Mean Lifetime of Muons in Matter

INTRODUCTION

Cosmic rays with energies ranging from 10^8 to 10^{20} eV continually bombard the earth. These electrons, nuclear particles and photons are thought to be released in supernova explosions. They interact with particles in the Earth's upper atmosphere producing secondary particles including pions and kaons, which subsequently decay to muons:

$$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu} \text{ and } K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$$

The lifetimes of the pion and the kaon are on the order of 10^{-8} sec (The exact values may be found in the Particle Data Booklet, http://pdg.lbl.gov/). These are weak decays:

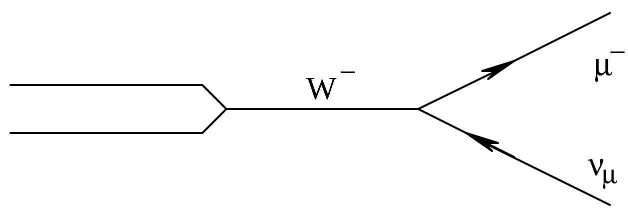


Figure 1 shows the components of cosmic ray flux. At sea level, about 80% are muons. The rest are electrons and protons. The flux is on the order of 10^{-2}/cm^2 sec sr.

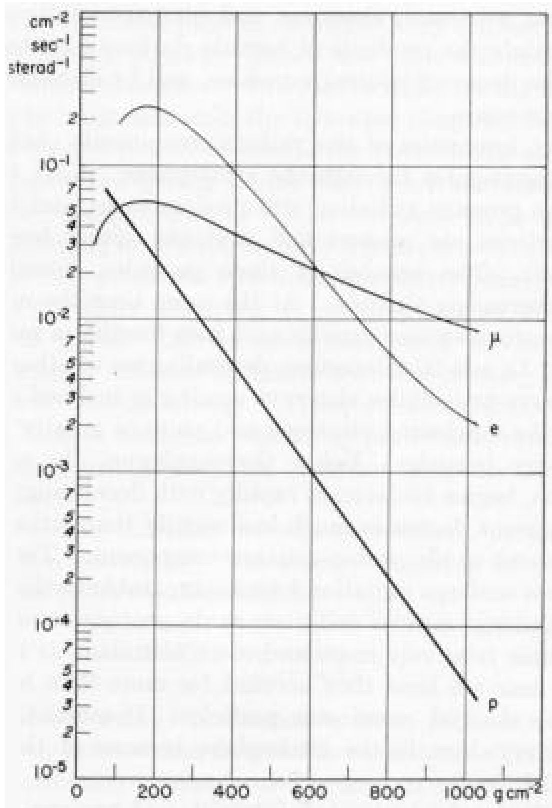


Figure 1. Vertical intensities of various cosmic-ray components at 50° geomagnetic latitude as functions of atmospheric depth. (B. Rossi, *High Energy Particles*, p. 8.)

Muons are unstable particles with the same charge as electrons but approximately two hundred times the mass. Positively charged muons decay into a positron, muon antineutrino and an electron neutrino:

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

The corresponding antimatter decay is:

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

The μ^- can also be captured by the nucleus via

$$\mu^- p^+ \rightarrow n \nu_\mu$$

The probability of capture depends on the atomic number Z of the absorbing material and goes like Z^4 for small Z. For example, the lifetime due to nuclear capture, $\tau_{capture}$, is 1.93 μsec in carbon and 0.142 μsec in iron (Rossi, p. 170). The lifetime measured in this experiment will reflect both decay and capture since the positive and negative muons are not distinguished from each other. Figure 2 shows the different lifetimes of positive and negative muons in aluminum.

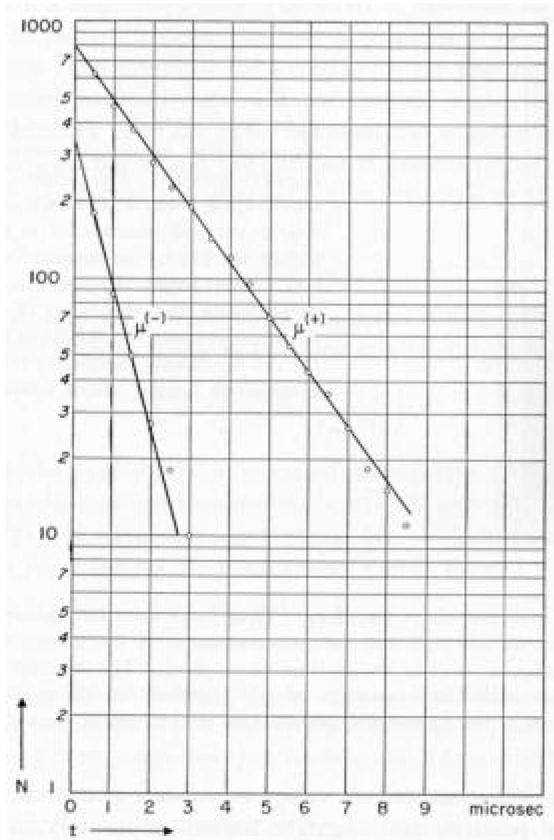
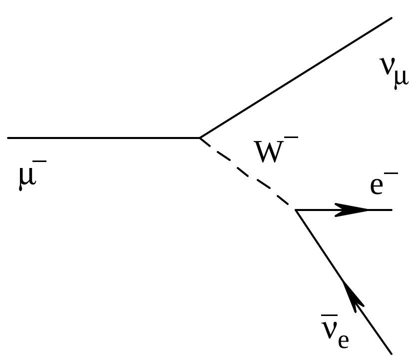


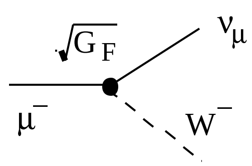
Figure 2. Disintegration curves of positive and negative muons in aluminum. (Rossi, p. 168.)

We measure the lifetime of positive and negative muons in a scintillator. The muon decay is characterized by an exponential. If we have $N(t)$ muons at time t, then $dN = -N\Gamma_m dt$, where Γ_m is the decay rate. The solution of this differential equation is $N = N_0 \exp(-\Gamma_m t)$, and thus the number of muons decaying at time t is $-dN/dt = N_0 \Gamma_m \exp(-\Gamma_m t)$. One can measure the lifetime $t_m = 1/\Gamma_m$ by fitting the observed decay rate.

The muon decays weakly via



The neutrinos are not detected in our apparatus. The probability that this decay occurs depends on the couplings



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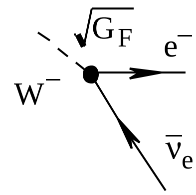


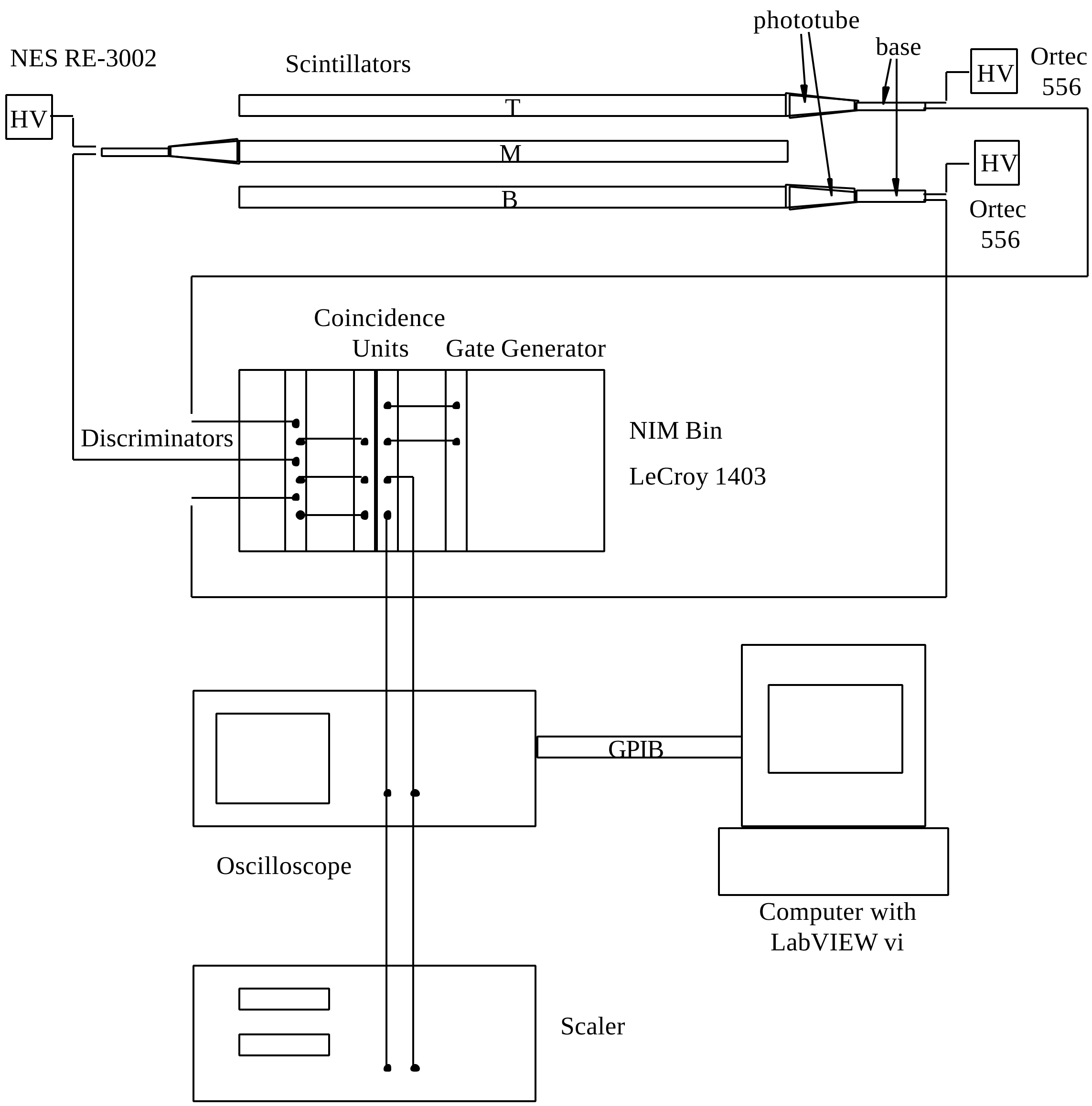
where the Fermi constant G_F is the strength of the coupling of the weak force. Since the decay rate Γ_m is proportional to the square of the amplitude of the above diagram, one expects $\Gamma_m = 1/t_m \propto G_F^2$. In fact, the lifetime of the muon is:

$$t_m = \frac{192 p^3 \hbar^7}{G_F^2 m_m^5 c^4}$$

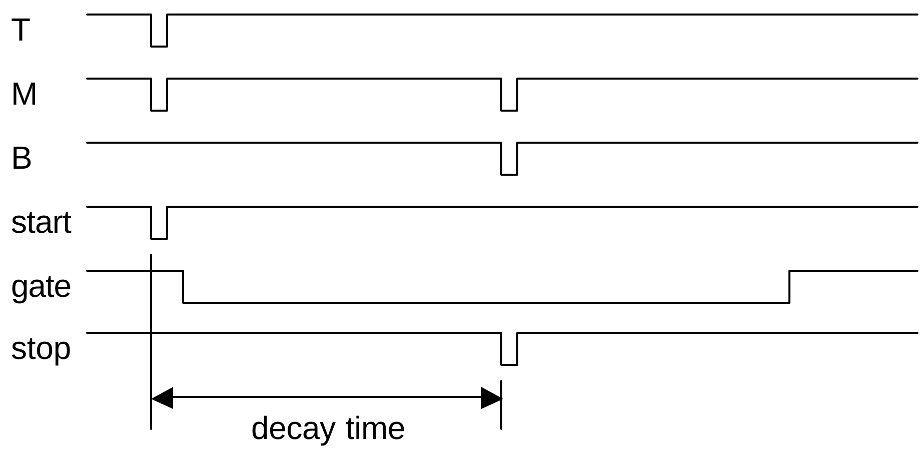
where m_m is the mass of the muon. If we measure t_m and m_m, we have found G_F !

APPARATUS AND INSTRUMENTATION

The main part of the apparatus is three plastic scintillators stacked vertically. The scintillator material (polystyrene plus a phosphor, p-terphenyl) emits a light pulse when an ionizing particle deposits energy in it. The light pulses are converted into electrical pulses by the photomultiplier tubes (PMTs). The signals from the three PMTs are detected by the discriminators, which generate logic pulses when they receive signals larger than a predetermined threshold. Coincidence units and a gate generator form the trigger logic that defines when the events should be captured by the digital storage oscilloscope. The computer and LabVIEW data acquisition programs transfer information from the scope, record and plot the data. A “home-made” scaler counts the number of triggers.



In the lifetime measurement, the particles of interest are the muons that stop in the middle detector. Only a small fraction of the incident muons stop. A typical muon incident upon the apparatus has energy of 20 GeV and only loses about 10 MeV in the plastic scintillators. The signature of a muon, which does stop in the middle detector is a pulse in the top (T) detector, in coincidence with a pulse in the middle (M) detector as well as no pulse in the bottom (B) detector. We call this triple coincidence our "start" signal: i.e., $start = T \wedge M \wedge \overline{B}$. We determine the lifetime by measuring the delay between this signal and the subsequent signal that has an electron signature. The simplest electron signature is any pulse from the middle detector, i.e., $stop = M$. One could also stop on an electron that goes back up ($T \wedge M \wedge \overline{B}$) or one that goes down ($\overline{T} \wedge M \wedge B$).



We are only interested in stop pulses that follow a start pulse within a small time window. One can define a "gate" pulse, using a delay gate generator that starts shortly after the "start" pulse and has a width of, e.g., 10 times the expected muon lifetime. The "stop" signal is then defined as an AND between an electron signature and the gate pulse.

The delay measurement is repeated for a large number of muon decays. A histogram of the results should show a negative exponential distribution.

Scintillation Detectors

The scintillators are made of clear plastic. A small amount of phosphorescent material added to the plastic emits light in response to stimulation by ionizing radiation. The light is bluish to soft UV (distribution centered around 450 nm). The plastic is wrapped in a reflecting layer and then covered with black plastic to keep out ambient light. The body of the detector is long, flat and thin. It is coupled to a photomultiplier tube by a trapezoidal light pipe made of the same plastic. When the cathode of the photomultiplier is struck by a photon of sufficient energy, an electron is liberated through the photoelectric effect. The cathode is operated at a large negative voltage. The photoelectron is accelerated toward the next electrode, called a dynode, which is held at a potential closer to ground. The energy gained by the electron is sufficient to liberate several electrons from the first dynode. A series of dynodes creates an avalanche effect, multiplying the original electron by a factor on the order of 10^8. The electrons are collected at the anode (the last electrode) and generate a fast, negative current pulse. A BNC coaxial connector on the base of the PMT is connected to the anode.

NIM Modules

Discriminator (LeCroy 821)

The purpose of the discriminator is to reject pulses smaller than a threshold. Input to the discriminators comes directly from the phototubes. The input pulse polarity is negative. If the amplitude of an input pulse is greater than the threshold, the discriminator gives an output pulse. If the amplitude of an input pulse is less than the threshold, the discriminator does nothing. A small recessed potentiometer is used to adjust the threshold. The threshold voltage times ten is present at a front-panel analog output. The output is a negative current pulse of 16 mA, which corresponds to a –0.8 V pulse into 50 Ω. This is referred to as a NIM pulse. The width of the output pulse is adjustable by another recessed potentiometer. The LeCroy 821 is a quad discriminator.

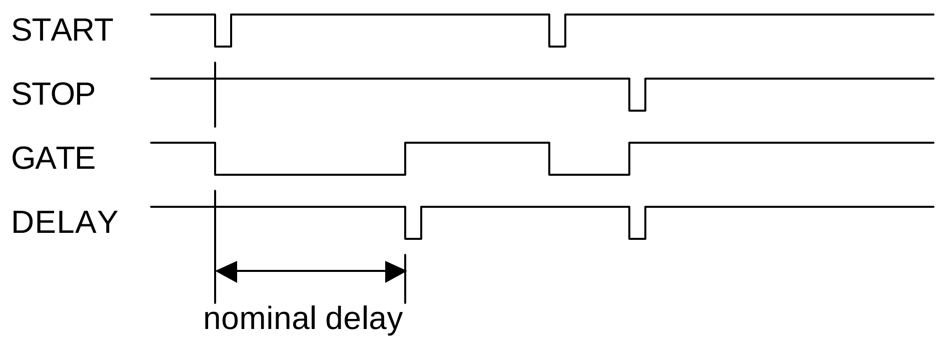
Coincidence Units (LeCroy 622)

Each unit has two inputs and a switch to choose between AND and OR. There are two pairs of NIM outputs, one fast negative output and one complimentary output. The width of the NIM output pulse is varied with a front-panel recessed potentiometer. The LeCroy 622 is a quad coincidence unit.

Note on "vetoing": When you try to form, e.g., $A \wedge \overline{B}$ by taking an AND of A and $\overline{B}$, it is important to make sure that the $\overline{B}$ pulse fully overlaps the A pulse. In other words, the $\overline{B}$ pulse must arrive earlier and stay longer than the A pulse. One can achieve this by delaying the A pulse using the coaxial line delay box (located underneath the scaler) and widening the $\overline{B}$ pulse.

Gate Generator (LeCroy 222)

The LeCroy 222 is a dual gate generator. Each channel has a START and a STOP inputs. There are two main outputs: GATE and DELAY. The former produces a pulse that starts immediately after a START pulse and has a width determined by the rotary switch and the potentiometer. The latter produces a pulse that starts when the GATE is closed. The STOP input (not used in this experiment) can be used to terminate the GATE prematurely.



In this experiment, one half of the 222 can be used to generate a delayed pulse, which in turn triggers the gate in the other half to produce the gate signal.

Data Acquisition

The Tektronix digital storage scope is used to capture the electronic signature of muon and electron decays. The "start" and the "stop" signals must be fed into the scope. The scope must be configured in such a way that:

- It triggers on "stop". The trigger mode must be normal (not auto).
- The horizontal range is adequate to capture both the "start" and the "stop" pulses for the longest possible decay time (=gate width). The position of the "stop" pulse must be close to the right edge of the screen.

A LabVIEW virtual instrument (vi) called "lifetime.vi" communicates with the scope and records lifetime data. The vi queries the scope for a measurement after each acquisition. If you choose to use a pulse from the middle detector only as a "stop" signal, the start and stop signals will be on the same channel of the scope, so the scope can be set to measure period on a single channel.

Another LabVIEW instrument called "pha.vi" queries the scope for the amplitude of a pulse. The "Min" measurement is appropriate for this since the pulses are negative. See the Tektronix manual for a complete description of the Measure function. The vi plots a histogram of the data and saves it to a file.

EXPERIMENTAL PROCEDURE

First, familiarize yourself with the equipment. Measure the dimension of the scintillators. Identify cables and find out which power supply is connected to which detector. Set the high voltage to –2.0kV to –2.2kV and observe the signals on the oscilloscope. Try to identify the pulses due to through-going muons (which tend to leave nearly constant energy to the detector) by triggering on one detector and observing another. For example, trigger on B and watch signal from T. Some tweaking of the trigger level will be needed to get a clear image. Switch the detectors. You may find larger time jitter in some combinations. Why?

Connect the signals to the discriminator. Adjust the high voltage and the discriminator threshold to optimize efficiency. This is an iterative process:

1. Set the high voltage and the threshold to some initial values. The high voltage should be around –2.0kV to –2.2kV. The discriminator threshold should be set between –50mV and –200mV. At this stage you are relying on known properties to set the rough operating parameters of the detectors.
2. Measure the **relative** efficiency of one detector as a function of its high voltage. To measure the efficiency of the middle (M) detector for example, measure the rate of the coincidences between (T&M&B) and between (T&B). The quotient (T&M&B)/(T&B) is the efficiency (ignoring the effects of the geometrical inefficiency and the random noise). If the voltage is set too low, the detector will be inefficient. If too high, noise will predominate. At intermediate voltages, a plateau should be observed. This is the desired operating regime.
3. Repeat 2 for other two detectors.
4. Now you have optimized the high voltage for the initial threshold setting. Next phase is a confirmation.
5. Measure the efficiency of one detector as a function of its discriminator threshold. Use the same technique as in 2. Repeat for all detectors.

You may have to repeat the process more than once if the initial setting was too far from the optimum.

Build the trigger logic with the coincidence and the gate generator modules. Check the relative timing of the pulses at the inputs of all the functional units. Remember: coincidence inputs must have good overlaps; veto input must be wider than the signal to be vetoed.

Once the logic is set up, record the complete schematic on the logbook. (You of course have a logbook, don't you?) The level of completeness must satisfy that "if your experiment is ripped apart during the weekend, you can rebuild it and it will work the first time." Don't forget to record the pulse widths and the delays. Also measure the counting rates for most, if not all, signals and record them.

Run the lifetime measurement. Try different "stop" signals. They will have different background level, which you can see as a constant component in your delay time distribution. While you are waiting for measurements, calculate how much data you will need to achieve, e.g., a 1% measurement of the muon lifetime.

Once the data are taken, fit the data. You may use any software packages you prefer. Popular choices are: Excel, CPLOT (available on the Linux box near the experiment), PAW. You need to learn how to use the software to fit the data to an exponential plus a constant background. You also need to be able to extract the error on the fit parameters.

If time permits, measure the pulse height spectra for muons and electrons and extract the muon mass. Consult the faculty or staff for details concerning the mass measurement.

LINKS TO UNIVERSITY WEB SITES

MIT

Rice

Caltech

PHOTOS OF APPARATUS

Electronics

Detectors

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