1 Muon Lifetime Determination Project Log Book

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1.1 Table of Contents:

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2 Background and Theory:

2.1 Origin of the Muon:

In this experiment, we observe cosmic muons. Cosmic rays are high energy particles produced in the sun and in supernovae and neutron stars of our galaxy. About 85% of the cosmic rays are protons and 12% are alpha particles (helium nuclei). The remainder are electrons and nuclei of heavier atoms. The cosmic rays travel in the space between the stars. In their path they interact with atomic nuclei and they produce new cosmic rays, like antiprotons, positrons, photons and neutrinos. The cosmic rays that reach our atmosphere are called primary cosmic rays. The energy spectrum of primary cosmic rays, i.e. the number of particles as a function of energy, has been measured over an enormous range. For the nuclear component, it is shown in Figure 1. A good fit to the data, except at the lowest energies, is the following:

$$I(E) \propto E^{-2.6}$$

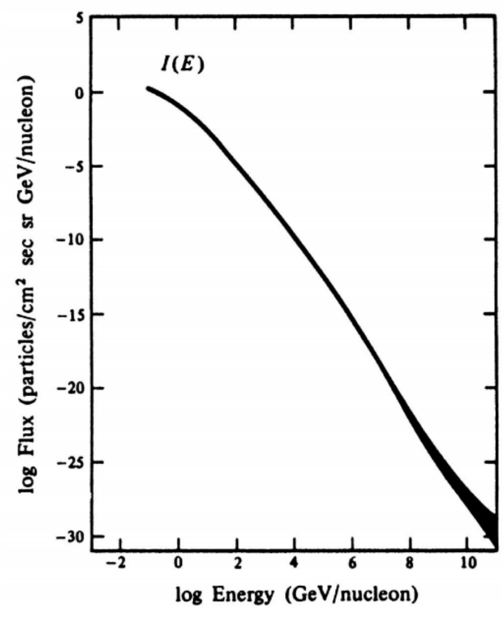

Fig. 1: Energy spectrum of the nuclear component of the primary cosmic rays. (credit: GOOGLE)

where $I(E)$ is the intensity (flux) of the nuclear component at energy E. When a primary cosmic ray, e.g. a proton, enters the Earth's atmosphere it interacts with the nuclei of the atmosphere's atoms (mainly oxygen and nitrogen). From the interactions, new particles are produced (secondary cosmic rays), inducing in their turn new reactions with atoms of the atmosphere. This creates a hadronic shower. The word *hadronic* signifies that the produced particles are hadrons, i.e. strongly interacting particles, like protons, pions, kaons, etc. The word *shower* refers to the way the particle production develops in space (see Figure 2).

Antiparticles, like antiprotons, are also produced in this process. Unstable hadrons then decay weakly to electrons, muons and neutrinos. Photons are also produced, e.g. by π^0 decays or electron bremsstrahlung. Electromagnetic showers are created by electrons or by photons converting into electron-positron pairs, which emit new photons etc. Overall, a very high energy proton can produce a very extensive shower, covering many km^2 of the Earth's surface. By the time the showers reach the ground, they mainly consist of electron- and muon-neutrinos and muons. These are the cosmic muons that we observe in our experiment.

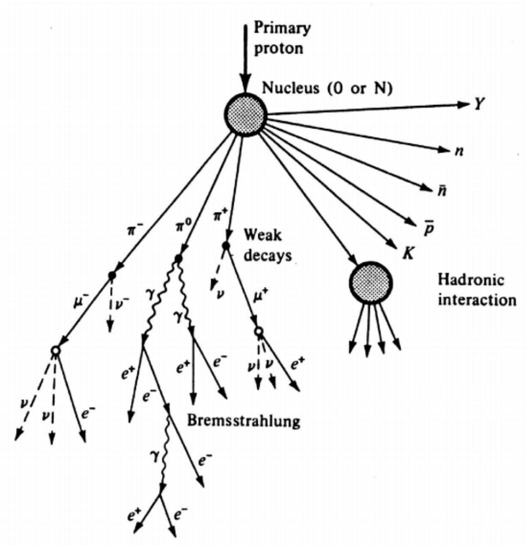

Fig. 2: Cosmic Ray Shower Generation Process. (credit: GOOGLE)

2.2 Muons and their decay:

Muons decays as follows:

$$\mu^- \rightarrow +v_\mu + \bar{v}_e + e^-$$
$$\mu^+ \rightarrow +v_e + \bar{v}_\mu + e^+$$

Most of the muons decay in the atmosphere but some have high enough energies to reach our detector. Depending on their energy, they will either go through it or stop in the aluminium plate, which is located in the middle of the detector (Figure 4), where they will eventually decay.

2.3 Lifetime of a particle:

The lifetime of a particle is something that we define in the rest frame of the particle. For the purposes of this lab, we will take the muon as an example of the decaying particle. If we take a muon and observe it in its rest frame, we can never tell in advance at exactly which moment the muon will decay, even if we know exactly when the muon was created. This means that the muon does not have a fixed time of life. The only thing that we can say is that at a specific moment in time, t, there is a probability, $P(t)$, for the muon to decay (i.e. has a statistical nature)

Let us assume that, at time $t_0 = 0$, we have N_0 muons. Each one of them has the same probability to decay in a specific time interval. For example, in the interval $[t_0, t_0 + 10ns]$, each muon will have a probability P_1 to decay. It is convenient to define the decay probability per unit time, λ, which is a constant. We can now find the decay probability for any time interval dt: this will be equal to λdt, as we can check from the units of the variables λ and dt ($[probability/time]x[time]$).

This means that the number of muons has decreased by a quantity $dN = -N(t)\lambda dt$. The minus sign is there because $dN = N_{final} - N_{initial} < 0$. If we integrate this relation, we find the exponential decay law:

$$N(t) = N_0 e^{-\lambda t} \tag{1}$$

From quantum-mechanics, we know how to use the above relation in order to calculate the mean life of the muon:

$$\langle t \rangle = \frac{\int_{N_0}^{0} t dN}{\int_{0}^{N_0} dN} = \frac{1}{\lambda} \tag{2}$$

The variable $\langle t \rangle$ is also denoted by τ and is called the lifetime of the muon. It is a constant because λ is a constant. We see that the lifetime of the muon is not a quantity that we can measure by detecting the decay of one muon only. We need to observe how an initial number of (many) muons decreases with time.

Let us now take Equation 1 and insert the lifetime of the muon, $\tau = 2.2\mu s$:

$$R(t) = \frac{N(t)}{N_0} = e^{-t/2.2}$$

where $R(t)$ is the ratio of the remaining muons at time t over the initial number of muons and t is measured in μs. We see this distribution in Figure 3.

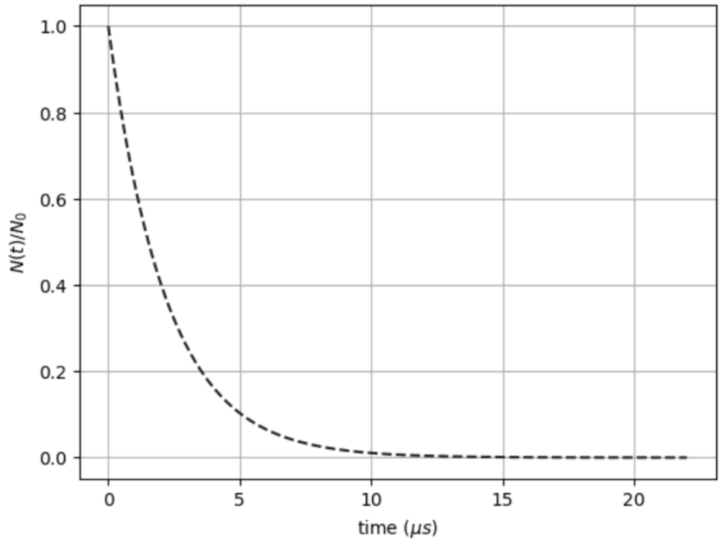

Fig 3: Exponential decay law for muons

2.4 Muon Lifetime Measurement

2.4.1 Detector Set Up

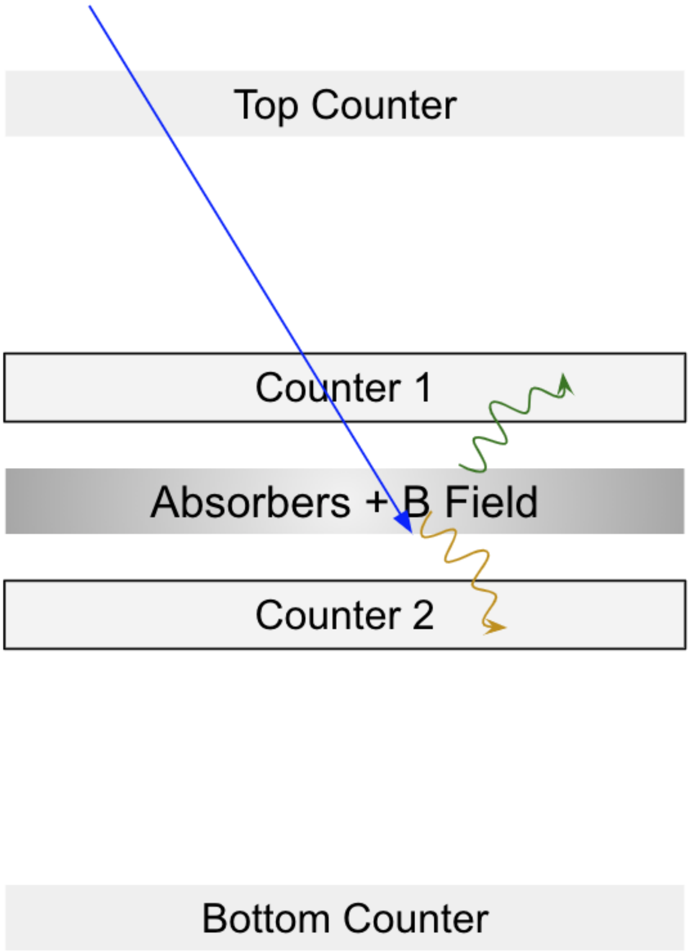

Fig. 4: The setup of the experiment

Our detector is shown in Figure 4. Most of the muons pass right through the detector, however a fraction is stopped in the aluminium absorber, where they will decay. The muons (blue) come from above and will pass two scintillators (TC and C1) before they stop (absorber). The positron (green/golden) from the decay can either be detected leaving the set-up upwards (C1) or downwards (C2). The direction of this emitted particle can be controlled through the use of a magnet.

2.4.2 Scintillators

Scintillators are devices that detect the passage of charged particles. Our scintillators are made of plastic. When a charged particle passes through the scintillator it excites (gives energy to) the molecules of the scintillator. Soon afterwards the molecules emit light and return to their ground state. A single charged particle will typically cause around 20000 photons to be emitted per cm of traversed scintillator. The scintillators are so called because the light which is emitted from their molecules is a scintillation, i.e., a small flash of light. The emitted light is directed to the photomultiplier.

2.4.3 Photomultipliers

A photomultiplier is mounted after each scintillator and collects the light that was emitted by the molecules of the scintillator. The function of the photomultiplier is to convert the light to an electric pulse (analog signal). This is done as follows: the incoming light (photons) hit a photocathode (a piece of material at a negative electric potential). 10 to 30% of the photons cause the emission of an electron (photoelectric effect). The electrons are accelerated between a series of dynodes (pieces of metal at increasingly positive electric potentials). When an electron hits a dynode, 5 new electrons are emitted from the dynode. As the electrons traverse the dynodes, an avalanche of electrons is produced. Finally, all electrons are collected at the anode, where their initial number has been multiplied by a factor 10^6 or more. This is the pulse (analog signal) that we obtain from the photomultiplier. The photomultiplier is so called because it takes originally light (photo-) that converts to electrons which it multiplies (in the dynodes).

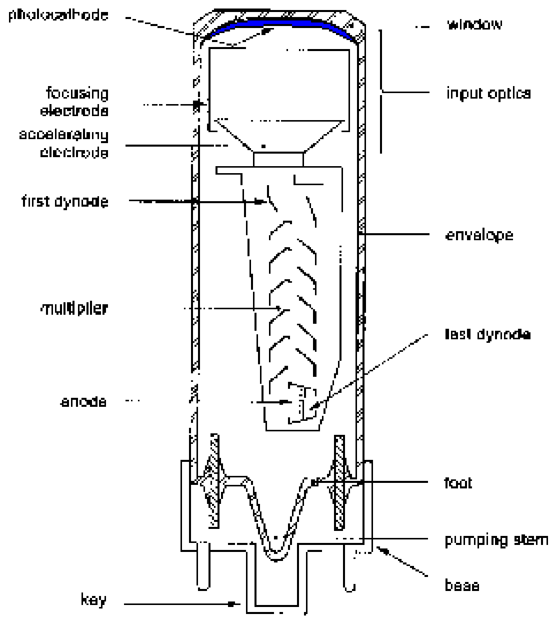

Fig. 5: The setup of the experiment (credit: CERN)

The design of a photomultiplier can be seen in Figure 5. The outputs from the photomultipliers are connected to preamplifiers which give a signal strong enough to be detected by the logic.

2.4.4 Discriminators

A discriminator is a device which converts analog to digital (0 or 1) signals as shown in Figure 6. When the signal A is given as input to the discriminator, the discriminator will produce a digital pulse C because the signal A exceeds the threshold of the discriminator. A low signal B which is smaller than the threshold, will be ignored and the discriminator will give a 0 pulse as output. The output of the discriminator is always a digital signal (square pulse).

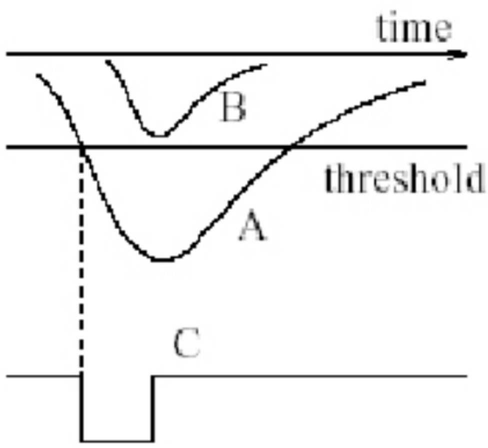

Fig. 6: Operation of a discriminator (credit: GOOGLE)

2.4.5 Electronic Logic

For our experiment, we use a common start approach where we start the "clock" when ever there is a signal in the top two scintillator counter and not the bottom most.

TC **AND** C1 **AND** (**NOT** BC)

We stop the clock whenever there is a signal on one of the counters touching next to the absorber (C1 or C2).

(C1 **AND** (**NOT** TC)) **OR** (C2 **AND** (**NOT** BC))

2.4.6 Lifetime Calculation

After setting up the required hardware and implementing the correct logical circuit, we record the timing difference between the **stop** and **start**. Using, this metric we create a histogram whose mean value represents the muon lifetime - τ

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3 Experimental Progress Report

3.1 Day 1:

We went to the physics building (RM 030) and were looking at the scintillator counters, power supply and the DAQ system next to it. We turned on the power supply for the PMTs connected to the scintillators without changing the configuration that the last group has devised out of curiosity to see the signals on the oscilloscope. Instantly, we realized that there was some significant light leak as the pulse generated by the PMT was almost constant - a rate that is simply not representative of muon hits at this elevation on the scintillation area.

We tried our best to cover it with black cloth but the leak stayed persistent. Further, we realized we were missing some much needed modules for the muon lifetime experiment. Thus, we contacted Dr. Akchurin who advised us to come the next day to meet with him in RM 030 to discuss the issue further.

3.2 Day 2:

Dr. Akchurin verified our observation of the light leak and wanted us to extend our project to refurbish the scintillator counter and its holder so that it is robust and is as immune to light leak as possible. He also advised us to use the Muon Telescope Prototype 1B set up at the Advanced Particle Detector Laboratory (APDL) to complete this lab. He gave us some two new scintillator blocks and PMTs and the required modules to complete this lab at APDL.

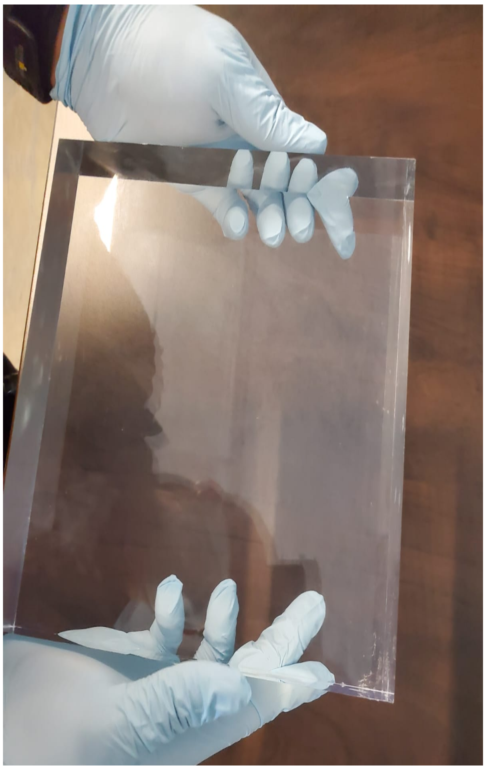


Fig. 7: A Scintillator block and The PMT's used in old counter.

3.3 Day 3:

We set up the new scintillator counters by creating a holder for them and wrapped it with black tape. We made sure the system was robust before we connected the PMT's. Once we have done that we took the rest of the day calibrating this set up and the PMT making sure we were registering proper muon hits.

Fig. 8: New Scintillator Counters.

3.4 Day 4:

We fixed up an old solenoid and used a Gaussmeter to map its magnetic field. We also continued work on integration of the new scintillators into the prototype 1B telescope. We also designed and bought the materials needed to make the robust light-tight frame for the old scintillator-PMT counters.

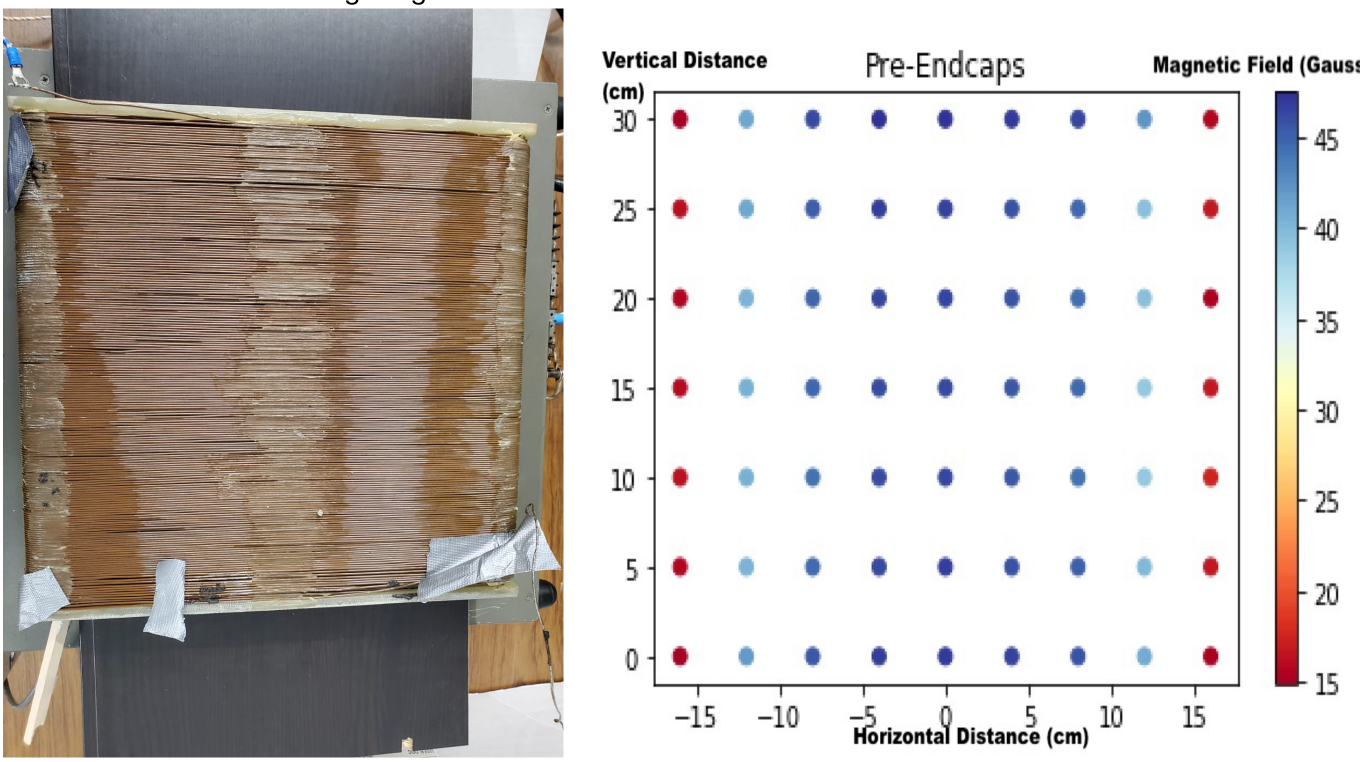


Fig. 9: The Solenoid after being fixed and the magnetic field along the plane of the solenoid

3.5 Day 5:

We finished the initial installation of the Counters into the prototype 1B telescope. Later, we installed another TDC unit to the bottom CAMAC crate so that we don't hamper with the functioning of the 1B telescope. I changed the DAQ code of the telescope to read from this new module and also added the functionality to include the outputs of the new addition into the data flow/report generation scheme of the telescope.

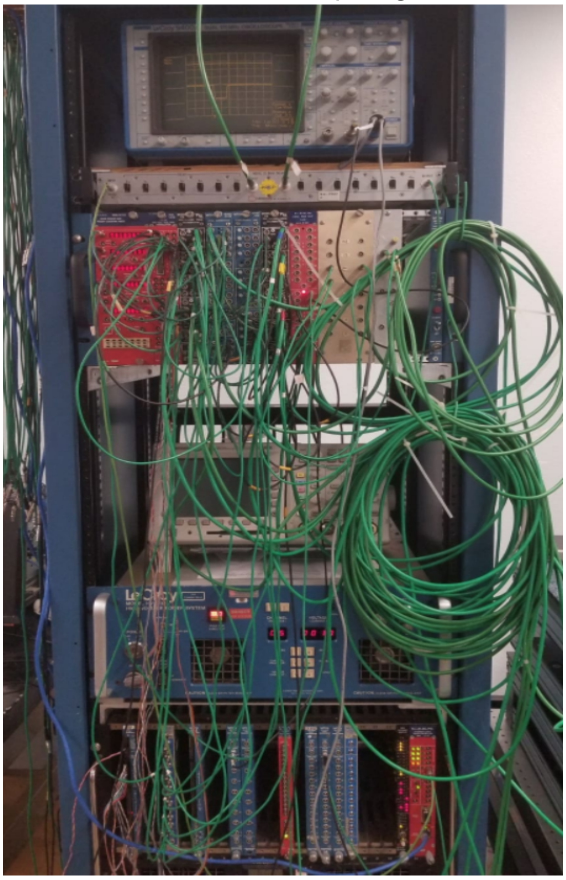


Fig. 10: The CAMAC based DAQ System

3.6 Day 6:

Since, the magnetic field was not as uniform as to our liking. We added two end caps to the solenoid in opposite polarity so that the field was more uniform in the edges.

We then mapped this new field using the gaussmeter.

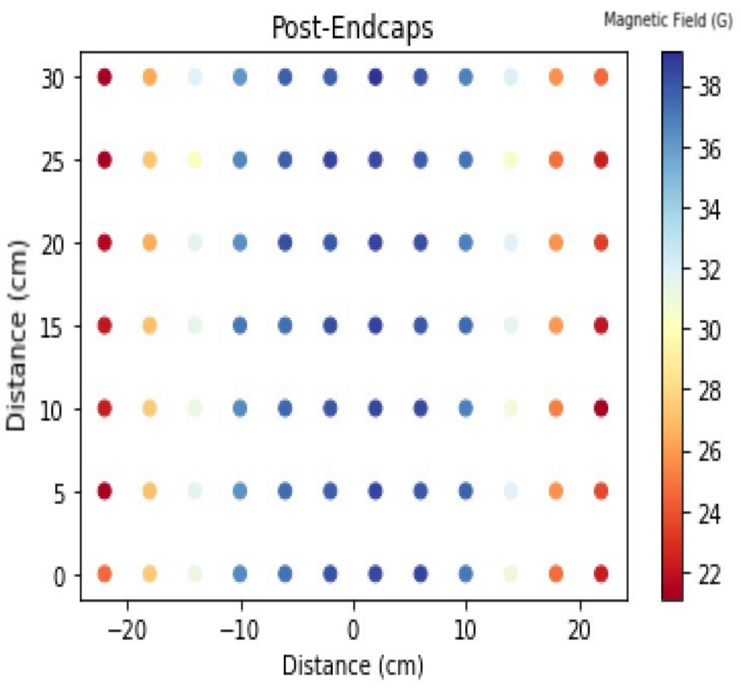


Fig. 11: The Solenoid with end caps and the magnetic field along the plane of the solenoid

3.7 Day 7:

Fig. 12: Set up of the scintillator and PMT counters with the absorber and magnet

We took pretty much the entire work day fully installing the apparatus for the muon lifetime experiment into the prototype 1B telescope. There was a lot of debugging and diagnostics involved in the process as we dealt with issues of light leaks, faulty connections, bad wiring, noisy signals, poor discrimination and burnt PMT. We also realized that due to clashing nature of the operations we wanted on the prototype 1B system - COMMON STOP for Muon Tomography and COMMON START for Muon Lifetime measurement - we cannot use the standard DAQ regime for our case. We had to stop the ongoing experiment and started our first trial run using the oscilloscope as the readout.

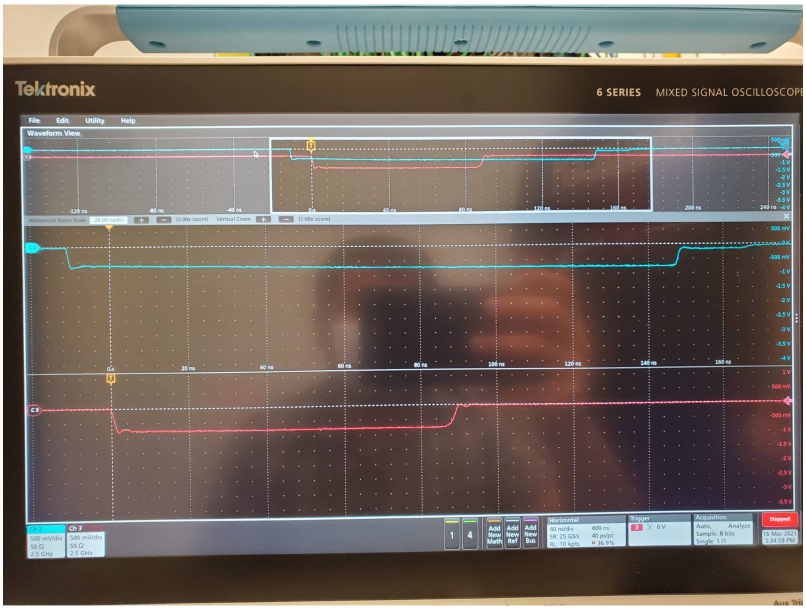


Fig. 13: Picture showing the discriminated output from the Start and Stop readouts

3.8 Day 8:

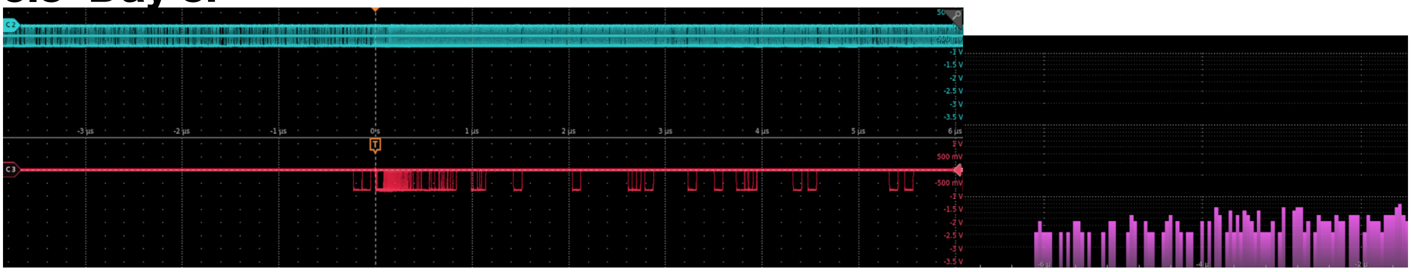


Fig. 14: Screencapture of discriminated outputs (inf persistence) and histogram of the time difference (delay of trigger)

The result of our overnight run was very noisy and not accurate. Upon investigation, we identified the source of the issue - faulty logic circuit (there was an AND gate missing on the STOP signal). After looking into it further we realized the issue was actually multifaceted as the oscilloscope and the discriminator were also not working properly. We informed Dr. Akchurin about this and planned to meet with him to work on it the following day. In the meanwhile, we worked on refurbishing the old counters.

Fig. 15: The plan for the new frame for the scintillator counters

3.9 Day 9:

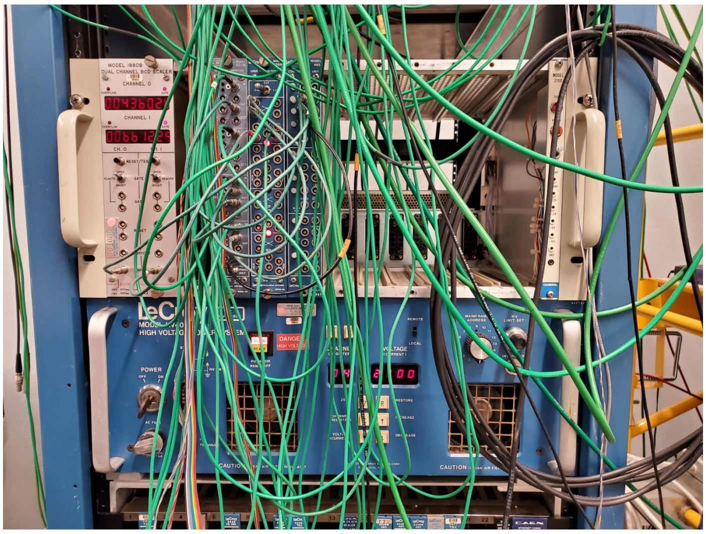


Fig. 16: The newly added DAQ crate

Dr. Akchurin added another crate to the DAQ system with new discriminator and logic modules. He also let us borrow a new oscilloscope which had the autosave option - a missing feature on our existing one. We tested and implemented several different logical circuits to ensure that our system health is good. Once, we were satisfied with the set up, we started another over night run.

3.10 Day 10:

Fig. 17: The oscilloscope showing the results of the over night run

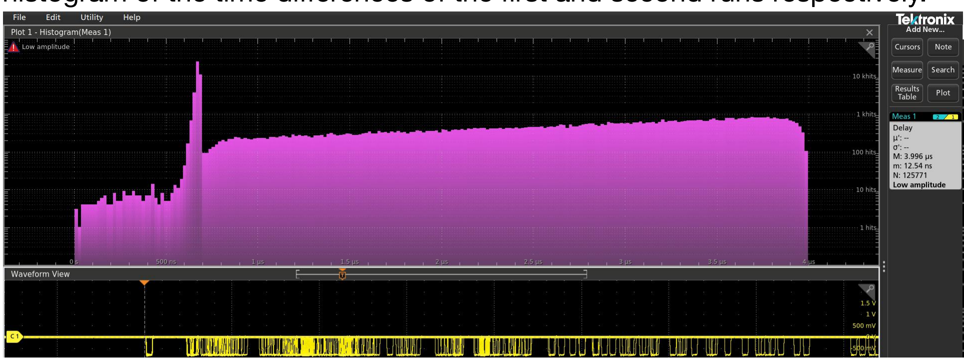
After we looked at the data from the overnight run, we were again made aware of yet another faulty logical issue. We fixed this issue and started another run, whose output had not been saved. Later that evening, Dr. Akchurin resolved another issue of trigger threshold that we had and finally our system was fully operational.

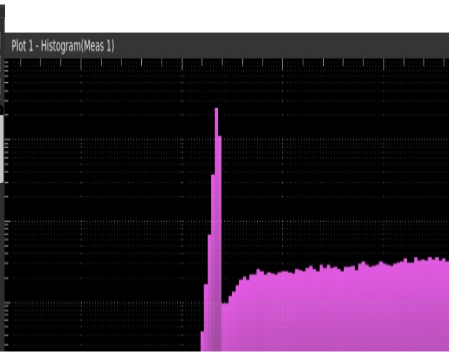
3.11 Day 11:

We have finished the assembly of the frame for the Scintillator-PMT counters and will be done with wrapping with them with dark cloth/tape soon. The counters should be ready for use by the next cohort by Sunday morning.

Fig. 18: Pictures illustrating the frame for the old counters

Also, we took two data runs this day and here are the results. The following are the dataframes for the histogram of the time differences of the first and second runs respectively.





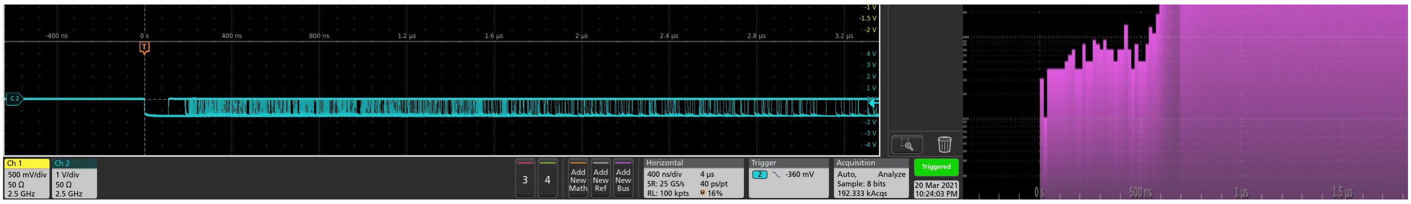


Fig. 19: Screencapture of discriminated outputs (inf persistence) and histogram of the time difference (delay of trigger)

Out[61]:

	time (microseconds)	freq
0	0.543744	0
1	0.558327	0
2	0.572911	0
3	0.587494	1
4	0.602078	0
...	...	...
245	4.116710	0
246	4.131300	0
247	4.145880	0
248	4.160460	0
249	4.175050	0

250 rows × 2 columns

Out[62]:

	time (microseconds)	freq
0	-0.163367	0
1	-0.145992	0
2	-0.128618	0
3	-0.111243	0
4	-0.093868	0
...	...	...
245	4.093430	0
246	4.110800	0
247	4.128180	0
248	4.145550	0
249	4.162930	0

250 rows × 2 columns

4 Conclusion & Summary

The muon lifetime can be calculated from the dataframe/histogram that we recorded. It is simply the mean value of the histogram.

$$\tau = \frac{\Sigma f \Delta t}{\Sigma f}$$

here, Δt is the timing difference between the STOP and START of our system and f is the frequency associated with that Δt for that run. The errors associated with these runs were roughly the same - $1.06\mu s$.

From the first data set we get τ to be $2.42\mu s$ and from the second run it is found to be $2.06\mu s$. Thus, taking the average of these two values to be our value for the muon lifetime, $\tau = 2.24 \pm 1.06\mu s$.

Our measurement is in accordance with the accepted value of $2.2.\mu s$.

5 Project Questions:

1. Discuss your setup. Write down exactly how you elect to set thresholds and the electronic logic for event selection.

The set up has been described in **Section 2.4**, the electronic logic is explained in **Section 2.4.5**. To determine the thresholds we fixed the PMT voltage and vary the threshold while observing the signals through the oscilloscope. Thus, we determine the threshold value experimentally (i.e. the value at which we no longer see the electronic noise and see both muons and the occasional positron from muon decay on the scope).

2. Plot the time distribution and calculate the muon life-time by making a fit. How good is the fit? What are the errors on your fit parameters? Statistical and systematic? Identify each source of error.

Our experiment did not rely on the conventional means of curve fitting to find the muon life-time. So, we can't make any comments on the fit parameters. However, we did have many sources of error in our measurement - light leaks in scintillator-PMT systems were a systematic source of error, there were also statistical errors due to the relatively short sample of events we used to make our measurement.

3. Assuming muons are created 30 km above sea-level and travel at the speed of light, what is the minimum time they must survive to be seen in your experiment?

Given, $d = 30km = 30000m$ and $v_\mu = cm/s$

$$t = \frac{d}{v_\mu} \sim 100\mu s$$

4.What is the maximum energy the decay electron can have? What distance such an electron travel in the scintillator? How many photons does it generate? Can we measure (or estimate) their energies with our setup? How about the neutrinos?

The most energetic muon decay involves the two neutrinos being emitted in the same direction and the electron recoiling. By treating the neutrinos as massless we get

$$pc + \sqrt{m_e^2 c^4 + p^2 c^2} = m_\mu c^2$$

which can be solved for p and the maximum electron energy found directly. From literature review, I found the value to be $53MeV$. The number of photons it generates can be found by the following relationship:

$$ E = N\hbar f $

Here, N is the number of photons that are generated with scintillation light frequency of f. We can measure their energy through our set up by passing the PMT output to an ADC module. We cannot measure the energy of the neutrinos in our set up.

5. What are the possible sources of backgrounds?

Some possible sources of background are light emitting sources such as bulbs and computer screens. There is also a nearby HVAC system that may also discharge time to time.

6. Compare your result with the accepted value (check http://pdg.lbl.gov) (http://pdg.lbl.gov)). Explain the differences, if any

The website has the accepted value of the muon life-time to be $2.1969811 \pm 0.0000022\mu s$. The percentage difference between this value and our measurement is 1.7%. Our value is thus accurate within the 2% significance level. The reason for a non-exact value is due to various systematic and statistical errors that we explain in question 2.

7. Muons come in two different charge states, positive and negative. The negative muon decays $\mu^- \rightarrow +\upsilon_\mu + \bar{\upsilon}_e + e^-$ and the positive one as $\mu^+ \rightarrow +\upsilon_e + \bar{\upsilon}_\mu + e^+$. Can you tell which type of muons you detected?

With our current set up (with the magnet not in use), we cannot distinguish between which types of muons we detect.

8. What is lepton number conservation?

The conservation of lepton number means that whenever a lepton of a certain generation is created or destroyed in a reaction, a corresponding antilepton from the same generation must be created or destroyed.

9. How do we know there are two neutrinos in muon decay? Why not just one or none? How can we experimentally answer this?

Muon decay are similar to Beta decay. There is weak interaction that makes use of an intermediate vector boson (W). The primary muon decays into a neutrino and a W boson. The W boson then further disintegrates into another neutrino and an electron/positron. This is why there is always two neutrinos in a muon decay. The flavor of the neutrino and whether an electron or positron is generated depends on the parity of the muon. Experimentally we can answer this by including a magnet in our set up and setting it up such that the generated positron is always sent to a distinct counter and the electron in the other. Of course, the material of the absorber in this experiment should be chosen such that it allows the muon to decay but doesn't trap any generated electrons. The detection of this electron/positron is proof of this mode of decay of electron and is thus an experimental answer to this.

Another experiment, would be to just have "neutrino detectors" enveloping the absorber. For events where we detect a positron in the scintillators we count the the number of neutrinos in the "neutrino detectors". We should see the answer to be 2.

10. Are there other muon decay modes? If so, what are they? Can we detect/identify them?

Other muon decay modes are:

$$\mu^- \rightarrow \gamma + e^-$$
$$\mu^- \rightarrow e^- + e^+ + e^-$$

Since, they do not involve neutrinos and thus violate the lepton flavor conservation. These modes are prohibited and therefore cannot be detected.