Measuring the lifetime of cosmic ray muons

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In this experiment, the mean lifetime of cosmic ray muons in their rest frame will be measured. We will obtain an exponential time distribution by measuring the time interval, from the point where the muon enters the detector to the point it decays, for a large number of muon decay events. By calculating the gradient, using curve fitting, of this distribution the mean lifetime of the muon in its rest frame will be determined. Another purpose of this experiment is to acquaint the student with workings of Photomultiplier tubes, scintillators and high-speed electronic modules such as discriminators, logic gates, time-to-amplitude converter, and multi-channel analyzer.

KEYWORDS

Cosmic rays · Muons · Angular Distribution · Lifetime · Coincidence · Exponential decay.

APPROXIMATE PERFORMANCE TIME 2 weeks.

1 Objectives

In this experiment, we will,

1. understand how photomultiplier tubes and scintillators combined work as a particle detector,
2. study the formation of muons from primary cosmic rays in the atmosphere,
3. analyze the working of high-speed electronic modules so that they can be used to obtain the time difference to calculate the lifetime,
4. understand the workings of the multi-channel analyzer and realize how it is a crucial part of counting different voltage pulses in this experiment, and
5. analyze how curve-fitting parameters influence the final answer.

References

[1] "*High Energy Cosmic Rays*", T. Stanev. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010.

[2] "*Muon Basics*", Universidad Nacional de La Plata, http://www2.fisica.unlp.edu.ar/ veiga/experiments.html. Retrieved April 25th, 2014.

[3] "*Lifetime of the Muon*", NP08, Oxford Physics, Particle Physics Projects Manual, revised MGB Oct 2006.

[4] "*Determination of the Muon Lifetime*", The University of California, Physics 122 course, Experiment Manual. Retrieved Winter 2014.

[5] "*The Speed and Lifetime of Cosmic Ray Muons*", Liu, Lulu, Solis, Pablo, MIT Undergraduate Experiment report. Retrieved Nov 18, 2007.

[6] "*PDGLive Particle Summary 'Leptons (e, mu, tau,neutrinos)'* ", J. Beringer et al. (Particle Data Group) (2012). Particle Data Group. Retrieved Jan 12, 2013 .

[7] "*EzyFit 2.44 - File Exchange - MATLAB Central*", Mathworks.com. https://www.mathworks.com/matlabcentral/fileexchange/10176-ezyfit-2-44. Retrieved Jan 05, 2019.

2 Introduction to Cosmic Rays

2.1 Origin of Cosmic Rays

Most of the content of this section has been taken from Todor Stanev's book "*High Energy Cosmic Rays*" [1].

Cosmic rays are charged particles of interstellar origin. The flux of hydrogen and helium nuclei dominates the cosmic ray spectra on earth in the GeV energy range. Then there is a steady flux of electrons followed by rare entries of anti-matter particles which include positrons and anti-protons.

Cosmic ray particles basically originate from nuclear fusion reactions occurring inside stars. Some of these reactions are:

$$4H^+ \rightarrow He + \gamma$$
$$p + p \rightarrow H_2 + e^+ + v_e$$
$$H^2 + p \rightarrow He_3 + \gamma$$
$$He_3 + He_3 \rightarrow He_4 + 2p$$

These nuclear fusion reactions power up the star and prevent the gravitational collapse of the star upon itself due to its mass.

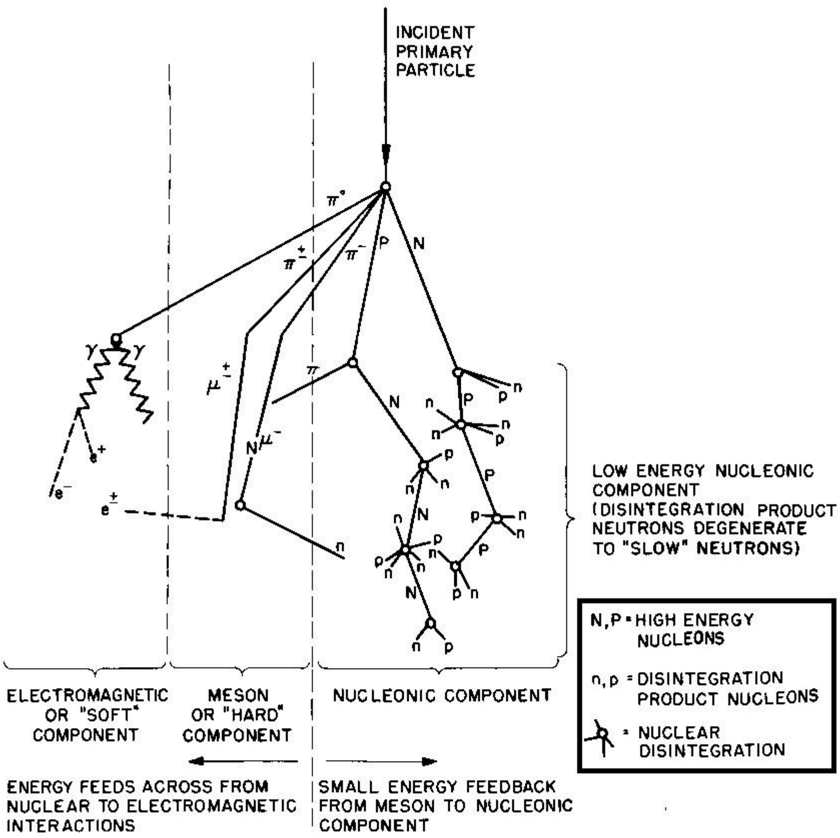
Cosmic ray nuclei also react with particles in the interstellar medium to produce all kinds of secondary particles. It is known that 90% of the interstellar medium consists of hydrogen iodide and H_2 and 10% of it is made up of Helium and other heavy nuclei.

2.2 Cosmic Rays at Earth

After originating in the cores of stars and traveling through an interstellar medium the cosmic ray particles finally reach earth. The atmosphere of earth provides more than ten interaction lengths for protons (or hydrogen nuclei) going straight down. Interaction length is the mean free path length required to reduce the number of relativistic charged particles by the factor $\exp^{-1}$ as they pass through matter. And the energy loss of these cosmic ray particles fluctuates from event to event. Heavier nuclei have significantly shorter interaction lengths and lose energy much faster.

Particles encounter the geomagnetic field of the earth once they have arrived at our planet. The strength and direction of the geomagnetic field vary with changing latitudes and longitudes. These two factors of the magnetic filed heavily influence the flux of the incident particles over an area on earth. There is also a general east-west effect in the flux of the charged particles. This means that the general direction of the geomagnetic field is such that more primary cosmic rays come from the west rather than the east.

Once these cosmic ray particles have entered our atmosphere and interacted with the air molecules they begin a cascade of nuclear reactions starting from the top of the atmosphere all the way to ground. At ground level, these are known as cosmic



Schematic Diagram of Cosmic Ray Shower

Figure 1: A general schematic representation of particle production in the atmosphere. It shows moderately energetic collisions taking place [2].

ray showers. And they have two components to them: the 'soft' electromagnetic component and the 'hard' muonic component.

Figure 1 shows a general schematic representation of these cosmic ray showers. By measuring the mass, charge, and energy of a particle at a certain altitude we can determine what exactly the particle was and what is its place in the cascade. Measurements are usually performed by detectors placed on hot air balloons, airplanes or by satellites high up in the atmosphere.

2.3 Secondary Cosmic Rays: Muons

Muons are basically a more massive copy of electron with mass 105.66 MeV and are spin-1/2 particles. They are approximately created around 30 km up in the atmosphere [3]. Muons coming from the atmosphere have speeds close to the speed of light, c.

Q 1. The measurement of the muon lifetime provided an early indication of time dilation which occurs at relativistic speeds($v_\mu \sim c$) according to Einstein's theory of relativity. Muons have a lifetime of around 2×10^{-6} s. If their velocity is assumed to be around $0.9997c$, what is the time taken by muons to travel 30 km to the ground in Earth's reference frame? How does this compare to their lifetime value? What is the distance traveled by muons in their own rest frame? Time dilation and length contraction are defined in the following way:

$$t_\mu = \frac{t_{Earth}}{\gamma} \tag{1}$$

$$l_\mu = l_{Earth}\gamma \tag{2}$$

Here γ is the Lorentz factor which is defined as $\gamma = 1/\sqrt{1 - v_\mu^2/c^2}$.

Muons are formed by the decay of pions in our atmosphere. Pions are also formed in our upper atmosphere through the interactions of primary cosmic rays, i.e. mainly protons, with the nuclei in the upper atmosphere. The reactions in which pions decay to produce muons occur through weak interactions and are:

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Muons are also formed by kaon decays in the atmosphere. Kaons are produced by nuclear reactions which are similar to the ones which produce pions in the upper atmosphere. However, the contribution of pions to the incident muon flux at ground level is 95 % as compared to only 5 % by kaons. Therefore for most calculations, the contribution by the kaons to the muon flux can be ignored.

The incident muon flux at sea level has the following relationship with θ (the zenith angle or the angle measured from the vertical) [4]:

$$I(\theta) = I_o \cos^2(\theta) \tag{3}$$

Here $I_o = 0.0083$ cm^{-2}s^{-1}str^{-1}.

For low energy incident muons, the muon flux decreases in general as the angle increases as shown by Figure 2. This is because at larger angles the muons have to penetrate a larger distance through the atmospheric layer of air particles to reach the ground. Therefore increasing angle increases the probability of the muons interacting with an air particle or decaying before reaching the ground. The exception to this general trend is the high energy muons, i.e. $p_\mu = 1000$ GeV/c, which are mostly not affected and their flux steadily increases with increasing angle.

Therefore one of the main parameters which concern us when performing such calculations is the amount of matter above any atmospheric layer through which these particles had to pass. This is atmospheric depth measured in g/cm^2. Temperature and density variations affect the interaction of cosmic ray particles and air molecules in the atmosphere.

Theoretically, we can also calculate the muon lifetime in its rest frame using the Fermi's Golden rule. The Golden Rule provides us with the decay rate for the muons which is given by:

$$\Gamma = \frac{G^2 (m_\mu c)^5}{192\pi^3} \tag{4}$$

Here G is the Fermi constant and m_μ is the mass of the muon which is roughly equal to $106 m_e$. The value of G is 1.136×10^{-5} GeV^{-2}. The lifetime is then given by $\tau = \hbar/\Gamma$ [4].

Q 2. Charged particles traveling at relativistic speeds lose energy by Coulomb interactions with the atoms of matter at a rate of about 2 MeV/gm/cm^2. How

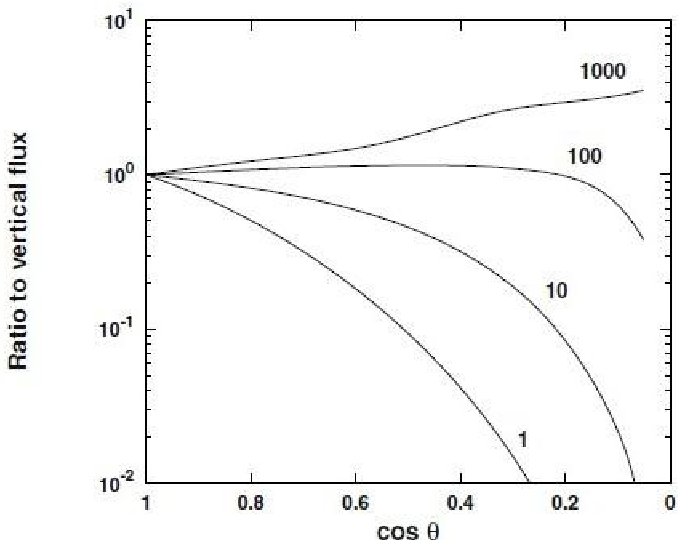


Figure 2: The ratio of inclined to vertical muon flux as a function of cos(θ). Each curve gives muon momentum in GeV/c [1].

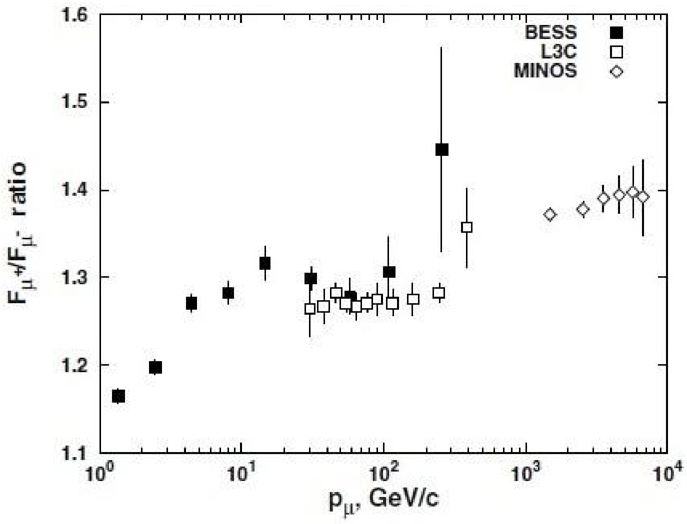


Figure 3: As the energy increases the muon charge ratio also increases. This graph shows data from the experiments BESS, MINOS, and L3C. The MINOS experiment contributions show that the higher value of ratio at higher energies is due to a larger contribution by Kaons. At high energies, K^+ are more commonly produced than K^- [1].

much energy is lost by a typical muon in traveling from its point of creation in the atmosphere to the ground [4]?

Q 3. Using the formula for the decay rate given by Fermi's Golden Rule calculate the lifetime of the muon. Compare your answer to the accepted value of 2.2 μs [4].

Q 4. How far will a muon of 1 GeV travel in the atmosphere if the muon lifetime is $2.2\mu sec$? How far will a 100 GeV muon go? A 10 GeV muon? Neglect energy loss of the muon, which would change its speed [4]. (Hint: Total energy of a relativistic particle is given by $E = \gamma$ mc^2)

One last thing that will concern us is the muon charge ratio known as $R = \frac{F_+}{F_-}$. Here F_+ and F_- are the respective muon fluxes of μ^+ and μ^- measured for varying momentum values of the muons. The ratio R always has a value slightly greater than 1 due to the nature of the nuclear interactions taking place in the atmosphere. This also gives the overall particle cascade a net positive charge. As μ^+ are produced from π^+ and μ^- from π^-, R is basically the π^+/π^- production ratio. In this experiment the value of R used will be $R = 56/44 = 1.27$ [5]. The relation of the ratio R and muon momentum can be seen in Figure 3.

3 The Muon Lifetime Experiment

The mean lifetime of the muon in its rest frame also called the lifetime measured in its proper time, is known to be (2.19698$\pm$0.00004) μs [6]. We aim to measure the average decay time of muons. Muon coming from the atmosphere from above will strike in scintillator and will give off some of its energy to it, this will excite scintillator's atom which will give off a photon. The photon will be sensed by the photo-multiplier tube (PMT) and will produce an electric pulse correspondingly. If the Moun does not have

enough energy to escape the scintillator, it will decay and will give off energy which would again excite an atom of the scintillator which will give off the second photon. Electric pulses generated by these detectors are then aligned, using delay box and delay cable, refined and filtered using discriminators and electronic logic units. A time-to-amplitude converter and a multi-channel analyzer are then used to generate a distribution of the time interval. The distribution is fitted with an exponential function whose gradient gives us the mean lifetime of the muons. Figure 4 shows a block diagram of the experimental scheme.

The plastic paddles of detectors A and C are relatively thin and therefore generally are unable to stop the incoming muons. However, there is a very large probability that paddle B, which is five times thicker than A and C, will stop the incoming muon inside it.

Three scintillators are used so that logic could be built to filter false positives, the logic would be as follows:

If a muon is detected on all three scintillators at the same instant then it means that scintillator was unable to capture Muon and so the pulses generated would not be of any use in measuring lifetime and should be discarded. If muon is detected on first

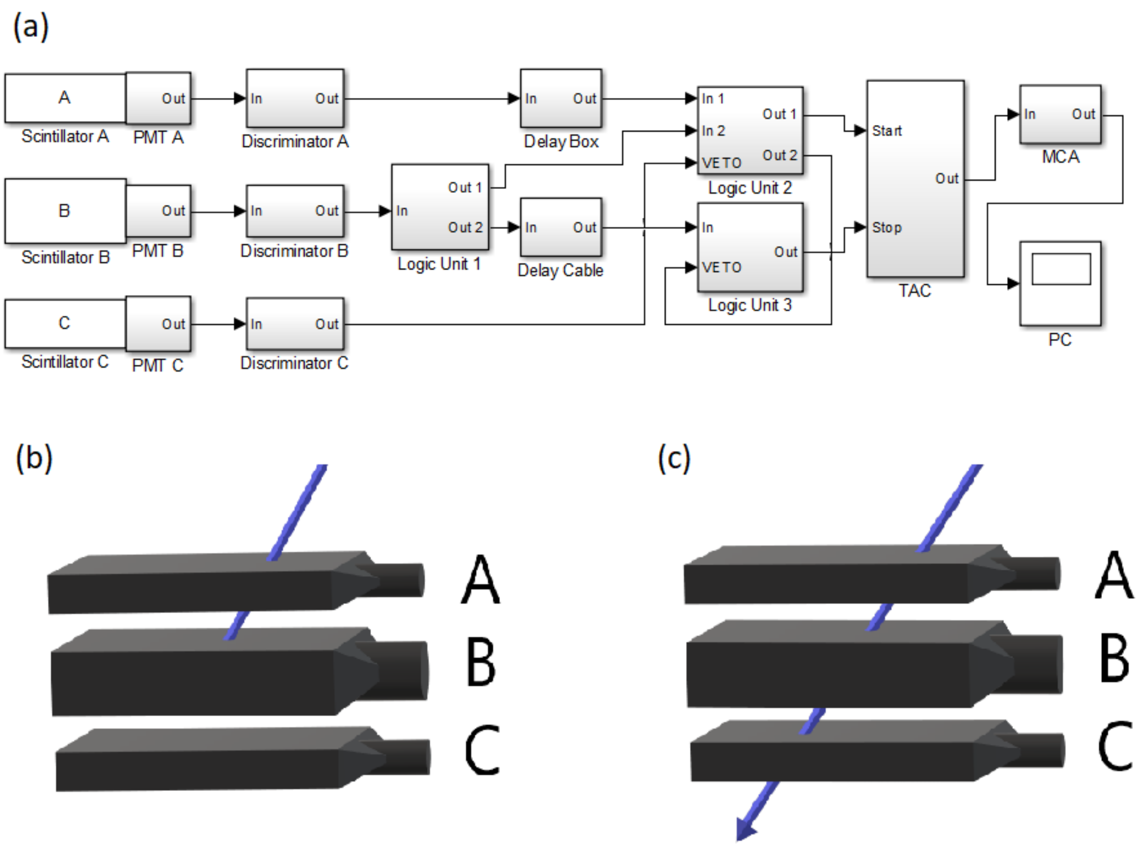


Figure 4: (a) The schematic diagram of the muon lifetime experiment. (b) When the muon is stopped in B, only A and B generate pulses. This generates the $AB\bar{C}$ signal. (c) When a muon passes through all three detectors, all three generate pulses. This is known as an ABC signal.

two scintillators then its a timer starts signal, and if another signal in the window of $10us$ only from the second scintillator is measured then it is timer stop signal. If we name scintillators A, B, and C respectively from top to bottom then in terms of Boolean logic it can be represented as follows:

$$START = A \ \& \ B \ \& \ \overline{C}$$

$$STOP = B \ \& \ \overline{(START)}$$

Using Moun count and the time difference between START and STOP can be used to plot a Moun decay graph. Further data analysis is discussed in Section 4

3.1 The PMTs and Scintillators

Q 5. What are scintillators? Compare the advantages and disadvantages of organic and inorganic scintillators?

Polyvinyl toluene (PVT), which is a plastic scintillator, will be used in this experiment. Polyvinyl toluene has a refractive index of 1.58 and a density of 1.038 gcm^{-3}. Three plastic scintillators were required to conduct this experiment. Their shapes were in the form of paddles as shown in Figure 5. Two of them have the same dimensions of $20 \times 300 \times 500$ mm ($h \times w \times l$) and the third one has dimensions of $100 \times 300 \times 500$ mm. The scintillators are wrapped in aluminized mylar sheets which are highly reflective and are made light-tight by covering them with black tape.

Q 6. Using the value of I_o and the size of the detectors estimate the number of muons incident on the detectors per second per steradian [4]. See Equation 3.

Q 7. Given the density of PVT (1 g/cm^3) and the rate of energy loss(through Coulomb interactions) of a charged relativistic particle (2 $MeV/gm/cm^3$), estimate how much energy will a 100 MeV muon lose in 2 cm of scintillator [4]?

Q 8. Briefly explain the working of a photomultiplier tube. You may attach a diagram to aid your explanation

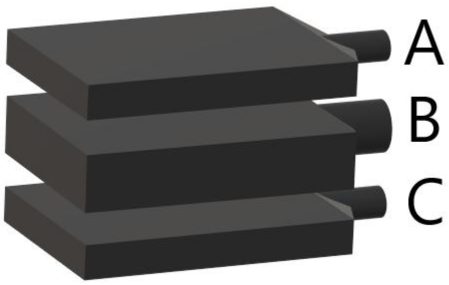


Figure 5: Plastic scintillators with PMTs attached at the back and wrapped in aluminized mylar sheets.

Three PMTs will be used in our experiment; one for each scintillator paddle. Two identical smaller ones (20 mm diameter PMT) for the thinner paddle and the bigger one (80 mm diameter PMT) for the thicker paddle. The PMTs used with their respective model numbers were Hamamatsu E990MOD2 for the 20 mm and REXON $RB14-8E$ for the 80 mm one.

The PMTs and scintillators joined together are collectively referred to as the detectors. They are labeled as A, B, and C respectively with detectors A and C being the identical smaller and the detector B being the larger one.

3.2 Setting up the electronic apparatus and the electronic units

At this point, all the apparatus and electronics involved are OFF. Now we are going to go through the function of each electronic unit one by one in order as they come up in the experiment. The function of each electronic unit and the place of the unit with respect to the rest of the experimental setup will be studied and analyzed. At the end of this exercise, you would have set up all the electronics and will be ready to take data to calculate the mean lifetime of the muon.

The oscilloscope is an integral part in setting up of this experiment. It will help you navigate around waveforms and pulses as you proceed through the electronics towards the MCA. At each point use the oscilloscope to determine what actually a module does to the waveform by observing the waveform before and after it has passed through a module. This will help you in understanding the whole system much better. The oscilloscope will also help you determine the noise levels of the PMTs and will give you a sense of where exactly should the thresholds for these PMT pulses should be set at. The oscilloscope being used is PicoScope 5203 from Pico Technologies.

Inputs and outputs of the logic electronics in the NIM modules have a standard impedance of 50 ohms. However as the oscilloscope has a high input impedance, so be sure to terminate the scope inputs with 50 ohms. Un-terminated lines will cause reflections of pulses due to the impedance mismatch with the 50 ohm cable.

In this experiment, you will be working with high-speed electronic pulses so the timing of the pulses would be extremely crucial. For every extra foot of wire used a delay of 1.5 ns in the signal would be generated. Any electronic module can generally add a time delay of around 10 ns in your pulse. As the time intervals, we are working with are extremely small so attention to such details would be very crucial.

3.2.1 Photomultiplier tubes

You may now turn on the high voltage supplies for the PMTs. Set the voltages of all three high voltages to 1100 V. **DO NOT EXCEED THIS LIMIT** or otherwise, the PMTs will be damaged.

The PMT outputs are used as inputs for three discriminator units on the NIM module. Observe the pulse from each PMT on the oscilloscope before entering it as input to the discriminator unit. The PMT waveform should look something like as shown in

Figure 6.

Q 9. What are electronic signal reflections? Are they visible for these three PMT signals on the oscilloscope?

Q 10. What is 'ringing' in electronic signals? Are they visible for the three PMT pulses?

Q 11. How can the reflections and ringing be minimized?

The pulses A and C will be quite similar and different from B pulses. The B pulse would also have a larger width and amplitude as compared to A and C. This is due to the larger scintillator and PMT combination for B. This also means that B generates greater noise as the PMT has more dynode stages.

Observe the amplitudes for 'noise' and the muon signals in raw waveforms for A, B, and C and try to come up with a threshold level for each PMT pulse to render the noise unobservable.

Q 12. What is the primary source of 'noise' in the PMTs? Does changing voltage or threshold level have any effect on these signals? Please explain your answer.

3.2.2 Discriminators

Pulses from the PMT's are negative but not square. However, the electronic logic units only work with negative square pulses of $-1.3V$ amplitude which are also known as logic pulses. The function of the discriminators is to convert the negative pulse of the PMT into a negative square pulse so that they can be then used by the electronic

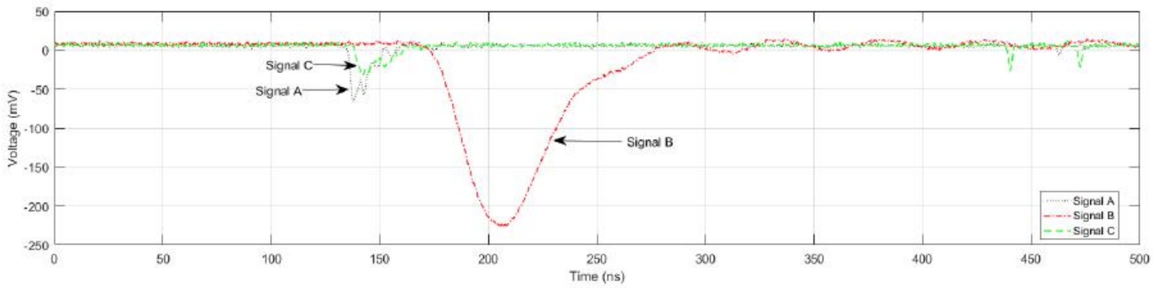


Figure 6: Raw signals from A, B, and C PMTs.

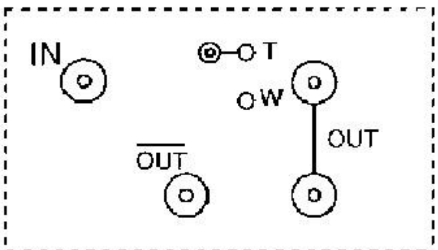


Figure 7: A single discriminator unit interface [3].

logic units.

Discriminators take PMT pulses and produce negative logic pulses **ONLY IF** the PMT pulses exceed a certain threshold voltage which is variable. It also helps to eliminate the electronic noise which becomes significant at very high voltages. This makes sure that a logic pulse would only be generated if the detector has actually 'seen' a particle because a particle would give off a pulse with a large amplitude, much larger than the amplitude of the noise signal.

We have used Phillips Scientific's Octal Discriminator Unit Module (Model 705). It contains eight discriminators. Each discriminator unit has the channels shown in Figure 7.

The threshold and the width of the pulse can be varied however they will be kept **FIXED** throughout this experiment. The width and threshold have already been set by the instructor and you will not be altering them during the course of the experiment. The discriminator has two negative outputs and one inverted (i.e positive) output. The threshold of discriminator units of PMTs A and C will be kept at -50 mV and the threshold of discriminator unit of PMT B will be kept at -75 mV.

Observe the PMT pulses on the oscilloscope after they have been passed through the discriminator units. Note down the width of each pulse produced by the individual discriminator units.

3.2.3 Logic units

We have used Phillip Scientific's Quad Four Fold Logic Unit Module (Model 755). The module contains four logic units. Electronic logic units are needed to implement the START and STOP logics explained in the start of Section 3.

So, if pulses arrive from A and B together in time, only then an output pulse would be generated, which will be called $AB\bar{C}$. Furthermore, only $AB\bar{C}$ and the second B pulse will be allowed to go ahead. However, if a pulse from C also arrived together with the A and B pulses then the signal will be 'vetoed' or rejected.

Q 13. Why are ABC signals (i.e., the pulse generated when all three PMTs generate a pulse simultaneously) rejected?

Q 14. Explain what is meant by a coincidence level in the logic unit?

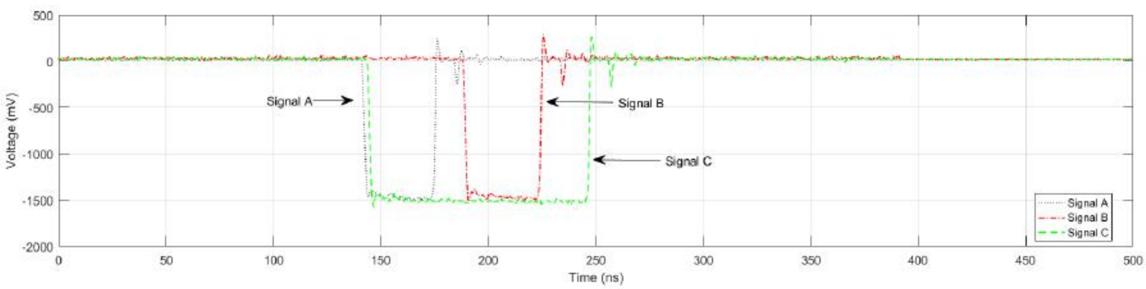


Figure 8: Discriminated signals from A, B, and C Discriminators.

For logic unit 2 to work we need to make sure that A and B pulses overlap each other. Therefore the A pulse has to be delayed such that it coincides with the B pulse. This

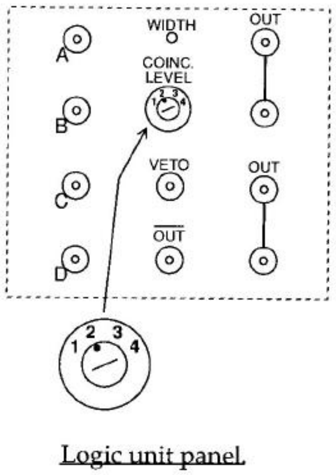


Figure 9: The Quad Four Fold Module [3].

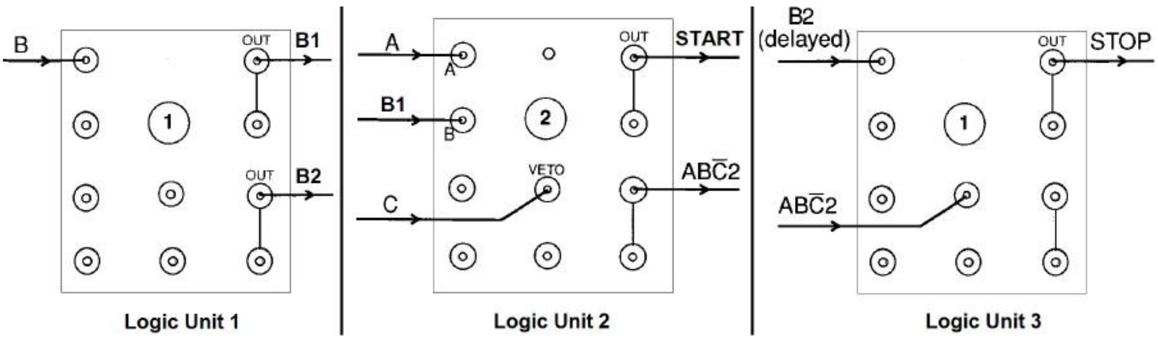


Figure 10: Logic Unit connections [3].

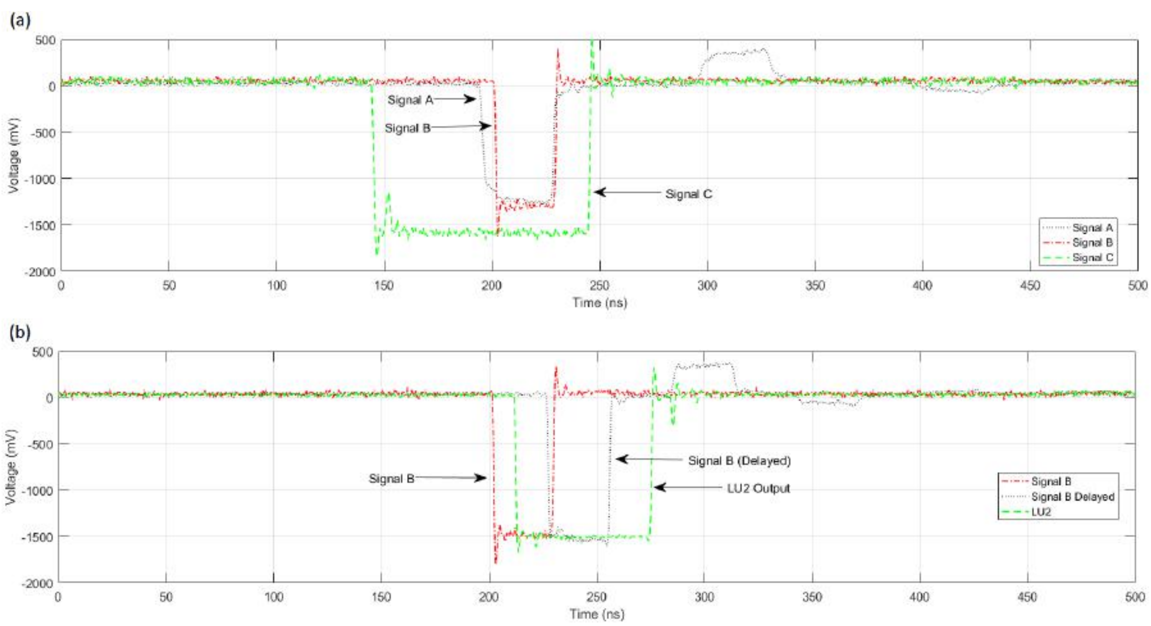


Figure 11: (a) Logic Unit 2 and (b) Logic Unit 3 inputs.

delay is empirically selected. This is done by introducing an electronically passive delay box. It is a Stanford Research Systems delay box (Model DB64).

Observe the pulses being produced by discriminator units A and B side by side on the oscilloscope. Measure the time delay of the discriminator B pulse as compared to the discriminator A pulse.

Q 15. By how much time does the A pulse need to be delayed in order for it to coincide with the B pulse?

Furthermore, the C pulse also has to be delayed to overlap with A and B pulses so that it can veto them if the muon passes through all the three detectors.

Before giving input to Logic Unit 2 ensure the following (Refer to Figure 11),

1. A has to be delayed by a certain amount to coincide with B.
2. The width of A is increased so that it overlaps B.
3. The width of C is increased such that it overlaps both A and B.

Observe Figure 4 for the following discussion. Detector B generates two pulses. One from the muon stopping in it and the second from the muon decay. Although the AB$\bar{C}$ pulse starts the timer but the first B pulse undesirably stops the timer as soon as it starts as the first B pulse arrives together with the AB$\bar{C}$.

Therefore to avoid this first pulse stopping the timer, logic unit 3 (LU3) implements the logic $B\overline{(START)}$. When the B2 pulse and the AB$\bar{C}$2 pulse arrive in sync the first pulse from detector B gets vetoed and only the second pulse from B is allowed to go forward to the STOP input of the timer.

Another delay which has to be introduced now such that B pulse coincides with AB$\bar{C}$2 pulse because the first B pulse has to be vetoed.

Before giving input to Logic Unit 3 ensure the following (Refer to Figure 11),

1. B has to be delayed by a certain amount to coincide with AB$\bar{C}$ pulse.
2. The width of AB$\bar{C}$ pulse is increased so that it overlaps B.

Logic Unit 1 is only used to split discriminator output pulse B and so that both the Logic Units, 2 and 3, could get standard input pulses, which was not possible when signal is split using Tee connector.

3.2.4 Time-to-Amplitude Converter (TAC)

A TAC measures the time interval between two pulses and then generates an output pulse of magnitude proportional to the time interval. The time to voltage scale of the TAC can be varied. For example, if we have a TAC time scale of 10 μs, it means that for a time difference of 4 μs TAC would generate a positive square pulse of amplitude 4 V. The output pulse range of the TAC is fixed and is from 0 to 10 V. If the time

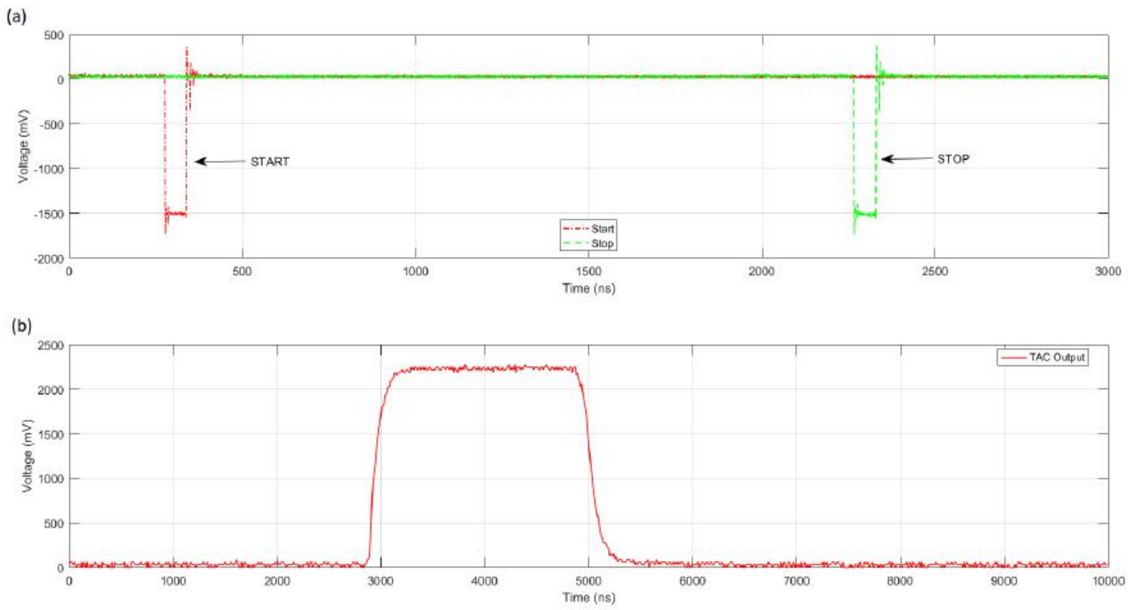


Figure 12: TAC Input/Output signals, shown in (a) and (b) respectively.

difference exceeds the time scale then that pulse is rejected and the TAC is reset. The TAC has two inputs the START and the STOP and one output called OUTPUT.

Q 16. Taking into consideration the lifetime of the muon and different timescales available which timescale of TAC should you select for this experiment? Give appropriate reasoning with your answer.

In our experiment, we have used the Ortec TAC/SCA Model 567. Output of logic unit 2 is fed into the START input of the TAC, output of logic unit 3 is fed into the STOP input and output of TAC is connected to MCA.

Q 17. By how much is the B2 pulse delayed using the electronic delay generator?

A typical START and STOP input, and output pulse generated by TAC which is a positive square pulse is shown in Figure 12.

3.2.5 The Multi-Channel Analyser (MCA)

The MCA is a device which takes only positive square pulses and distinguishes and counts them according to their amplitude (voltage). It contains channels and each channel corresponds to a specific voltage. Whenever the MCA receives a pulse of a specific amplitude it makes a count of that pulse on the corresponding amplitude channel. So each channel tells us that how many pulses the MCA received of that particular amplitude.

In our experiment, we have used AMPTEK's MCA8000D. This MCA accepts voltage pulses in the range 0-10 V which corresponds to the output voltage of the TAC. The MCA has a range of 8192 channels which means that it has a resolution of 10V/8192channels = 0.00122 V/channel. Using the data from the MCA a count vs channel histogram is generated. The histogram shows the number of counts in-

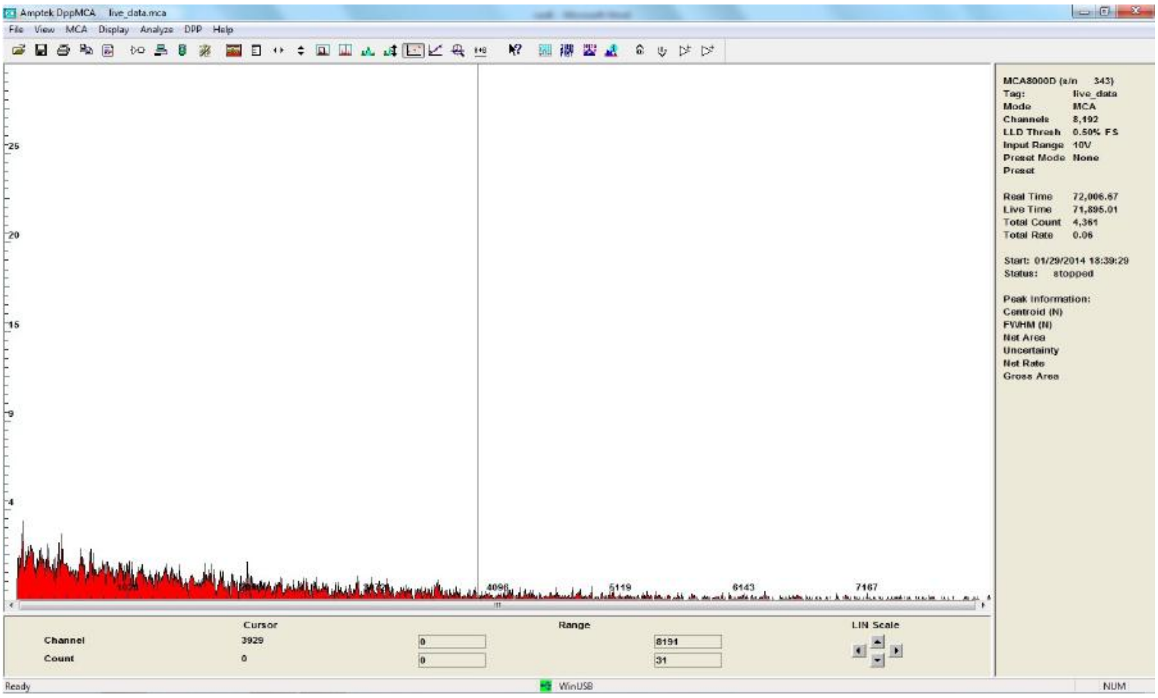


Figure 13: Output of MCA software, Amptek DppMCA.

side each channel. The channel scale must also be converted to a voltage using the 0.00122 V/channel scaling factor. The voltage scale is then converted to a time scale using the V/s scaling factor of the TAC which in this case is 1 V/μs. The histogram is then fitted with an exponential decay curve and using that the muon lifetime is calculated. This will be discussed in detail in the next section.

A typical output of the MCA software, named Amptek DppMCA, can be seen in figure 13.

4 Analysis of a Typical Lifetime Experiment

Six experimental parameters and their respective values are shown in the Table below. We will strictly stick to these parameters. You are not allowed to change these values.

A,C voltage	1100 V
B voltage	1100 V
A,C threshold	-50 mV
B threshold	-75 mV

The lifetime experiments are generally run for around 40,000 s. A typical result is shown in Figure 14.

Data is taken from the MCA software, named "Amptek DppMCA", and analyzed using MATLAB (See the next subsection describing the analysis procedure). The raw MCA data is loaded onto MATLAB and the histogram is constructed. The x-axis scale is then converted from the channel scale to time scale. The histogram is then fitted with the exponential function:

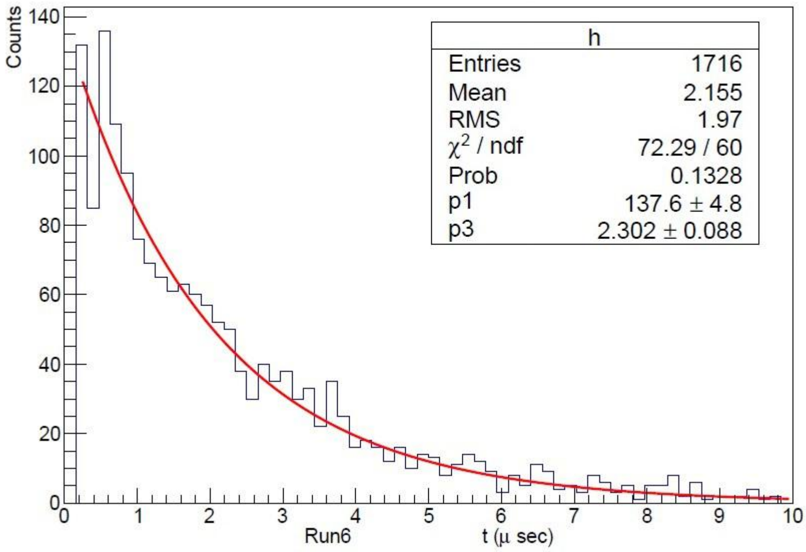


Figure 14: The histogram obtained for a typical muon lifetime experimental run.

$$f(t) = C + Ae^{\frac{-t}{\tau}}. \tag{5}$$

The histograms, obtained from the MCA data, have the general form of a decaying exponential function. Computing area under the curve will give the mean lifetime value. When the histograms are fitted with the function given in Equation (5) we obtain an estimate of τ for the experimental distribution.

After fitting the histogram, the curve-fitting program returns to us the values of A, C, and τ.

Q 18. What are your values of A, C and τ? Quote their respective uncertainties.

Q 19. Explain why, if the START pulse due to the muon arrival were delayed by 1 μs, the value of the mean lifetime we get is not 1.2 μs? [4].

4.1 Notes for Analysis in MATLAB

The traffic signal button on the top left will start or stop data acquisition when required. As the analysis will be carried out in MATLAB, save the MCA data as `.mca` file.

Import the following function files in your current MATLAB directory:

- `MCAFileReader.m`
- `DownSample.m`
- `MuonLifetime.m`

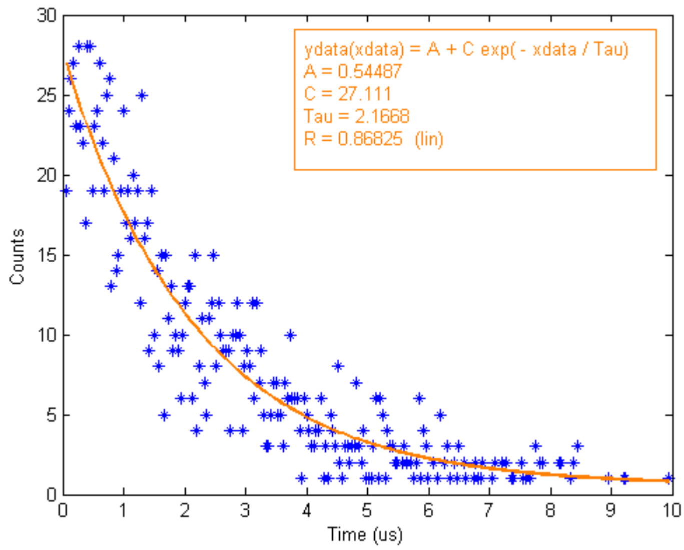


Figure 15: Raw data with the fitted exponential curve. The total counts for this plot are 1520.

The above files can be found on the Physlab website.

`MCAFileReader` function takes filename with file extension .mca as an input argument and will return xdata and its corresponding ydata.

$\gg$ `[xdata,ydata] = MCAFileReader(run_1.mca);`

`DownSample` function takes xdata, ydata, and the number of channels it is required to downsample it to. The last argument is only to be given in terms of the power of 2. The function will return the downsampled `xdata` and `ydata`. Also, this function maps xdata which is in terms of channels to time from 0 to 10 μs.

$\gg$ `[xds,yds] = downsample( xdata, ydata, 8);` % the function will downsample the data to $2^8 = 256$ channels of $binwidth = 32$, that is (8192/256).

`MuonLifetime` function takes `xdata` and `ydata` as input arguments and plots `(xdata, ydata)` and the fitted function on the graph. The figure also displays the estimated values of the unknowns in the fitting function. The `MuonLifetime` function returns input and output parameters and their values as a struct.

$\gg$ `f = MuonLifetime(xds,yds);`

This function is coded to first remove all the zero values from ydata and their corresponding xdata points. Then it uses `ezfit` tool to fit equation 5 on the dataset. Learn more about ezfit at [7].

5 Apparatus

Figure 16: Apparatus used in the experiment.