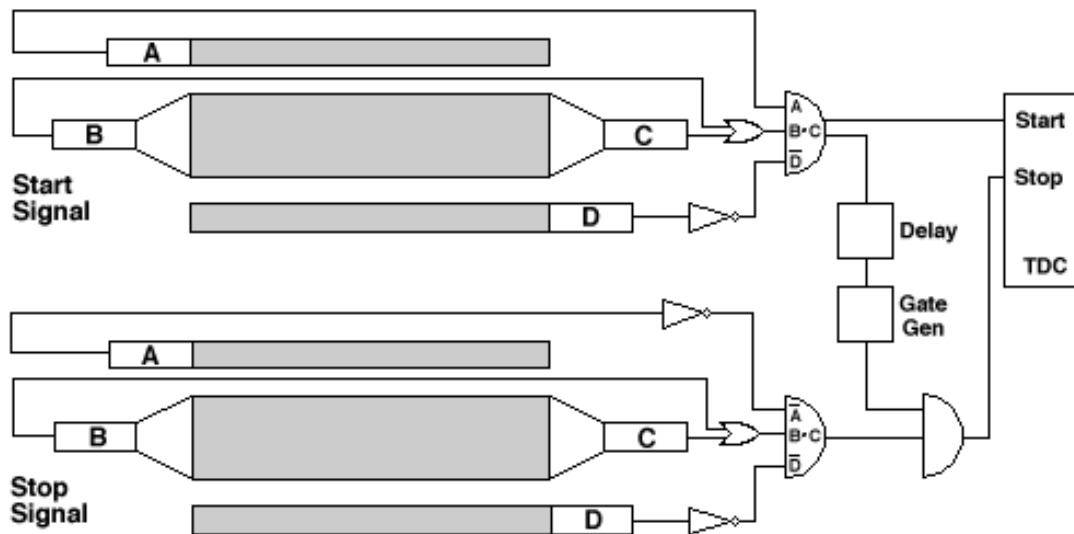


Figure 3. The basic logic for start and stop signals in the muon lifetime experiment

It is difficult to see the signal from the TAC on the scope when using the signals from muons. However, it is easy to see the TAC output when using the time calibrator. You should do this now, using reasonable values for the time calibrator parameters (see below). In other words, we will temporarily replace the inputs to the TAC with signals from the time calibrator as explained in step 5. In addition to viewing the TAC output, also observe the SCA (single channel analyzer) output on the scope.

We will need a “trigger” signal to tell the computer when to sample its input from the TAC. Ideally, this trigger would occur at the center of the TAC signal. See Figure 4. To create the trigger, take the TAC’s SCA output and delay it about $0.5 - 0.75 \mu\text{sec}$. Then put the signal through the gate generator and shorten it to about $1 \mu\text{sec}$. Use the TTL output (not the NIM) to trigger the computer. Also connect the TAC output to the analog input of the computer. Use the LabView 8.5 program “Muon Lifetime 2010.vi” to acquire data.

5. Using the model 462 time calibrator:

To check the bin size more precisely, we will use the calibrator. The model 462 can produce its output pulses with a precision and stability in the $\sim 0.05 \text{ ns}$ range. It works by sending out pairs of pulses -- a start pulse, and then a stop pulse after a random interval. This random time interval is equal to nT , where T is the “period” you chose by a front panel switch and n is a random integer. The multiplier n ranges from 1 to n_{max} , where n_{max} is determined by the “range” R (also selected via front panel switch), according to the equation $n_{\text{max}}T \leq R$. As the calibrator produces pairs of pulses, the integer n will vary randomly within $1 \leq n \leq n_{\text{max}}$. Notice that you must choose $R > T$, or else you will not get any pulses.

Also note that you must send the 462's stop and start pulses through a discriminator to convert them to the type of NIM pulses used in the rest of the experiment. Otherwise they are not the correct shape that the TAC requires as input. Accumulate a spectrum of pulses, save your LabView data to a file, and determine the relation between time and voltage.

6,7. Accumulate a short run of data to check that everything is working, and accumulate a long (overnight) run to get data with good statistics:

Take a short data run. In about half an hour, if everything is working, you will see a very rough exponential histogram. If so, take a long run overnight or over a weekend.

Hints

1. Set the widths of the output pulses from the discriminators to be short, say $\sim 20 - 50$ ns. All widths should be the same. The discriminators also have an input threshold control. This allows you to ignore low-energy noise pulses. Note that the monitor voltages are scaled up by a factor of 10 from the actual threshold voltages.

Note that if you set the discriminator output pulses too wide (say, greater than 500 ns), they will become distorted and shallow. It may appear that the discriminator is not working at all. To make the pulses shorter, turn the adjustment screw CCW. Turn CW to make them longer. BE VERY GENTLE WITH THE ADJUSTMENT SCREWS – THEY ARE DELICATE!

2. Recall from the introductory experiment on electrical pulses that impedance matching is very important when working with fast signals. You must make sure you are using cables of the correct type in this experiment. We have been using cables with 50Ω nominal impedance, such as RG 58A/U, RG 58C/U, RG 223/U, and RG 174/U. If other types of cables with different characteristic impedance get mixed in with the 50Ω ones, your signals will become distorted and the experiment will not work well.

You must also terminate the inputs to the scope, with 50Ω .

3. With the LeCroy model 365AL Logic Unit, the “Veto” input can be used as a “Not” function. For example, suppose the “A” input is connected to a Veto input. Then if a signal is present from A, the output of the Logic Unit will be zero (i.e. “false”), regardless of the condition of any of the other inputs. Therefore “Veto A” is equivalent to “AND \bar{A} ”.
4. The model 365AL can also be used for “OR” functions. For example, if three inputs are connected, and “Coinc. Level = 2” is selected, then when any two (or more) of the input signals are “on”, the output of the Logic Unit will be “true”.
5. The LeCroy model 465 Coincidence Unit can be used as an “AND” function.
6. The fan-out creates duplicates of its inputs. So if you need to wire a certain logic signal to multiple inputs, use the fan-out. Don't try to split the signal with “tees”; not enough current will be produced.

7. If you need to add or remove any NIM units from the crate, make sure the bin power is turned off!
8. The DAQ board in the computer requires TTL pulses, not NIM.
9. When you want to turn off the power supplies, set all the knobs to zero first (slowly!).

References

1. William R. Leo. Techniques for Nuclear and Particle Physics, a how-to approach

Read sec. 7.1 – 7.2

Read chapter 16

Our experiment is similar to the one on p. 315. but we will not be using a layer of lead.

We will look at signals from muons that become trapped and decay in scintillator “B”.

Read sec. 12.3

Skim chapter 14, 8

2. Adrian C. Melissinos. Experiments in Modern Physics.

Ch 9, Sec. 2.3: Operation of a Coincidence System

Explains how to adjust the delays on signals coming from the discriminators. Ignore all the parts that look “outdated”. Ignore all the stuff about clipping the pulses with cable stubs – our electronics can make the pulses as short as you want. Also ignore the part about building the mercury switch pulser. You need to make graphs like figure 9.13.

3. Muon Lifetime special notes and supplement to special notes.

Two volumes of articles about muon physics and various muon lifetime experiments, and excerpts from user manuals for equipment used in our experiment. Located in room 2087 next to the experiment. Please do not take them out of the lab. You can xerox portions of the booklets if needed.