

School and Workshop on Dark Matter and Neutrino Detection

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Measurement of the muon lifetime

Abstract

In this experiment we will study cosmic muon decays using plastic scintillator detectors. The aim is to obtain the muon lifetime by stopping the muon and measuring its decay at rest to an electron. The experimental signature is given by a light signal from the muon decay, followed by a delayed light signal coming from the electron. We will select muon event candidates and subsequently identify events with a clear signature of their decay. The muon lifetime will be obtained from a fit to their decay time distribution. We will discuss the experimental setup and detection techniques, take data and analyse it to estimate the muon lifetime.

Objectives

- Study the properties of the muon using cosmic rays;
- Understand charged-particle detection mechanisms in scintillation detectors;
- Understand light detection and signal formation in photomultipliers;
- Gain practical skills in data acquisition using a scope and specialised readout electronics;
- Practice data selection techniques and data mining skills.

General recommendations

Use the folder “Documents/YourName/” to store any files.

There are questions in the script highlighted with a  sign – try answering them. These questions will help guide the discussion.

Muon properties, production and interactions

Muons are leptons from the second generation, with a unit electric charge and a mass much heavier than that of the electron: $m_\mu = 105.7 \text{ MeV}/c^2$. Their mean lifetime has been measured with great precision by combining data from several experiments to be $\tau_\mu = 2.1969811(22) \mu\text{s}$ [1]. It is obtained by studying the distribution of the decay time of large samples of muons, which has the same exponential form as radioactive decays.

In this experiment we will use as a source of muons the abundant cosmic rays that shower us constantly. High-energy cosmic rays are made up of about 90% protons (see Fig. 1) that scatter off nuclei high in the atmosphere and the muons are produced as a secondary product of their reactions. [How can cosmic-ray protons end up creating muons?](#)

Figure 1 gives the fluxes for different types of cosmic-ray particles as a function of altitude. Muons are the second most abundant at sea level, after neutrinos. It is usually considered that the flux of muons is $I \approx 1 \text{ cm}^{-2}\text{min}^{-1}$ for horizontal detectors. [What is the expected muon rate in each one of our scintillators?](#)

Let us solve a quick exercise to understand how the cosmic muons created high in the atmosphere could reach the Earth's surface, given their lifetime is so short. Consider a muon of 2 GeV, which is a typical energy, produced at an altitude of 15 km above the sea level. [How far will it travel before decaying? Consider first a non-relativistic muon, and compare it to the relativistic case.](#)

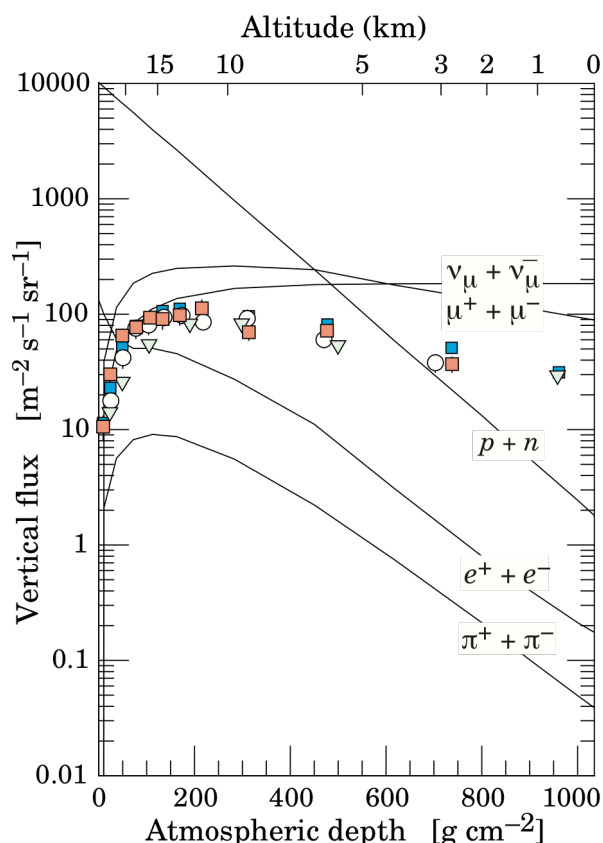


Figure 1. Typical cosmic ray fluxes as a function of altitude. From [1].

Muons decay exclusively to electrons/positrons and two neutrinos via the process:

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

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

This is the decay we will select in the experiment.

The passage of muons through matter is mostly characterised by single collisions with atomic electrons and nuclei, in which the energy lost by muons is transferred and causes ionisation or excitation. The energy loss per unit path length, divided by the density of the medium, $-dE/dx$, is described by the famous long Bethe-Bloch formula and shown in Fig. 2. For our typical muon of 2 GeV energy, the energy loss is small, around 2 MeV/cm multiplied by the density of the medium, and that is why muons can travel great lengths in matter (and why it is called a Minimum Ionising Particle, or MIP). [Do you know what causes the rise in Fig. 2 for very high energies?](#)

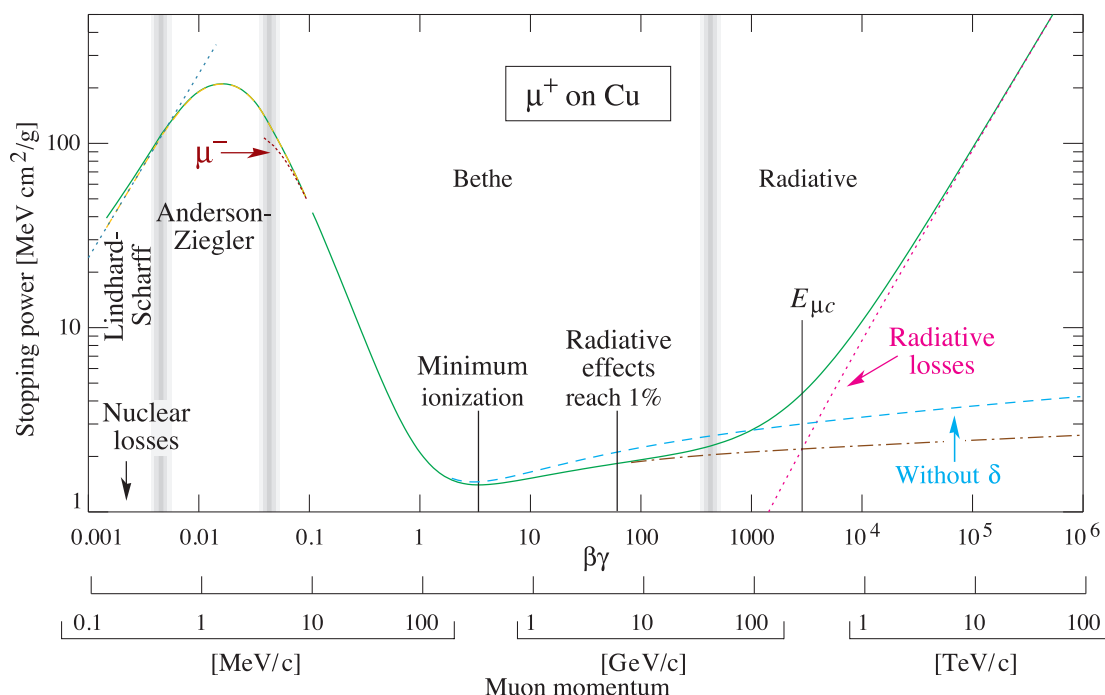


Figure 2. Muon stopping power, or energy loss per unit length ($-dE/dx$) of positive muons in copper. From [1].

Experimental procedures

Experimental setup

To detect muons, we will use plastic scintillators attached to photomultipliers (PMTs) via a light guide. [What is the physical process of scintillation inside our detector?](#)

The number of photons produced by scintillation is proportional (within statistical considerations) to the energy loss of the passing particle. Those photons will enter the PMT and produce electrons that form the electrical pulse we measure. A diagram of a PMT is shown in Fig. 2. [How do PMTs work?](#)

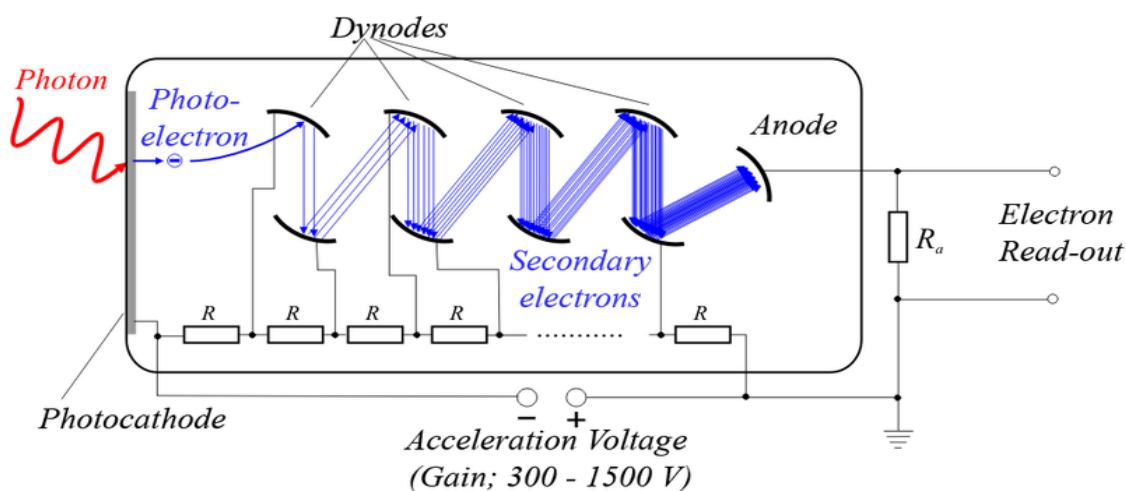


Figure 2. Diagram of a photomultiplier. From Wikimedia Commons.

The size of the electrical pulse in a PMT is proportional to the number of photons detected. To maximise the number of photons that reach the photocathode it is necessary that the scintillator, light guide and photomultiplier tube all be wrapped in reflective aluminium foil. To block external light the assembly is then wrapped in black paper and sealed with black tape.

The experiment assembly uses three scintillator bars and an aluminium plate, as shown in Fig. 3. The top two scintillators form a sandwich and are required to fire in coincidence.

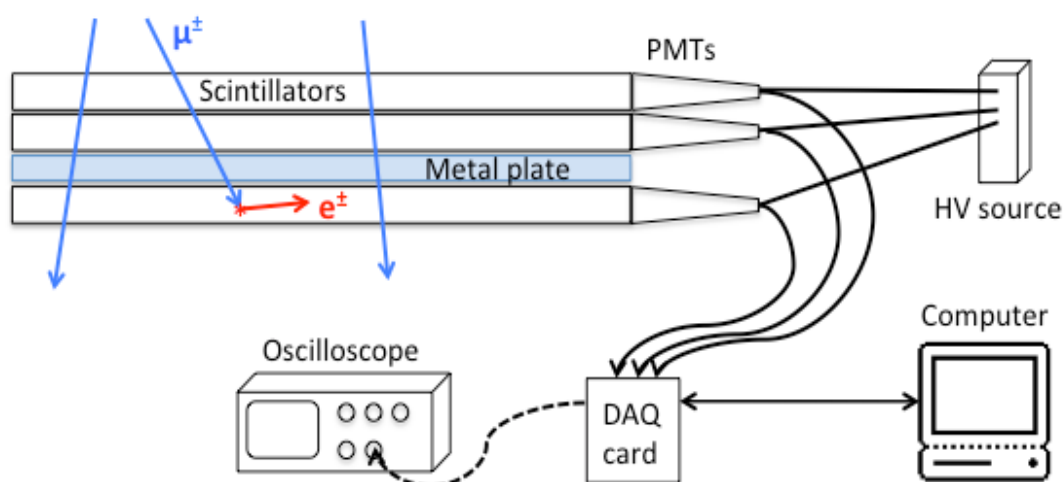


Figure 3. Diagram of the experimental setup.

The choice to use an aluminium plate was made due to its relatively high density, which makes muons suffer larger energy loss compared to the scintillator. Because of the many collisions experienced as the muons travel through the metal, some muons lose sufficient energy that they slow down until they can be “captured” by

one of the atoms in the scintillator. The captured muon will eventually decay into an electron or positron and two neutrinos. The goal is to select only the muons that cross the top two scintillators, slow down in the metal and then stop and decay in the bottom scintillator. [Are muons with 10 MeV likely to stop in the third scintillator? Find out from Fig. 2, with the density of aluminium 2.7 g/cm³ and its height 2 cm \(you can neglect the top scintillators\).](#)

To select only muons that stop, we will require a coincidence in time of the signals from the top two and a veto on any signal in the same time window from the third, bottom scintillator. These stopped muons will decay within several microseconds, emitting an electron, which in turn will interact with the scintillator material and generate more photons. This will cause the detection of a delayed signal from our scintillator.

A data acquisition (DAQ) card has been designed to apply this selection and read out data. It triggers on any occurrence of a coincidence between the top two scintillators and veto on the third one. It then opens a time window of 25 μ s and records the next pulse that fires in the bottom scintillator. It records these three electrical pulses and their occurrences via the time difference between the first two (simultaneous) and the third one.

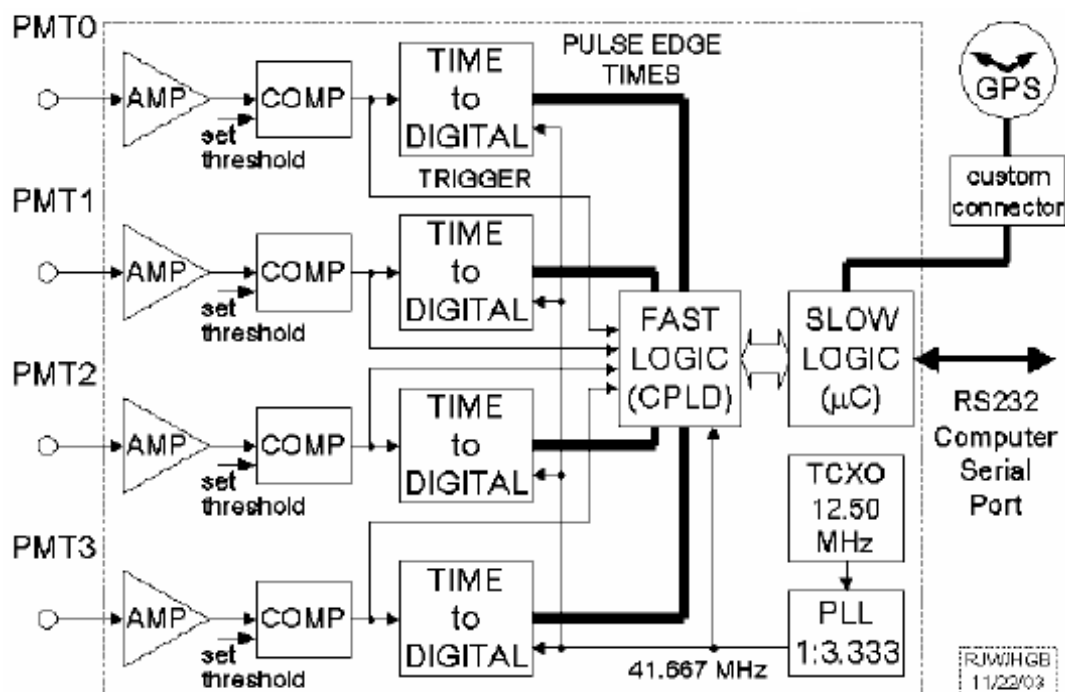


Figure 4. Block diagram of the QuarkNet DAQ board. From [6].

A diagram of the DAQ card is shown in Figure 4. It can take up to 4 PMT signals as input. Each signal passes an amplification and a discrimination stage. The timing information of its leading and trailing edges is then converted to a digital signal (TDC). The board also contains clock distribution and fast and slow logic for triggering, receiving commands and sending the data to a computer via a RS232 serial cable.

Setting up the detector

Check that the scintillators are mounted on top of one another and that each PMT is connected to a high voltage channel on the ORTEC 456 HV module using an SHV cable. The HV module provides two equal adjustable output voltages of up to 2.5 kV. Turn on the HV module and choose **900 V** to supply to the PMTs.

Let us first look at the PMT signals using an oscilloscope. Connect the signal BNC cables of the two top scintillators to channel 1 (top scintillator) and channel 2 of the scope. Use the 50 Ω impedance adapter at the channel entrance to match impedances. Select the top scintillator signal as trigger and adjust the scope time and amplitude menus to see both signals. Adjust the trigger menu:

Mode: Normal

Source: CH2

Coupling: DC

Falling edge

Examine the signal shapes and amplitudes. [How can we distinguish which signals come from muons that cross both scintillators?](#)

Sometimes scintillators assemblies can be suffer from light leaks. This is why we are using a black cloth to cover the detector set up. Try removing the cloth and observe if the signal rate increases. [Are both scintillator assemblies light tight?](#)

Using the DAQ card

Now that we understand the detector signals, let us use the readout card to apply amplification and discrimination to them. Connect the signal cables (without the impedance adapters) to input channels 0 and 1 of the card. Make sure the readout card is powered and connected to the computer using an ethernet cable.

We can communicate, control and read the DAQ card using the **minicom** program on the computer. Open a terminal and type:

```
cd Documents/YourName/
```

```
ll /dev/
```

The second command lists all devices – if the DAQ card is connected, it should appear as **ttyUSB0**. If it doesn't appear check the ethernet cable connection.

The **minicom** program is already set up to communicate with the card using the correct port, device name, etc. Start the program from the terminal and choose a file name to save to, for example "test.dat":

```
minicom -C test.dat
```

Inside the **minicom** program we can give commands to the DAQ card, change its settings, and transfer data from it. Explore the command descriptions by typing **HE** then Enter (for help). Make sure you understand the commands **CE**, **CD**, **TL**, **View** and **Veto**.

We can use the oscilloscope probes to view the signals in the DAQ card. Connect the probes to channels 1 and 2 of the scope. Choose "Probe 10x" on both channel menus, as the probes amplify the signal ten-fold.

In the next steps, take care not to touch any components on the card and cause a short circuit! Connect the two ground clamps of the probes on to the GND loop, located near the middle of the DAQ card. Very carefully connect the channel 1 probe pin to the **TPINO** point on the DAQ card – this is where the input signal 0 can be looked at, before any processing is applied to it. You should see on the scope the same signal as before. Connect the channel 2 probe pin to the **TPDSO** point on the DAQ card – this is where the discriminator output can be viewed.

Select on the scope channel 1 as trigger source. Vary the trigger level and observe the two signals – what can you infer about their characteristics?



Discriminator thresholds

The discriminator thresholds on the DAQ card can be adapted so that noise from spurious signals is reduced, while the selection efficiency for muons stays high. For this we need to perform a threshold scan and measure the coincidence counting rate for each value.

Check the applied discriminator threshold value to input line 0 using the command: **TL**.

The threshold can be varied between 0 and 4095 mV. Set it to 10 mV for all inputs with the command: **TL 4 10**. Measure the coincidence rate during one minute using the LED counter on the DAQ card (you can reset the counter from the “COUNTER RESET” button). Repeat for thresholds of 20, 50, 100, 150, 200, 400, 700, and 1000 mV. Plot a graph of the rate versus threshold. What is your choice of discriminator threshold based on the graph?



Another operating characteristic that can be investigated by monitoring the muon count rate is the PMT high voltage. However, it would require an HV source that measures accurately the output voltage.

Data acquisition

Set the discriminator threshold to your chosen value, based on the scan. Disconnect the scope probes from the DAQ board to avoid any electrical disturbance to the circuit.

Data from the DAQ card can be written to file using the **minicom** command **CE** (count enable), and the acquisition can be stopped by typing **CD** (count disable). Let it take data during at least half an hour.

The data are saved in the form of a table with several columns of hexadecimal numbers, where the first column has the event clock counter and the following 8 columns contain TDC values for the leading and trailing edges of signals 0–3. The final columns have values of GPS, barometer, etc. sensors.

A script can convert this text file with hexadecimal numbers into a ROOT file containing a tree called “dataTree” with the TDC values. To execute it, type in the terminal:

/home/neutrinos-exp-10/Documents/Macros/convert/qNet2root6000.exe <input file> <output root file>

Data analysis

The aim of the final data analysis is to create a histogram of the time difference between the muon and electron signals. This time difference is the decay time of the muons.

Use ROOT or pyROOT to visualise the data in the form of a histogram of the number of counts vs. time difference.

As a starting point, use the ROOT script ***muon_lifetime.cc*** that reads in the data tree and creates the decay time histogram. It saves the histogram in a new ROOT file, and also lets you visualise it in an interactive ROOT session. You can analyse it and fit a function to it in the interactive session, or, if you prefer, you can write your own fitting routine and add it to the script (copy it to your folder and edit it).

To create the histogram, run in your folder:

root

.L /home/neutrinos-exp-10/Documents/Macros/muon_lifetime.cc

readData("<root file>")

where <root file> is the same file created in the previous step and containing the TCD values.

Plot the histogram and fit a function that describes it. [Think about what mathematical function\(s\) to use.](#)

Obtain from the fit the mean muon lifetime and its uncertainty. [How does it compare to the world average?](#)
[Where could the differences come from?](#)

[Once you measured the muon lifetime, can you find its half-life?](#)

Additional literature

- [1] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018). Online at <http://pdglive.lbl.gov/>
- [2] W. R. Leo, "Techniques for Nuclear and Particle Physics Experiments", Springer-Verlag, 2nd edition, 1994.
- [3] Glenn K. Knoll, "Radiation Detection and Measurement", 3rd edition, John Wiley and Sons, 1999, Chapters 8 and 9.
- [4] David Griffiths, "Introduction to Elementary Particles", John Wiley and Sons, 2nd edition, 2008.
- [5] Francis Halzen and Alan D. Martin, "Quarks and Leptons: An Introductory Course in Modern Particle Physics", John Wiley and Sons, 1984.
- [6] J. Rylander *et al.*, "QuarkNet/Walta/CROP Cosmic Ray Detectors User's Manual", <http://quarknet.fnal.gov/toolkits/at/det-user.pdf>
- [7] ROOT Data Analysis Framework, <https://root.cern.ch>