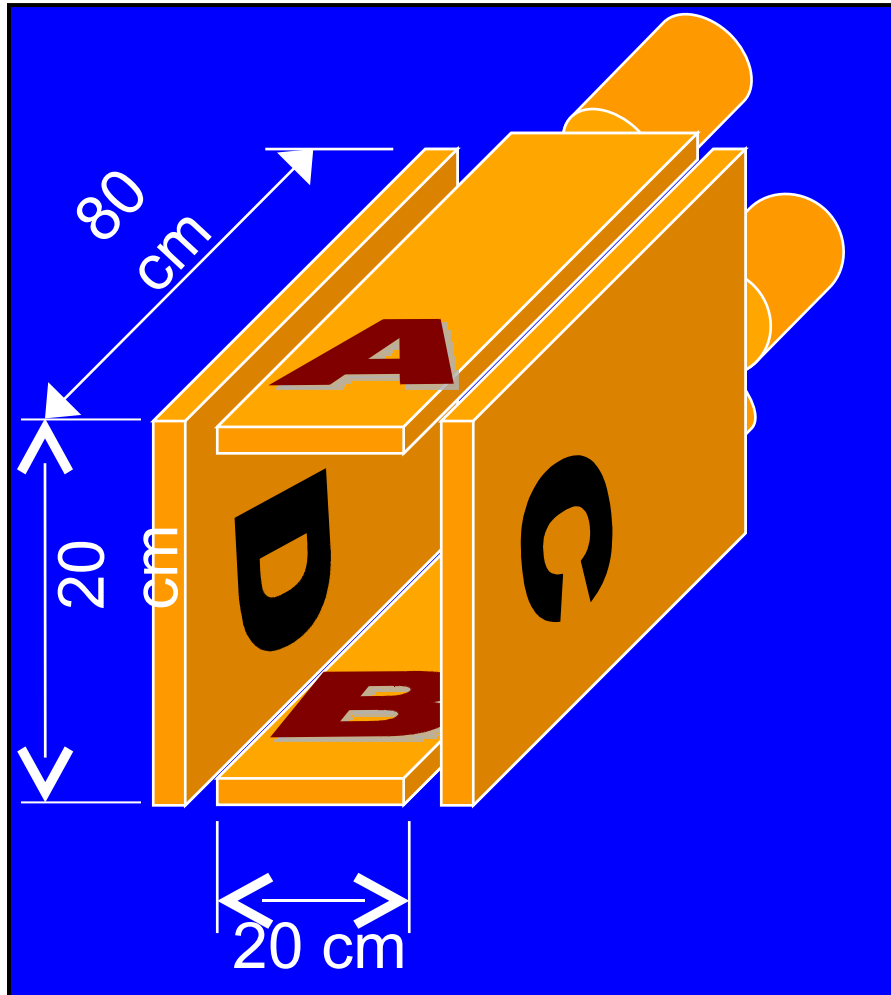


# Design of the Muon Lifetime Experiment

By Steve Kliewer



## Abstract:

This report develops the theoretical background and design criteria for a practical high-school classroom-ready experiment to measure the lifetime of the Muon particle. This planned device will use 4, low voltage, classroom safe scintillator detectors and a data acquisition electronics board developed by Quarknet of FermiLab. Analysis will be accomplished using web-based resources provided by Quarknet or specially developed software.

## Objectives:

The purpose of this project is to develop the hardware, software, and techniques for a system that can accurately measure the lifetime (decay constant) of the muon particle. It must be simple, safe, and easy to use in the typical high school classroom.

1. Scintillator Detectors: Build a set of 4, low voltage, classroom safe, detectors
2. DAQ: use the electronics developed by Quarknet (QNET2)
3. Analysis: Develop tools, and methods of analyzing muon lifetime data.
4. Design a practical classroom-ready Muon-Lifetime Experiment.
5. Document the process as well as the final result.

## What is a muon?

Muons in space

- Primary Cosmic Rays are particles accelerated by astrophysical sources:  
e.g. AGN, supernovae, solar flares
- Mostly made up of protons  
(some electrons and helium, C, O, & Fe nuclei)
- Energies from a few GeV to more than 100 TeV
- They are charged particles and therefore are affected by magnetic fields both interstellar as well as Earth's.

Cosmic Rays in our Atmosphere

- Primary Cosmic particles interact with our atmosphere via strong force, bremsstrahlung, Cerenkov radiation, as well as ionization
- Strong Interactions produce kaons & pions
- These particles decay almost immediately into  $\tau$ ,  $\mu$ ,  $e$ ,  $\gamma$ , &  $\nu$
- $\gamma$  rays interact by electron-positron pair production
- $\tau$  particles decay very quickly to  $\mu$  &  $e$ .
- electrons are quickly stopped by the dense atmosphere
- Most  $\mu$  are produced at 15km altitude; they lose about 2 GeV to ionization and arrive at the surface with a mean energy of about 4 GeV.

Cosmic rays at Sea Level

From the Review of Particle Physics:

- Mean energy is  $\approx 4$  GeV
- Energy spectrum ( $dN/dE$ ) is flat below  $\approx 1$  GeV
- Low energy Muons ( $E < \approx 1$  GeV) are mostly vertical. (Solid angle  $\approx 1$  sr)

## What is a lifetime?

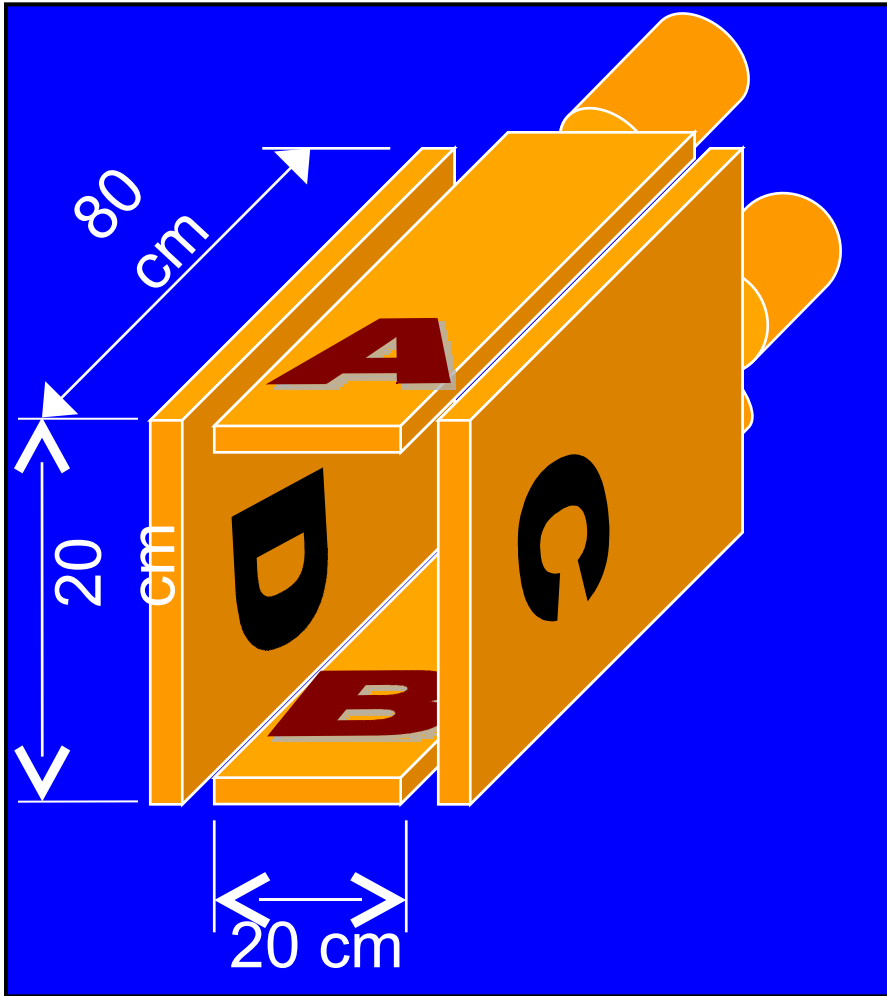
Muons decay randomly but with a fixed probability. Any one muon may or may not decay and the event is totally random. However, the expected number of decays in a large sample of muons can be statistically predicted with some accuracy. The decay rate is proportional to the number of muons in the sample. With time this number goes down. Therefore the decay rate observed in any sample goes down exponentially with time.

Muons, no matter how old they may already be, decay exponentially.

$$N = N_0 e^{-t/\tau} \quad dN/dt = -N / \tau$$

$\tau = -N / dN/dt$  this is the Muon Lifetime

**Basic Design:**



A muon enters thru A and is trapped in the cavity. After a time it decays and an electron exits thru A, B, C or D. A frequency graph of counts vs. decay time is analyzed

Timing starts when count: A and not (B or C or D)

Timing stops when count: A xor B xor C xor D or timeout

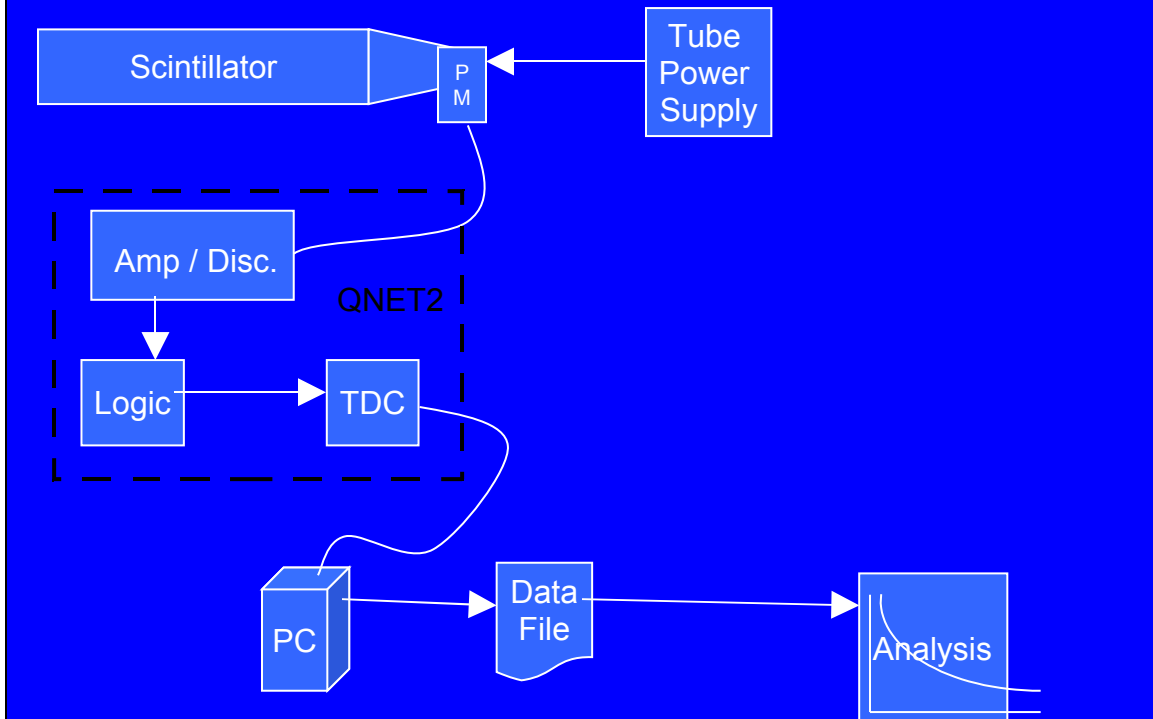
The cavity is filled with phone books (wood pulp) so as to maximize the trapping of muons and still minimize the loss of decay produced electrons.

$\rho$  = Density = 0.64 g/ cm<sup>3</sup>

V = Volume = 32000 cm<sup>3</sup>

A = Top Surface area = 1600 cm<sup>2</sup>

# Components



Four detectors are made from 20cm x 80cm x 2.5cm scintillator plastic with acrylic light guides. Mounted on each light guide is a Hamamatsu 931A photomultiplier tube with an HC123-01 low voltage base. Power to the bases is provided by a custom designed power supply that allows adjustment of a separate control voltage to each tube.

The output of each tube base is input to the QNET2 board where each channel has a separate discriminator voltage setting. This requires that each channel has two parameters (total of 8) that must have optimum settings determined and set. The QNET2 board communicates with a computer via serial connection. Using this connection, the data collection mode of the board can be set and data can be logged on the computer.

The logged data file can then be processed via the QNET.exe program or can be uploaded to the Quarknet website for analysis.

## ***Estimates of counting rates:***

The Particle Data Group at the Lawrence-Berkeley National Laboratory has posted an average expected cosmic ray rate of  $\sim 1$  muon per second per  $\text{cm}^2$ . This is at sea level, for all energies, and all angles.

Wood is chosen as a medium because it maximizes the opportunity to trap a low energy muon but still allow the much lower energy electron (decay product of the muon) to escape and trigger a counter.

It is expected that muons with kinetic energies up to 40 MeV will be trapped in the volume. We expect to trap about 19 muons per minute.

These will decay into electrons with at most 52 MeV of energy. Electrons will lose 1.9 MeV per cm and we expect that 20% will never make it out the volume. In addition, the detectors, at best will have 90% efficiency. All together we expect to detect about **10 decays per minute**.

This is developed in more detail in "MuonLifetimeExperiment.ppt".

## ***Procedures***

Operation of this system is expected to include the following steps:

1. Setup for testing (stack the detectors)
2. Tune-up (plateau) the scintillator detectors
3. Setup for measurement (arrange the detectors around a cavity filled with phone books)
4. Initiate the QNET2 board to log singles (no coincidences) events with a gate of about 10 micro seconds.
5. Log data to a txt file leaving the instrumentation undisturbed for as long as possible. Over a weekend ( $\sim 60$  hours) should log about 36000 decay events.
6. Use the QNET.exe program to identify these events and produce a text file with decay times.
7. Sort this decay time data. Group it into enough bins that a reasonable frequency graph (number of decays vs. time) may be produced.
8. Do an exponential-line fit of this frequency graph to determine the decay constant. This is the measured muon lifetime.

## ***Recommended Settings and Analysis***

Based on the simulation of data and example of analysis done in LifetimeAnalysisSimulation.mcd.

Assuming that the instrument has been optimized, plateaued, and has little systematic error, then one can make the following recommendations.

Set the QNET2 DAQ board for 1-fold coincidence, with a gate window of 400 24-ns clock ticks, and a minimum TMC delay of 2.

Use Hyperterminal to log the serial output of the QNET2 to a text file. Then use QNET.exe, written in Visual Basic, to process this data into a file of decay times. It will discard any events that have more than one detector triggering at a time, or with a time between events of less than 10 ticks.

Use Mathcad (see the above mentioned example worksheet) to input the data into an array. Sort the array and then use histogram to group the decay times into bins. It is recommended to use 10 bins (Bins=10) with at least 10 events in each bin ( $N_{\min} = 10$ ).

(Note: 10 bins are recommended because this gives sufficient points to distinguish an exponential relation from other possible relations and to recognize the presence of systematic errors. The minimum of 10 events is because below this the assumptions of Poisson statistics, specifically that sigma is the square root, are no longer valid.)

The expected lifetime is  $2.2\mu\text{s}$  ( $t = 2.2\mu\text{s} = 92$  ticks).

Set a gate width to match the one used on the QNET2 board (GateWidth = 400 tick =  $9.6\mu\text{s} = 4.364$  lifetimes). Be sure that the bin width is an integral multiple of 24-ns ticks (BinWidth = 40 ticks =  $0.96\mu\text{s} = 0.436$  lifetimes).

Assuming that the data is purely randomly distributed (little or no systematic errors) then the minimum number of valid events needed to do this analysis is:  
 $N_0 = N_{\min} * \exp(\text{GateWidth}) / \text{BinWidth}$  Where both GateWidth and BinWidth are in lifetimes.

For this example:

$$N_0 = 10 * \exp(4.364) / 0.436 = 1800$$

This means that we would need a Decay Times file with at least 1800 events in it. This would require a QNET log with at least twice as many lines.

If we use the projected muon decay rate of 19 per min, then this will experiment will require at least 100 minutes to obtain sufficient data.

## ***Resources and References:***

### Books and Manuals

“Particle Data Review D”, published by Particle Data Group

[Cr\\_user\\_man\\_final.pdf](#)

### Websites:

<http://pdg.lbl.gov> Particle Data Group at the Lawrence-Berkeley National Laboratory

### PowerPoint presentations:

[MuonLifetimeExperiment.ppt](#)

[Muon Lifetime Project Overview.ppt](#)

### MathCAD Analyses

[LifetimeAnalysisSimulation.mcd](#)

[Count Rate Analysis.mcd](#)

[Litetimedata.mcd](#)

[Exponential Curve Fitting.mcd](#)

[MuonScintillationCounterSetup.mcd](#)

[MonteCarlo.mcd](#)

### Sample Data

[GoodMuonData.txt](#)

[Testdata.txt](#)

### Software

[QNET.vbp](#)