Measuring Cosmic Muon Flux in Lubbock, Texas

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Abstract

In this paper I explore the experiment and data analysis done to measure cosmic muon flux in Lubbock, Texas. We've utilized two paddles consisting of a scintillator and a PMT each, and measured output voltages at a threshold of 500 mV. We repeated these measurements at angles $-90^\circ \leqslant \theta \leqslant +90^\circ$ as well as with lead shielding to attempt to confirm our results in different settings.

1 Introduction

1.1 Background Information: Muons

Cosmic Muons are an elementary particle produced by $\pi^\pm$ decay resulting from high energy proton collisions in the Earth's upper atmosphere. $\pi^\pm$ and $\mu^\pm$ from such collisions are considered relativistic, traveling at incredible speed, causing time dilation within Einstein's Relativity. Although $\pi^\pm$ do no live long enough to reach the surface of Earth even with time dilation (decay within approximately 30 nanoseconds), $\mu_\pm$ do live long enough to reach the surface of Earth, allowing for this experiment to be performed. $\mu^\pm$ carry the elementary charge ($\pm e$), but are much more massive (approx. 200x) than electrons. $\mu^\pm$ live approximately 10^{-6} seconds and decay into an electron and two neutrinos (μ and e neutrinos) [1].

1.2 Background Information: Experimental Tools

We have utilized scintillator and photomultiplier tube technology for cosmic muon flux measurement. Scintillators contain some form of "luminescent" material, which means that the material will produce light upon ionization. Charged particles traversing the scintillator will ionize the luminescent medium, depositing energy within the material to be re-emitted as a photon. This is the means of production of photons for use in the PMTs. Photomultiplier tubes contain a photocathode and several dynode stages. A luminescent photon from the scintillator stage strikes the photocathode and induces the photoelectric effect, releasing a photoelectron into the PMT. The photoelectron begins a cascading effect as it strikes the first dynode stage, releasing 2-4 secondary electrons per striking electron. Secondary electrons strike the next dynode stage, and the process repeats for some amount of stages (12 in this case), generating approximately $(10^6)(1.6 * 10^{-19})$pC, or 0.02 milliamps of current [1]. The ending stage of the PMT is a output voltage detector that we have wired to a standard dual channel oscilloscope. In this experiment, we use two Scintillator/PMT detection paddles on a 500 mV threshold, and we only count events that trigger both paddles.

1.3 Background Information: Mathematics

To accurately obtain flux measurements, we cannot simply count on the raw $\mu_\pm$ count as this number could only give us information about perpendicularly incident particles, and we want all particles incident on both paddles. In order to make this calculation, we've estimated the area of the paddles and will calculate the solid angle Ω of incident $\mu_\pm$ in the following way.

$$\Omega_{Sr} = \int_0^1 \int_0^{2\pi} \int_0^\theta \rho^2 \sin\theta d\rho d\phi d\theta \tag{1}$$

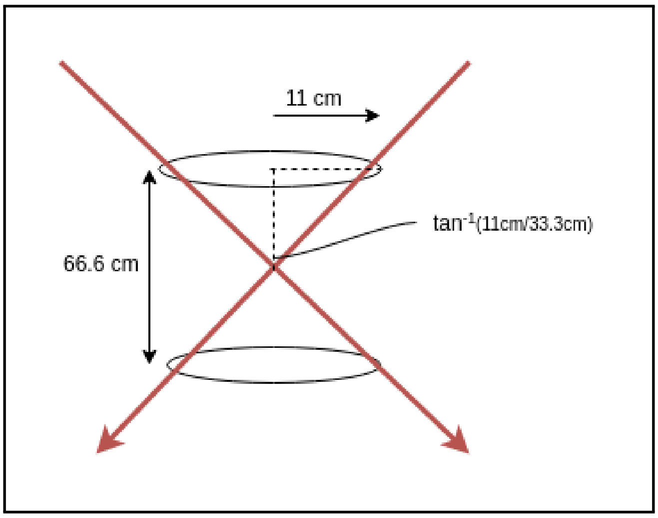

Figure 1: Estimating circular paddles, we used this symmetry to calculate solid angle. The red lines denote incident $\mu^{\pm}$ traversing both paddles, where the $\arctan(\frac{11}{33})$ term is the key to the solid angle calculation. Radius and separation were measured in the lab.

Equation (1) is the formulation of solid angle [2] for spherical coordinates, accounting for the spherical symmetry of incident cosmic $\mu^{\pm}$ on the surface of the Earth. We've allowed for the ρ integral to be 1 as the height of the apparatus is negligible compared to the Earth and the solid angle in this symmetry does not depend on ϕ so this integral will evaluate to 2π.

$$\Omega_{Sr} = 2\pi \int_0^{\theta} \sin\theta d\theta \tag{2}$$

$$\Omega_{Sr} = 2\pi(-\cos\theta)\Big|_0^{.343rad} \tag{3}$$

$$\Omega_{Sr} = .378 \tag{4}$$

We will use this value of the solid angle to calculate true incident $\mu^{\pm}$ rate in the following, Equation (5):

$$\mu_{rate} = \frac{\mu_{count}}{tA\Omega_{Sr}} \tag{5}$$

Which yields proper units of $\frac{1}{sm^2Sr}$ for parameters time (t), area (A), and Solid Angle Ω_{Sr} (Sr). Note that the value of the Solid Angle changes with different separations of the paddles, which we will take into account when we change the separation distance in one of our experiments.

2 Experimentation

During this investigation, we were able to complete two experiments.

2.1 Experiment 1: Cosmic Muon Flux (Angled)

Experiment 1 consisted of measuring the cosmic muon flux in Lubbock, Texas at angles off the vertical. To achieve this, we took measurements of equal lengths of time sweeping from $-90°$ to $+90°$ in increments of $30°$.

We chose to take 5 minute exposures at each angle, for three measurement trials. We chose this time index because we believed that this would be adequate enough time to find a statistically reasonable and/or significant value for the cosmic muon rate in Lubbock, Texas. Our measured cosmic muon flux rate is within reasonable error of the value provided in the manual [1], however we feel that the amount of error would be better reduced by more trials, rather than by the same number of trials over a longer amount of time.

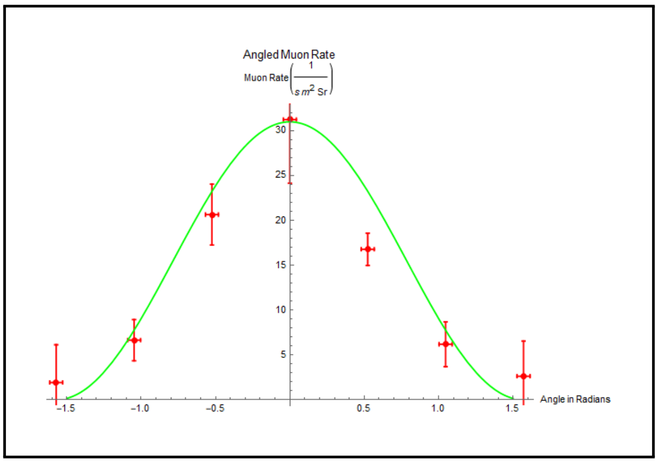

Figure 2: Cosmic $\mu^{\pm}$ flux in Lubbock, Texas plotted against $\cos^2(\theta)$

Angles(deg)	$-90°$	$-60°$	$-30°$	$0°$	$30°$	$60°$	$90°$
Trial 1	10	31	90	123	66	20	16
Trial 2	9	21	80	141	80	26	3
Trial 3	6	34	97	140	71	34	15
Averages	8.33	28.66	68.00	134.66	72.33	28.66	11.33

Table 1: Angled $\mu_{\pm}$ raw count data before calculation with Equation (5)

Using each value from the raw count data in Table 1 in Equation (5) gives us Cosmic Muon flux with proper units, where we have used the Std. Deviation as a means of error analysis for a repeated measurement experiment [3].

Angles(deg)	$-90°$	$-60°$	$-30°$	$0°$	$30°$	$60°$	$90°$
Angled Muon Rate	1.93	6.65	20.65	31.25	16.79	6.19	2.63
Std. Dev.	± 4.2	± 2.3	± 3.4	± 7.1	± 1.8	± 2.5	± 3.9

Table 2: Cosmic $\mu_{\pm}$ flux in Lubbock, Texas at 30° increments, 5 minute intervals, 500 mV threshold.

2.2 Experiment 2: Cosmic Muon Flux (Lead Shielded)

In this experiment we will use lead bricks to reduce the flux of cosmic $\mu^{\pm}$ on the bottom detector, while leaving the top detector unshielded. We will use this to attempt to demonstrate a reduction in cosmic $\mu^{\pm}$ flux traveling through dense material like lead.

For this experiment, we set up the detectors in a rack such that the paddles remain aligned with each other, but we do not place lead bricks directly onto the fragile detectors. Since we are using a different setup we must recalculate the Solid Angle Ω_{Sr} to create an accurate representation of the muon flux detected with this configuration. Once again, we've done 5 minute exposures because we feel this is adequate time to demonstrate a statistically accurate muon flux. Equation (6) is the result of solid angle recalculation when the paddles remain at the same area, with the same exposure time, but separation distance increases to 81 cm.

$$\Omega_{Sr} = 0.220 \tag{6}$$

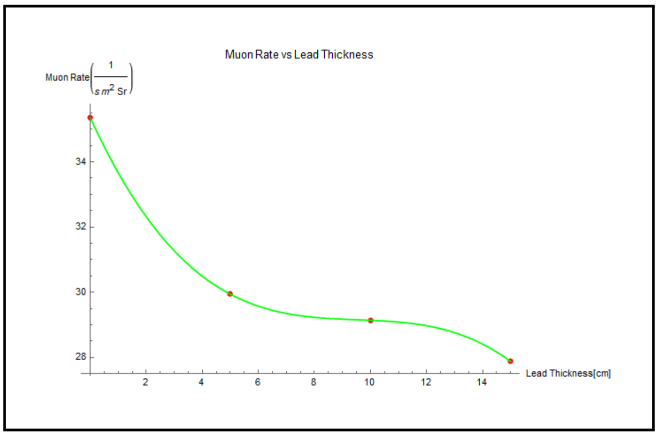

Figure 3: Cosmic $\mu^{\pm}$ flux in Lubbock, Texas fitted to a 3rd Degree Polynomial.
$35.3624 - 1.88514x + 0.194035x^2 - 0.00677493x^3$

Absorption Media	0 Bricks	1 Brick	2 Bricks	3 Bricks
Trial 1	79	68	65	74
Trial 2	106	81	69	76
Trial 3	84	66	86	75
Trial 4	92	84	71	61
Trial 5	96	-	-	62
Trial 6	73	-	-	-
Trial 7	88	-	-	-
Averages	88.26	74.74	72.75	69.6

Table 3: Raw $\mu^{\pm}$ count data with 0,1,2, and 3 lead brick absorption layers

Absorption Media	0 Bricks	1 Brick	2 Bricks	3 Bricks
$\mu_{\pm}$ Rate	35.24	29.84	29.05	27.78
Std. Dev	$\pm$10.99	$\pm$9.07	$\pm$9.18	$\pm$7.44

Table 4: $\mu^{\pm}$ Data with Lead Shielding after calculation using Equation (5). Std. Deviation was used as means for error analysis in a repeated experiment [3].

3 Discussion of Results

3.1 Experiment 1: Cosmic Muon Flux (Angled)

Comparing our experimentally determined data to the test data provided in the manual [1], we can draw the conclusion that our data follows in a reasonable fashion. Our experimentally determined value at 0° off the vertical is approximately 31 while the test value provided is approximately 26. Taking into account the Std. Dev. of a repeated experiment [3] (determined to be an error of $\pm$7.1) we have demonstrated a correct measurement of cosmic muon flux. Additionally, the test data provided [1] fits very cleanly to a graph of the form $\cos^2(\theta)$, which we have also demonstrated to be the case in our experimentally determined data. Looking now to the other data points measured, we have shown that our data matches the test data provided within error margins across the board, with the exception of the +30° case, similarly to the result discussed for the 0° case.

In the discussion of errors, we have decided that it is more meaningful to use the Std. Dev. of repeated measurements rather than an analysis of errors built up in hand measurements (paddle separation, stopwatch, etc.) [3]. Additionally, it is necessary to discuss the variance in the +30° case, and possible reasons for this disruption in a rather smooth trend. The unsatisfying answer is that we could not be totally sure how this outlier came about, but our best guess comes to a statistical anomaly that would be eradicated with more measurements.

3.2 Experiment 2: Cosmic Muon Flux (Lead Shielded)

We began this experiment absolutely sure we would see a drastic and undeniable reduction in cosmic muon flux, however it would be just as reasonable to say that the reduction in flux present in this data is a statistical outlier just like the $+30°$ from Experiment 1. We have no test data on lead shielded muon flux in Lubbock, Texas to compare to so this analysis will come out of a vacuum. While, graphically, we have demonstrated a decrease in cosmic muon flux, it is by no means conclusive in demonstrating that this is a legitimate effect taking place here, as the difference between shielding and no shielding is just not large enough. This is clearly demonstrated by a comparison of data point to error, in which the error in each point is approximately 20 to 30 percent of the value.

4 Conclusions

To conclude, we have shown that an accurate and statistically sound measurement of cosmic muon flux rate in Lubbock, Texas can be reproduced utilizing scintillator and PMT technology and sufficient time. We have reproduced a test plot found in the muon manual [1] to a satisfactory degree for angles sweeping through $180°$ in $30°$ increments, taking into account the solid angle associated with particles incident on the Earth. We were not able to show any meaningful amount of reduction in cosmic muon flux when lead shielding is placed between the detectors, although we are reassured of our vertical muon flux rate as we've produced similar values within error for the $0°$ case at different paddle separations.

5 Going Further

Two obvious improvements to the experiments detailed in this paper come to mind. The first improvement would be to compare these measurements to measurements done at vastly different times of day to test if incidence of sunlight has any significant change on cosmic muon flux. We could also conduct the experiment at higher altitude, like the top of the a taller building on campus, or perhaps if we could gain access to a much deeper basement than that of the TTU Science building. The second improvement to this experiment would be to use many more layers of lead bricks. While our data has very loosely suggested the cosmic muons can be slowed by lead, in order to truly confirm we must use many more lead layers and exposures.

References

[1] TTU Phys 3304. Physics with cosmic muons. *TTU Phys 3304*, 1(1):1–8, 2018.

[2] Eric W. Weissten. Solid angle. *From Mathworld – A Wolfram Web Resource.*

[3] John R. Taylor. *Introduction to Error Analysis.* University Science Books, 1982.