Cosmic Muons

Parker Lewis
Amadie Wijenarayana
Ohio University
Department of Physics and Astronomy, Athens, OH, 45701, USA

October 25, 2024

Abstract

The main purpose of this lab was to perform time delay calibrations for the delays of muon counts, obtain threshold voltages, get 2-fold, 4-fold muon count rates, and to prove $\cos^2(\theta)$ per muon count rate relation. Also, normally muon mean lifetime would have been an important measurement of this experiment but that was not taken into account for this iteration of the lab due to equipment maleficence [1]. [Count: 67]

1 Introduction/Theory

1.1 Cosmic Rays

Cosmic rays, are essentially high energy particles that are made up from astrophysical events like supernovae, gamma ray bursts and other astrophysical sources/events that are outside/inside our solar system. Cosmic rays are classified as primaries and secondaries. Primaries are the ones that are made from outside of our solar system primarily. They are most composed of protons, and lightly composed of alphas, heavy nuclei and electrons. They also have very long life times that range to the order of magnitude of about 10^6 years or longer. As primary cosmic rays approach the solar system and Earth, some of them are modulated by the solar wind from the Sun and deflected by the Earth's geomagnetic field. This deflection prevents many of the lower-energy particles from entering the Earth's atmosphere [1]. For the primaries that pass through modulation, they travel through the earths atmosphere and collide with atoms that compose of the earth's atmosphere. These collisions are what produce the secondaries and this is where muons come into the picture. The figure below gives a demonstration of what was explained above [Figure 1]. [Count: 187]

1.2 Muons

To reiterate secondaries are produced as a cascade of other particles from the primaries interacting with the nuclei from the atmosphere. Secondaries are composed of pion, kaon, gamma, electrons and other lighter nuclei. The pion has short half-life and decays into a muon and neutrino. A muon is a lepton, fermion, and has a heavier mass than the electron. A muon decays into an electron and corresponding neutrinos [Figure 2]. Muons also should note experience special relativity effects by traveling .997c, which matter if they can make it to the earths without decaying to an electrons composite. In the rest frame muons decay times is about 2.2 μs and can only travel 600 meters towards earth before decaying. That's why special relativity matters or it won't make it to the earth. By applying special relativity effects the muon can travel about 10-40 km [1]. Muons in earth's atmosphere have different paths of travel based on initial trajectories and they are classified by their corresponding zenith angle of travel. Muons at different zenith angle of entry has a greater or lesser likelihood of having either bunches or not much of its constituent self to make it the earth before it decays. Figure 3, gives a good demonstration of the muon path to travel of different zenith angles. Finally then muons can then be detected by scintillating telescopes, and this is what this lab is based on. [Count: 236]

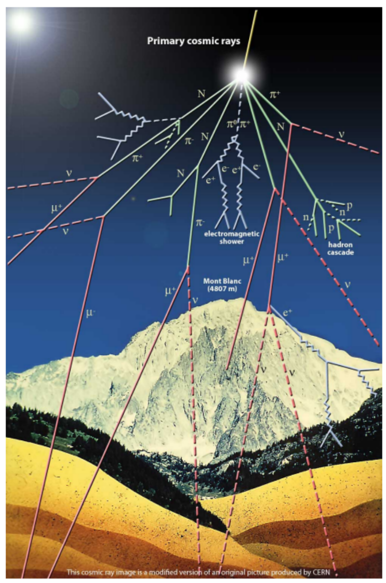


Figure 1: An illustration, showing when primaries interact with other nuclei from nitrogen and oxygen gas from Earth's atmosphere it creates from nuclear processes/reactions and collisions other cascade of particles called secondaries.

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

Figure 2: Decay relation that shows that a muon/anti-muon pair decays into electron/positron with corresponding neutrinos.

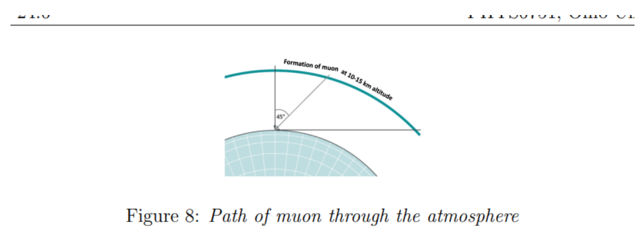


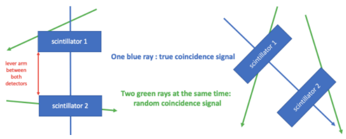
Figure 3: Representation for what zenith angles muons travel to enter the earth and being detected. The larger than zenith angle of entry the lesser of amount of muons to make it to the earth.

2 Equipment/Procedure

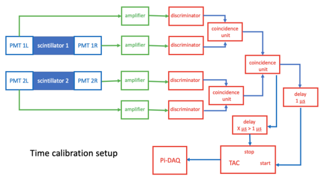
2.1 List of Equipment

Here is a list of the equipment used in this lab:

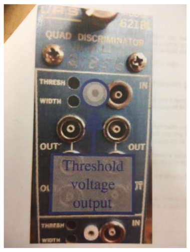
1. Two scintillating telescopes
2. Four photomultipliers
3. Rotating apparatus
4. Electrical equipment:
   - Wires/Wiring
   - Four amplifiers
   - Four discriminators
   - Two delays
   - Potentiometer
   - Three Coincidence Units
5. Time-Analog-Converter (TAC)
6. Phone Timer
7. Oscilloscope
8. Protractor
9. Multimeter
10. Power supply



(a) Scintillation detector that the muons will enter and be absorbed by scintillator.



(b) General setup on how to design equipment, perform calibration step and do counting trials.



(c) Example of where to change individual threshold voltages when running counting trials.

Figure 4: Different setups in the cosmic muon lab: a pictorial view of muon/electron either be detected separately or same time, time calibration setup, and the discriminator machine that is used to connect wires of specific PMT's and running individual counting experiments. This rotating apparatus is what is used to take azimuth angle trials per count rate of muons. Convert to zenith angles later.

The above figure outlines the steps that were taken to data collect on this lab and how to run the equipment. Specifically there were four important tasks to do: time delay calibration, threshold calibration, measuring coincidence rates, and measuring count rates for different zenith angle values ranging 0 to 90 degrees [Figure 4]. [Count: 53]

2.2 Equipment Calibration

Time Calibration

Time calibration is crucial because it ensures that muons are counted accurately by eliminating systematic errors, which ultimately allows for an accurate determination of the muon's mean lifetime. However, due to equipment issues, the mean lifetime measurement could not be performed in this experiment. In this step, the threshold was set 8 mV then the start and stop times on the oscilloscope were defined based on the pulse wave, and data was collected accordingly. The Time-to-Analog Converter (TAC) digitized the pulses, with each delay counted over 1-minute trials for consistency, resulting in a histogram displayed on the Data Acquisition System (DAQ). The histogram represented counts per channel. The stopping times spanned approximately 1-8 μs, with increments of 1 μs. Linear fitting was then applied to the mean channel numbers for each peak at different delays to verify that they corresponded well. As shown in Figure 5 and Table 1, the linear fit confirms that the TAC is properly calibrated. [Count: 159]

Peak	Total Count	Time Delay (μs)	Mean Bin	RMS
1	235 ± 15	0.44	1480 ± 0.041	0.617 ± 0.032
2	295 ± 17	1.50	2647.55 ± 0.14	2.221 ± 0.126
3	266 ± 16	2.80	3810.930 ± 0.598	6.217 ± 0.502
4	255 ± 16	4.0	4967.68 ± 1.16	9.310 ± 0.913
5	202 ± 14	5.14	6063.310 ± 0.786	9.225 ± 0.670
6	124 ± 11	6.30	6238.06 ± 1.45	10.370 ± 1.519
7	257 ± 16	6.98	6776.16 ± 0.82	9.850 ± 0.840

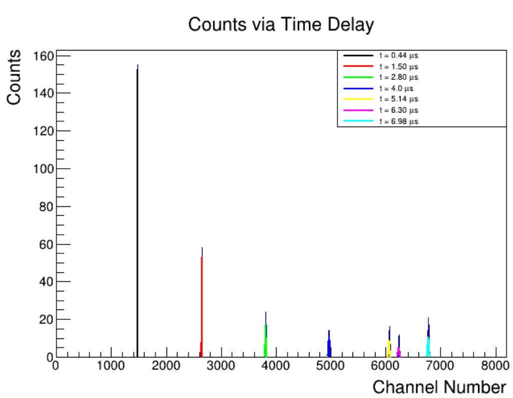
(a) Raw data for time delay calibration. Each peak represents a Gaussian distribution from multiple trials. For column 2 these values are stop and start differences.

.

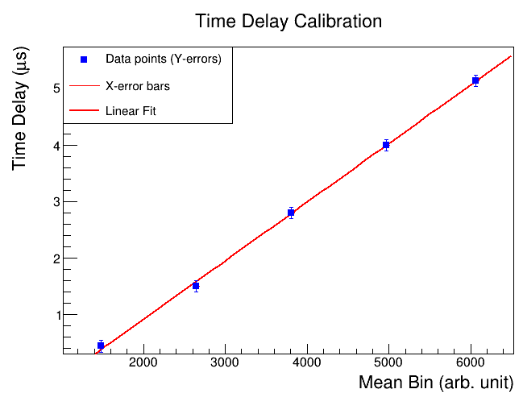
$$t_{delay} = a \cdot x + b \tag{1}$$

- $a = 0.001036 \pm 0.000028$
- $b = -1.15 \pm 0.11$

(b) Linear fit equation used to calibrate time delay, with slope and intercept values.



(c) Delay histogram generated from voltage pulses converted to spectrum by DAQ. The difference of stop and start were used as display.



(d) Calibration plot of delay peaks showing linear relationship to convert bin to delay time. The measured uncertainty used here was 0.1 μs for each data point.

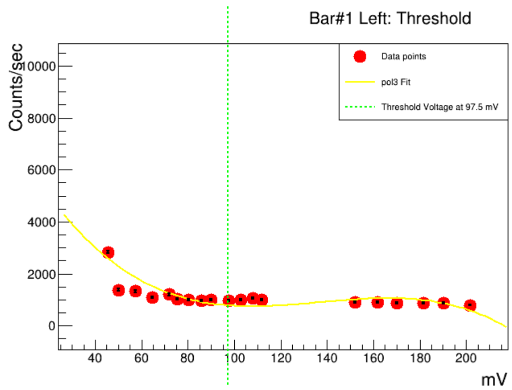
Figure 5: Combined results of time delay calibration: table, equation, and histogram. This comprehensive display includes raw data, calibration plots, and linear fitting.

Fit Type	Residual	Uncertainty
	0.057	0.91
	-0.093	1.8
Time Calibration	0.0019	2.4
	0.0035	2.8
	0.0084	3.2

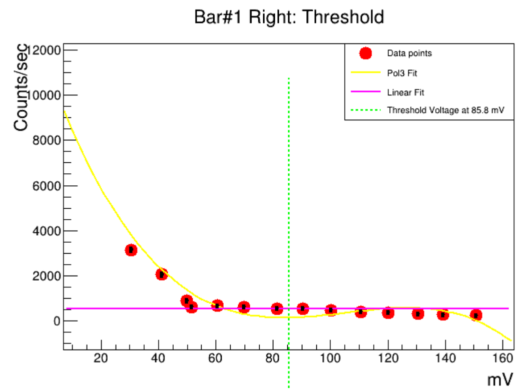
Table 1: Residuals for time calibration fits with corresponding uncertainties.

Threshold Calibration

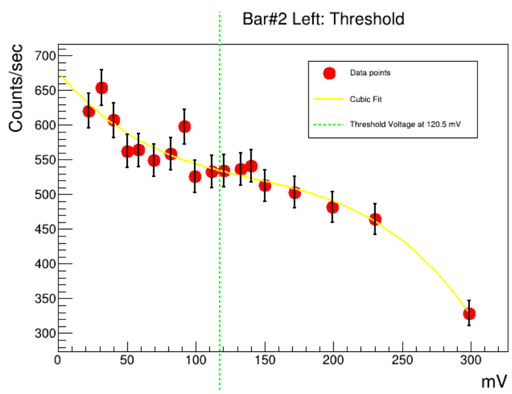
For this part the experiment we have to determine thresholds of the left, right sides of the top and both photomultiplier tubes. They're classified as Bar 1, Bar 2 left/right. Determining thresholds help calibrate to get correct coincidence rates for muon count rate for total top side and bottom PMT and for all 4 sides of the same time. To get thresholds you run multiple trials for all 4-sides where you setup correct wiring connections, adjust potentiometer, run the timer multiple times and recorded muon count for that side. In the end you have enough data to where you can see a pattern of initial count rate drop, plateau and another count rate drop. By picking a region with a plateau region of plotting and where the count rate is about the same for a while, then threshold is found. Once both criterion are met then a threshold value is chosen. Figure 6 and table 2 are the data was collected and fit the process I explained above. [Count: 168]



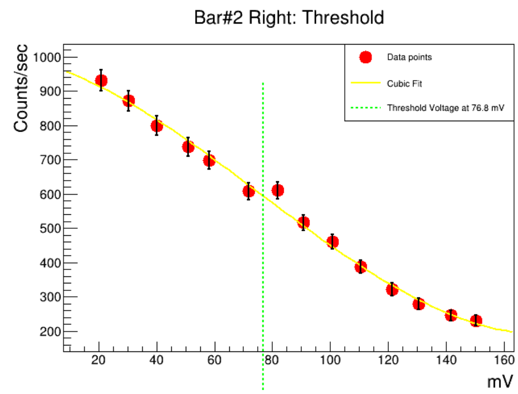
(a) PMT top Left sided plot.



(b) PMT top Right sided plot.



(c) PMT bottom left sided plot.



(d) PMT bottom Right sided plot.

Figure 6: Plots that are Representative of count rate and thresholds to get a threshold voltage for each sided PMT. Data collected within 30 second intervals.

PMT	Threshold Voltage (mV)	Counts	Count Rate (counts/sec)
Bar 1 Left	97.5	30433 ± 174	1014 ± 5.8
Bar 1 Right	85.8	15347 ± 124	512 ± 4.1
Bar 2 Right	76.8	17362 ± 132	578 ± 4.4
Bar 2 Left	120.5	17776 ± 133	592 ± 4.4

Table 2: Threshold voltages and count rates for PMT detectors left and right sides. Count Rates follow Poisson counting statistics so uncertainty for both count and count rate follows $\sqrt{N_{counts}}$

3 Analysis

3.1 2-fold and 4-fold Count of Muons

Now with all the thresholds found setup each discriminator with the corresponding thresholds. Finish each wiring connections to collect for 2-fold and 4- fold trials. Each trial for this was about

30 seconds here. General trends should be that with 1-fold, 2-fold, 4-fold that the muon counts and count rates should decrease which is shown on tables 2, 3, and 4.

PMT	Bar 1	Bar 2
	Trial 1	Trial 2
Coincidence 1 (counts/sec)	93.5 ± 1.8	97.5 ± 1.8
Coincidence 2 (counts/sec)	107.7 ± 1.9	106.9 ± 1.9
Bar 1 (counts)	2806 ± 53	2924 ± 54
Bar 2 (counts)	3232 ± 57	3207 ± 57

Table 3: 2-fold coincidence rates for the top and bottom PMT tubes. Collected for 30 second frames.

All PMT's Sides	Trial 1	Trial 2	Trial 3	Trial 4
Count Rates (counts/sec)	5.333 ± 0.422	5.30 ± 0.42	4.733 ± 0.397	5.10 ± 0.41
Bar (counts)	160 ± 13	159 ± 13	142 ± 12	153 ± 12

Table 4: 4-fold coincidence rates for both PMT's including the sides. Collected for 30 second frames.

3.2 Angular Dependence of Muons

This is the most crucial part of the lab to see if the muons count rates follow angular dependence by the corresponding zeniths. For this part, we rotates the leaver arms of telescope to corresponding zenith going from 0° to 90° in steps of 10°. At each corresponding angle we took count measurements for about 30 seconds. As shown in Figures 7a and 8c the fit is not perfect based on plot and residuals, but it's good enough to show that muon follow angular dependence. Also, fitting parameters were determined based on the muon count rate that shows it does okay matching the data. Count Rates follow Poisson counting statistics so uncertainty for both count and count rate follows $\sqrt{N_{counts}}$. Side note: we forgot to include angle uncertainty so that's why that's not addressed. [Count: 115]

θ (deg)	θ (rad)	Counts	Count Rate (counts/sec)
0	0.0000	11 ± 3	0.366 ± 0.110
10	0.1745	12 ± 3	0.4 ± 0.1
20	0.3491	17 ± 4	0.566 ± 0.137
30	0.5235	33 ± 6	1.1 ± 0.2
40	0.6981	53 ± 7	1.766 ± 0.242
50	0.8727	59 ± 8	1.966 ± 0.256
60	1.0472	87 ± 9	2.9 ± 0.3
70	1.2217	115 ± 11	3.833 ± 0.357
80	1.3963	135 ± 12	4.5 ± 0.4
90	1.5708	106 ± 10	3.533 ± 0.343

(a) Angular distribution parameters demonstrating muon zenith angular dependence.

$$f(x) = A\cos^2(\omega x + \phi) + B \tag{2}$$

- $A = 3.60 \pm 0.27$
- $B = 0.341 \pm 0.072$
- $\omega = 1.10 \pm 0.12$ rad/s
- $\phi = -0.043 \pm 0.139$ rad

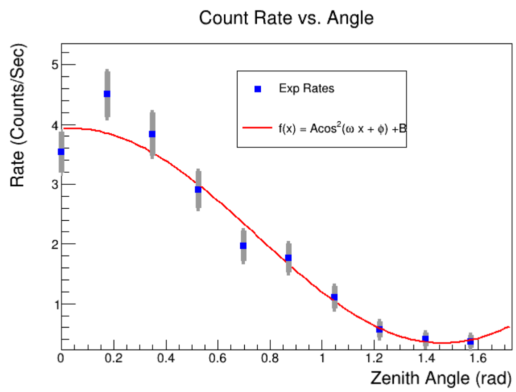
(b) Fit parameters for the angular dependence using the cosine-squared function.

$$f(x) = mx + b \tag{3}$$

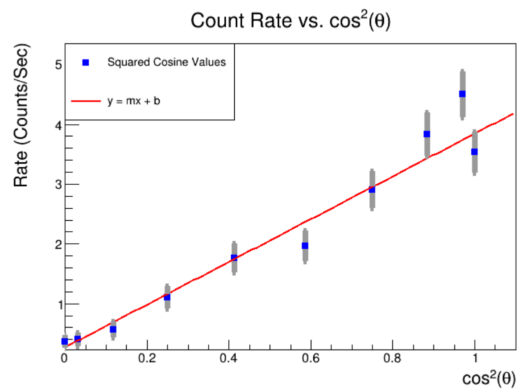
- $m = 3.57 \pm 0.20$
- $b = 0.273 \pm 0.070$

(c) Linear fit parameters for angular dependence linearized by $\cos^2(\theta)$.

Figure 7: Tables and equations for the analysis of muon angular dependence and fitting parameters.



(a) Muon count rate vs θ (rad) plot.



(b) Muon count rate vs $\cos^2(\theta)$ plot.

Fit Type	Residual	Uncertainty
$\cos^2(\theta)$	-0.307	2.7
	0.768	2.9
	0.411	2.7
	-0.048	2.4
	-0.398	2.1
	0.022	1.9
	-0.063	1.5
	-0.121	1.1
	0.022	0.88
	0.097	0.80

(c) Residuals for $\cos^2(\theta)$ fit with corresponding uncertainties.

Figure 8: Plots and residuals for the analysis of muon angular distribution, including fitting results.

4 Conclusion

In conclusion we demonstrated that calibrating works, were seeing the patterns of counting trends, and most importantly is seeing the angular dependence of the muon. Next time it would be great to test and get a mean lifetime measurement to get the full experience of this lab. [Count: 47]

Works Cited

[1] Dr. Paul King. *Physics 6751: Nuclear Lab Manual*. Version 24.5. Athens, Ohio, 2024.