SU QuarkNet Workshop 2012 — Lab Activity 1
MEASUREMENT OF THE MUON LIFETIME

Laboratory Goals

1. Learn about cosmic rays.
2. Understand the concept of a particle lifetime.
3. Take data using an actual HEP experimental setup.
4. Apply statistical analyses to a real problem in particle physics.

1. INTRODUCTION

Interstellar particles that impinge upon the earth are called *cosmic rays*. Such particles must be stable in order to travel the enormous distances from either within our galaxy or other galaxies to reach the Earth. The only truly stable particles we know are protons, electrons, neutrinos (and their antiparticles) and photons. Most of the primary cosmic rays are indeed protons, but there are also some stable nuclei.

Cosmic rays have been studied extensively starting in the 1920's and studies still continue today. Several particles have been discovered in cosmic rays. The muon is one of these particles. It was discovered in 1937 by J.C. Street and E.C. Stevenson and almost simultaneously by C.D. Anderson and S.H. Neddermeyer. However, for many years physicists thought this particle was the then theorized carrier of the strong force, the pion. Eventually they realized that this supposed pion actually did not interact through the strong nuclear force, and therefore could not be the theorized pion. They then renamed it the muon and the real pion was eventually discovered.

To produce muons, primary cosmic ray protons interact in the upper atmosphere and produce pions. These pions with a mass 273 times that of the electron are not stable. They decay *radioactively* into muons. The muons that are so produced, due to their longer lifetime and almost complete absence of nuclear interactions are the principle components of penetrating particles produced by cosmic rays that are observed at sea level; the sequence of events is illustrated in Figure 1.

The particles arriving from space are known as primary cosmic rays whereas the particles created in the collisions are known as secondary cosmic rays. Many of the new particles are very short lived and do not survive to reach sea level, but positive and negative pions created in the process decay into muons that are detectable at ground level. The total secondary flux at sea level is about 1 cm^{-2} min^{-1}. (See pdg.lbl.gov for more information). Roughly 75% of the flux consists of positive and negative muons, 25% of it consists of electrons and positrons. If the negative muons stop in matter then they can be captured by atoms whereas the positive ones remain free. The mean lifetime of both positive and negative free muons is a few µs (10^{-6} sec). Some µ$^-$ can be captured by atoms and these have a slightly shorter lifetime.
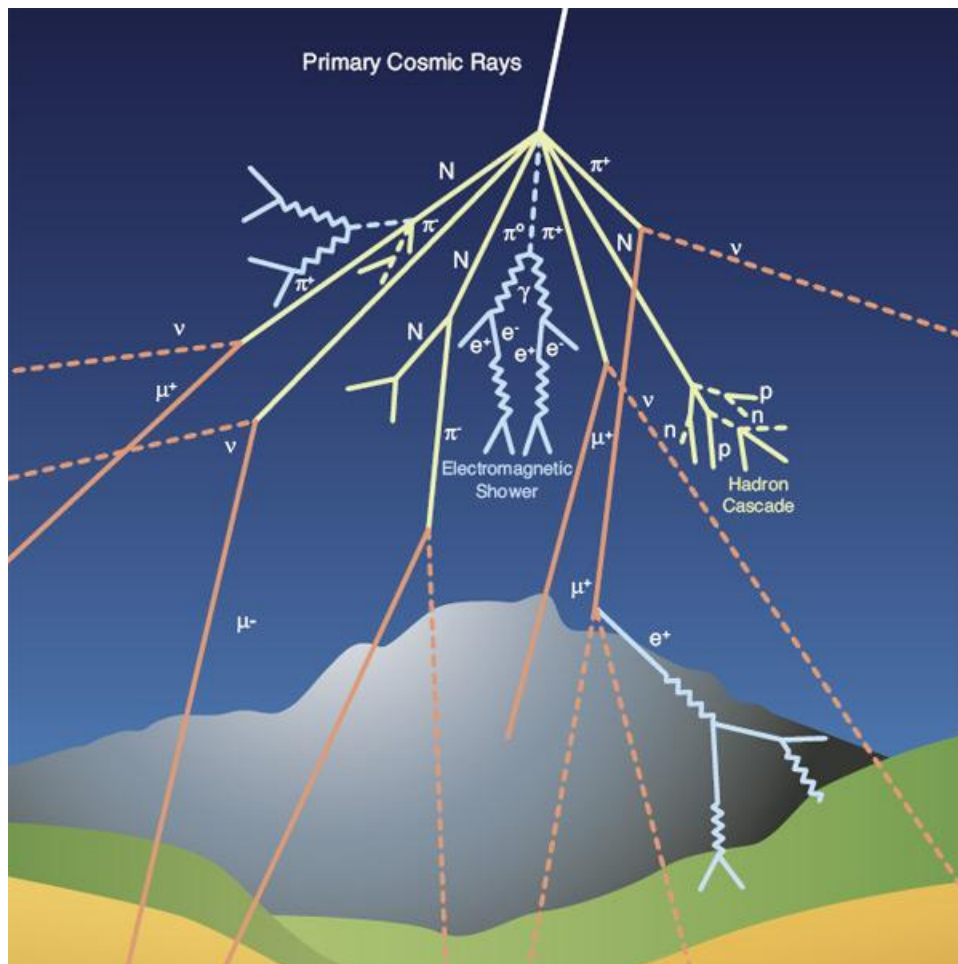
Figure 1. Diagram of a typical interaction between a cosmic ray proton and an atmospheric nucleus. Both electromagnetic and hadronic showers are created. From [9].

According to classical physics, if the mean lifetime of the free muons is a few μs then they should only travel a few hundred meters when traveling at the speed of light after being created in the upper atmosphere and many fewer than that indicated above would be expected to reach the ground. The only way to explain the large number of muons detected at sea level is through relativistic time dilation.

Muons continue to be of interest in many areas of physics, including precision studies of its magnetic moment (g–2), in investigating the structure of materials using spin-relaxation techniques.

2. RADIOACTIVE DECAYS

The physical mechanism that causes both pions and muons to be unstable is described by the theory of the weak interactions. It is quite natural that particles, states of nature, decay. In fact, particles are stable only if some rule forbids them to decay. For example, if there are no other particles of lower mass for them to decay into.

Consider any system of N particles where the probability to decay (or transform in any manner) is proportional to the total number present. Call the number that decay in a short interval dN. Then

$$dN \propto N, \text{ or } dN = -\lambda N ,$$

$$\frac{dN}{N} = -\lambda$$

where $\lambda = c$ is an arbitrary constant, called the decay rate. The negative sign indicates that the change, dN is a decrease. Integrating both sides of the equation from time to t_o time t, where the starting population is N_o at time t_o and N at time t gives

$$\int_{t_o}^{t} \frac{dN}{N} = -\int_{t_o}^{t} c$$

$$\ln\left[N(t)\right] - \ln\left[N(t_o)\right] = -c(t-t_o)$$

$$\ln\left[\frac{N(t)}{N(t_o)}\right] = -c(t-t_o)$$

$$\frac{N(t)}{N(t_o)} = e^{-c(t-t_o)}$$

Let us now take $t_o = 0$. Identifying $N_o = N(t_o)$ as the number of particle present at $t = t_o$, we then have

$$N(t) = N_o \, e^{-\lambda t}.$$

Identifying the lifetime (call it τ) as the inverse of the decay rate (e.g. $\tau = 1/\lambda$), we can write the master equation for radioactive decay as

$$N(t) = N_o \, e^{-t/\tau} ,$$

which is in the form of an exponential distribution. This is the equation of interest for this experiment.

3. EXPERIMENTAL METHOD FOR DETERMINING THE MUON LIFETIME

Muons decay via the weak decay process

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu \qquad \mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \qquad , \qquad \text{(Eq.1)}$$

where the νs are neutrinos, the subscripts indicate if they are electron-like or muon-like, and the bars indicate particle or antiparticle. This decay is illustrated in Figure 2.
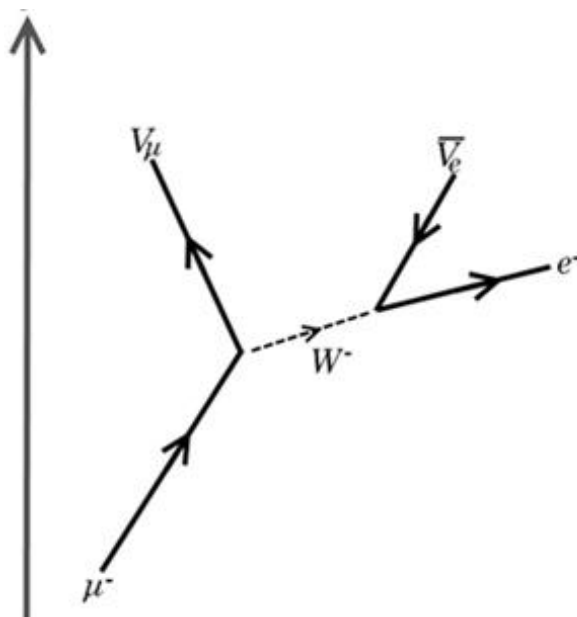
Figure 2.   Feynman diagram of the decay of a muon. Time is represented on the vertical axis. The decay proceeds as given in Eq. (1) in the text.

We use a tank filled with a liquid scintillator. This material is mineral oil with organic additives that are transparent and emit light when a charged track passes through. There are photomultiplier tubes placed at the top and bottom of the tank. It is possible, even usual, to do this experiment with only one such tube, so let's concentrate on that for now. The photomultiplier tube is capable of sensing photons produced by the liquid scintillator. It consists of a glass window, the inside of which is coated with a chemical mixture that is efficient at converting single photons to electrons (this part is called the *photocathode*, since it acts as a cathode). After the *photoelectron* is produced it is accelerated by an electric field until it hits another structure called a dynode. There it smashes into a metallic surface and produces more electrons. Photomultiplier tubes have several stages, usually 6 to 12. The tubes we are using have 12 stages. High voltage is used to accelerate the electrons between each dynode. This is usually supplied with one input and then the voltage is divided by a unit that is called the "base," because it plugs into the phototube. The typical conversion efficiency, the fraction of photons that make electrons, depends on the wavelength of the photon, but is around 16%. (This is usually called the "quantum efficiency"). It is made up of the efficiency of the photocathode and the collection efficiency of the first dynode. Many photons are produced when a charged particle

passes through the liquid scintillator. The number collected depends on several factors: the number produced, the collection efficiency and the quantum efficiency of the phototube.

Many muons pass through the liquid scintillator producing light and signals in the photomultiplier. We are not interested in the ones that traverse the tank fully. Occasionally one of them stops in the tank. Basically it gets slowed down by losing energy due to ionization and comes to rest. Subsequent it decays as discussed above. From these stopping muons we get two pulses: one from the muon and a second one a short time later from the electron arising from the muon decay. The time delay between the two signals is measured for a large number of decays and produces an exponential distribution.

We use two phototubes and make sure that they both produce a signal at the same time (this is called in "coincidence"). The reason to do this is that phototubes can produce a signal when there is none because an electron is spontaneously emitted from the photocathode or one of the early dynode stages. The phototube signal is typically quite short, ~10 ns. The output from the PMT is passed to a discriminator, an electrical circuit that fires if a signal is above a preset level (called the "threshold"). If a signal is above the threshold, a logic pulse is output with an adjustable width. The discriminated logic pulses are send to another electrical circuit called a coincidence unit. This unit produces a logic pulse if signals from both PMTs are present at the same time. (Descriptions of some of these circuits are available at PREP at FNAL). Output of the coincidence unit is sent to a special card in a PC that starts a counter, with a counting rate of 10 MHz, implying a resolution of 0.1 μs. If a second pulse (from the $e^{\pm}$) arrives after the first, the counter is stopped and the PC signaled to indicate that the counter has stopped and is ready to be read. A program running on the PC records the time interval and resets the electronics so it is ready for more decays. If a second pulse does not arrive, the counter continues until a count of 25.5 μs is reached. Then the circuit resets itself. It is possible to achieve an error of about ±0.04 μs with a few days of running.

4. APPARATUS

4.1. Description of the Apparatus

The basic components of the experiment were described above. They are: one tank (filled with liquid scintillator), two photomultiplier (PMTs) with electronics attached to them and a computer with ADC board. See the diagram shown in Figure 3.

Also you need one multi-channel discriminator (LeCroy 321B), one dual 3 fold logic unit (LeCroy 162); one level adapter (to convert from NIM logic level to TTL level), one scalar (ORTEC 770) to monitor the counting rate independent of the computer, one interface board (Multi-Function I/O Card NI 6023E), used to measure time, and LabVIEW software to interface with the card and record timing signals on the disk of the computer.
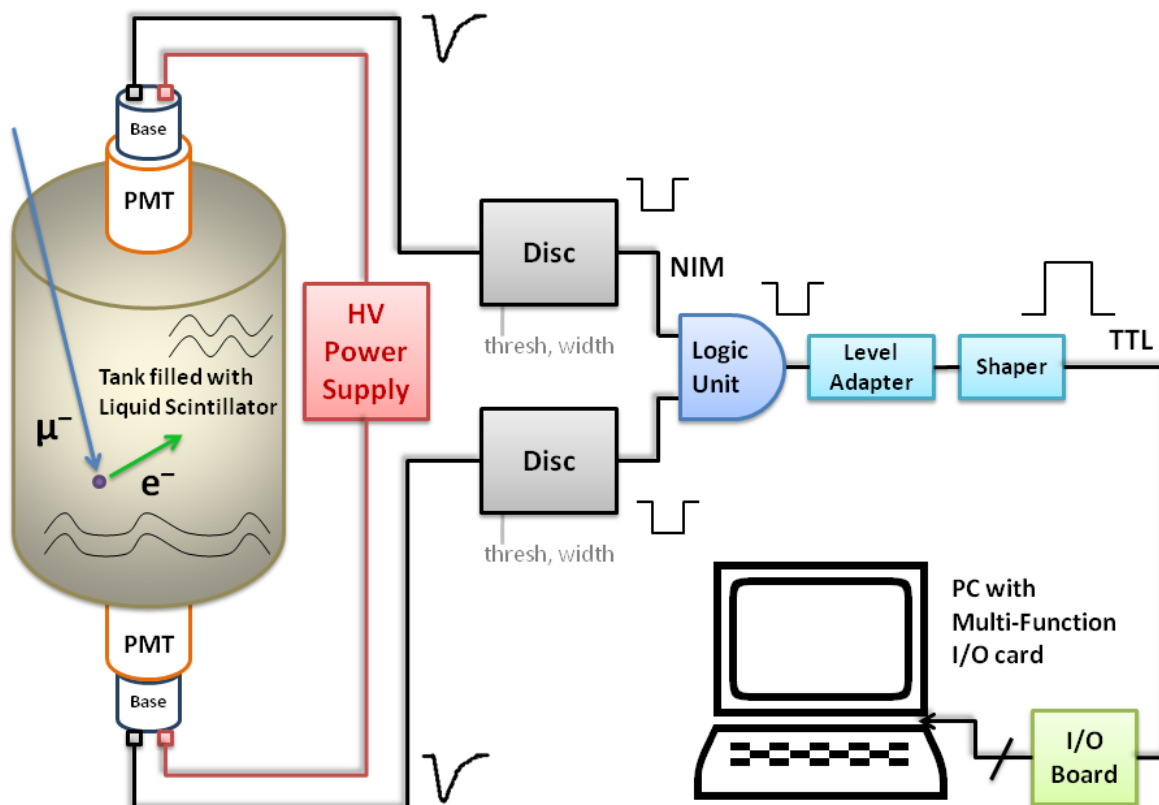
Figure 3.   Block diagram of the muon lifetime experiment. Shown are the functional units as well as the type of signal produced at each stage.

5.1. Set Up the Apparatus

Follow the description below and check that all the connections are made properly and that you understand the details of the setup.

SAFETY PRECAUTIONS:

- Be careful of the high voltage (the two red cables). Handle by connector only.
- Make sure your connections (especially the high voltage setting) are correct to avoid damaging the photomultiplier tubes.
- *Before you turn on any high voltage ask the instructor to approve the setup.*

1. Set the high voltage of the photomultipliers. There are two wires connected to each photomultiplier, the red one is for high voltage and the black one is for the signal. The voltage of the PMTs should be set as negative 2800 V. Key in the number on the digital switches on the front of the power supply.

2. Connect the signal wire of the PMT to discriminator (model 321B, quad discriminator), choose inputs labeled 1, 2 or 4 to connect (3 is broken).

3. Connect the corresponding output of the discriminator to the DUAL 3 FOLD LOGIC UNIT. (Actually we will only use two of the inputs, so we could have used a 2 Fold unit, but this is what we had available.) To record the coincidence of top and bottom PMT, connect the two signals to DUAL 3 FOLD LOGIC UNIT input. Only one output signal comes from the logic unit, and is input to the converter. Then connect the output to the interface board (green card on the table, which is connected to the computer). Make sure you do not touch the connections on the interface board. On the interface of the discriminator and the logic units, you need to terminate with 50 Ω the extra input and output connectors to make sure the signals are not influenced by them.

4. Make sure the connections are correct, *check with the instructor*, and then turn on the power to the PMTs.

5.2. Test the Apparatus

Now the various modules should be tested to make sure signals are being produced and processed. Using an oscilloscope and a counter, we can observe pulse shapes and event counts at the output of various modules.

1. Look at the pulse shape of the photomultiplier signals coming from the top and bottom PMTs. The cable that is connected to channel one (labeled channel A) of the discriminator is connected to the top PMT, and the cable that is connected to channel 2 (labeled channel D) of the discriminator is connected to the bottom PMT. Take channel one out of the discriminator and put it into channel one of the oscilloscope. Do the same for channel two, and observe what the pulse looks like from a PMT.

2. Look at the discriminated PMT signal. Put both cables back into the input of channels 1 and 2 on the discriminator. Then, connect the outputs of the discriminator to the oscilloscope. First, do each channel separately, and then look at them together. Are the pulses coincident in time? (i.e. overlapping?) What is the difference between the PMT signal and the discriminated PMT signal? You can adjust the widths and amplitudes of the pulses to get familiar with the oscilloscope, but set the final width to 25 ns.

3. Look at the count rate of the discriminated signal. Take the cables out from the oscilloscope, and put either one into the NEGATIVE output of the ORTEC counter (this is the brown module all the way on the right in the crate). Turn the module on if it is not already, and flip the count switch. You can estimate the rate in Hz by leaving it on for ten seconds and then dividing the count by ten. After you look at one channel, look at the other. Note the singles count rates.

4. After the discriminator, the next module that the signal goes through is the logic unit. Unlike the discriminator with two inputs and two outputs, the logic unit has two inputs and one output. Take the outputs of the discriminator and put them into the inputs of the logic unit. Make sure the coincidence level is set to two. Next, take the one output of the logic unit and look at it on the oscilloscope. What does it look like now? Finally, you can look at the count rate at the output of the logic unit. This is done in the same fashion as before.

5. DATA-TAKING

Put all cables back in their proper configuration. Check with the instructor that it is again set up correctly. If so, you are ready for data-taking.

1. On the PC, open the LabVIEW program called **Muon Lifetime v3.v**i. This program is written in the LabVIEW package, a modern program used widely to acquire data. You will see two data collection graphs. The left plot will display the difference between start and stop times when it is between 50 ns and 10 μs (or the settable limits on the front panel). You can change the vertical scale during the data collection if you like. The right plot will give the histogram of the time difference.

2. Click the RUN arrow on the top-left of the window to start collecting data. You will be asked to specify a file to save the data. You should name this file. If you happen to stop the run at any time, the file will be appended to if you start up again and give the same file name.

3. Let the data-taking continue overnight. The data rate is small, so you will need that time to collect enough events to get a reasonable measurement (~150 events or more).

6. DATA ANALYSIS

After you collecting sufficient the data, end the run. Look at the file you saved and you will see two columns of data. The first is the different time intervals for each muon's decay. These data must be separated into bins of equal time units. This is called a histogram. The time interval will depend on how much data you have recorded, since we want to make sure that all bins have at least a few events.

To make this histogram, you can use Origin. Open the data file (make sure the data is set to ASCII data). Select the column of data and then go to descriptive statistics, frequency count, and then hit apply and okay. Then select the first two columns, hit plot, and select scatter plot.

6.1. Find the Mean Lifetime

As with all measurements of physical quantities, determining the mean lifetime yields a number to which we need to assign an error. A measurement without an assigned error is meaningless, not just an oversight. If there is no error assigned, there is no way to evaluate whether your result is any different than any other possible result–different from zero, for example. Errors are of two types: statistical (dependent on the number of events in your data set), or systematic (depending on instrumental bias, outside influence, operator error, etc.)

There are many ways to calculate the mean lifetime. The best method is to fit the histogram with an exponential decay fit. The idea is that we can minimize the differences between the hypothesis of an exponential distribution and the data points and this minimization gives the best value of the lifetime. When the graph is open, click on analysis, exponential decay, and then first order. Origin will fit the graph and open a box that shows the parameters. The value for the mean lifetime is the decay constant t1. Be sure to write down the error for this number as well.

A second way to calculate the mean lifetime uses the fact that the ln of an exponential is a straight line and 1/slope of this line is the lifetime. If this does not make sense, try to convince yourself of this by looking at the equation for exponential decay that was stated earlier in the lab. To do this in Origin, right click on any number on the VERTICAL axis of your graph. Change the scale to ln. Then, do a linear fit to get the slope. The lifetime is just 1/slope.

A third way to calculate the lifetime is simply looking at the mean that was calculated when you made your histogram (Origin automatically calculates the mean, standard deviation and total events when you make a histogram and writes it down in the "logbook" in the lower right). You should calculate the standard error in the mean, as you have all the values you need.

6.2. Sources of Systematic Errors to Check

1. You might want to check the relative timing of the two phototubes. The signals from the phototubes come along a 50 Ω cable with a speed of about 1 ft/ns. The pulses may not be arriving at the coincidence unit at the same time. You can check this using the oscilloscope, just trigger on the pulse from one tube and see where the second tube signal is relative to the trigger. You can adjust the timing by adding or reducing the cable lengths.

2. You might want to insure that the discriminator output widths are sufficiently wide to take into account any jitter in arrival times of the phototube pulses, from for example where in the tank the muon decays.

3. In all real experiments there are many other data collection modes that are designed to specifically test for backgrounds or other systematic effects. You might want to try evaluating some of these by trying some of the next tests or others that you may devise. For example, take data using only one phototube. How will this affect the outcome?

6.3. Further Analysis and Open Questions

1. Report the value of the muon lifetime, the statistical error and the systematic error. Include a discussion of any checks you did to verify the systematic error. Note how the experiment could be improved.

2. Using your value for the lifetime estimate the mean momentum muons must have in order to reach the Earth's surface, about 15 km below the place in the atmosphere where muons are created. Here you must take into account relativistic time dilation.

3. Consider why don't you have to worry about relativistic time dilation in analyzing your data? This is a very important question from early 20th Century physics.

7. REFERENCES

[1] E. U. Condon and H. Odishaw, Handbook of Physics, New York: McGraw Hill(1967). See Page 9-159 for overview of muon nuclear capture.

[2] R. E. Hall, D. A. Lind, and R. A. Ristinen, "A simplified Muon Lifetime Experiment for the Instructional Laboratory", Am. J. Phys, 38, 1196 (1970).

[3] Physics Education Vol. 33(5) September 1998 page 296-302.

[4] A.C. Melissinos, Experiments in Modern Physics, Academic Press, New York (1966).

[5] B. Rossi, Cosmic Rays, McGraw-Hill, London (1964).

[6] M. W. Friedlander, Cosmic Rays, Harvard University Press, Cambridge (1989).

[7] W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd ed., Springer-Verlag, New York (1992).

[8] D. C. Baird, Experimentation: An Introduction to Measurement Theory and Experimental Design, Prentice-Hall, Englewood Cliffs, New Jersey (1962).

[9] DUSEL Experiment site [http://www.deepscience.org/contents/summary.shtml]