Muon Detection Experiment:
Using Scintillators to Determine Muon Lifetime and Directional Distribution of Local Muon Flux

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When cosmic rays collide with the atmosphere, the product decays into a particle called a muon, which is a fermionic lepton with a lifetime of 2.2 microseconds. Although a muon's lifetime is short, it can reach our detector on the Earth's surface because it travels close to the speed of light, and time thereby dilates for the muon. We used a scintillator, which is a special material that emits light when muons pass through, to measure the lifetime and flux of the muons that reach the Earth's surface. We found the mean lifetime of a muon to be 2.06018 ± 0.11686 microseconds, and the directional distribution of the flux to be 28 ± 0.61451 degrees to the south of the zenith. These values are consistent with what we might expect, since the theoretical value of the mean lifetime is 2.2 microseconds, and we would expect the directional distribution of the flux to be consistent with the direction of the sun, which travels from east to west across the south over the course of a single day. However, our equipment and setup may have introduced sources of error such as thermal noise, background radiation, and the movement of the sun.

I. INTRODUCTION

When cosmic rays (i.e., protons) collide with molecules in the atmosphere, the hadron collision will create a charged pion, which decays into a muon and a muon neutrino. The theoretical average lifetime of a muon is 2.197 μs, while it takes about 30 μs for the muon to travel from the atmosphere to the surface of the Earth. However, we can detect muons from the Earth's surface because the muons travel close to the speed of light and thereby undergo relativistic effects such as time dilation. In special relativity, two objects at different velocities will experience time differently; specifically, a moving muon will appear to decay more slowly than a stationary one with respect to the rest frame of Earth. We are able to measure the muon lifetime by measuring detections that occur from 20 ns to 40 μs apart. We expect the graph of these successive detections to fit an exponential, and we use the scaling factor on the exponential to measure the lifetime of the muon.

II. METHODS

A. Experimental Methods

We used a scintillator and photomultiplier tube to detect the muons at the Earth's surface. A scintillator is a special type of material that emits blue light when a charged particle passes through. A photomultiplier tube (PMT) creates electron pulses from incident blue light using the photoelectric effect. A PMT is constructed in a vacuum tube and contains a photocathode (where the light is initially received and the original electrons are emitted), several dynodes (the metal that allows for current multiplication), and an anode (where the electrons are received). When the light hits the photocathode material above a certain threshold frequency, an electron is emitted. The photomultiplier multiplies the current by up to 100 million using secondary emission (i.e., the electrons in the vacuum tube strike the dynode and excite more electrons, and this process occurs several times). The anode receives the multitude of secondary electrons, which flow to the electronic equipment. Since the photomultiplier emits many electrons, the polarity of the PMT pulse should be negative. The size should be relatively large due to the current multiplication via secondary emission.

B. Raw Data

The data collected to determine the lifetime of the Muon can be found in the following tables.

0 degrees from the zeinth, 9.5 cm between detectors

Time (ns)	Time Error (ns)	Count	Count Error
40	5.773502692	119	10.90871211
60	5.773502692	40	6.32455532
80	5.773502692	18	4.242640687
100	5.773502692	12	3.464101615
120	5.773502692	7	2.645751311
140	5.773502692	6	2.449489743
160	5.773502692	10	3.16227766
180	5.773502692	13	3.605551275
200	5.773502692	11	3.31662479

Here is this raw data graphed.

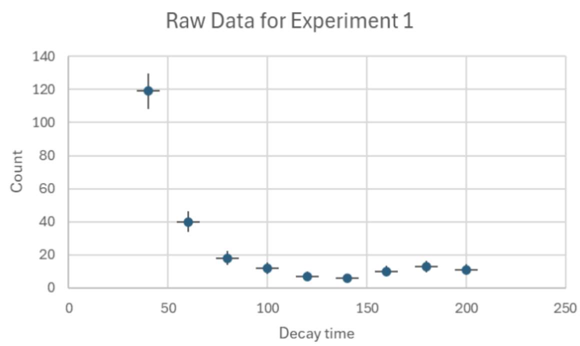

FIG. 1: This exponential allows us to find the experimental mean lifetime of the muon.

We collected flux data at several different angles and compared close versus far detector proximity. The following data shows how many seconds it takes for the detector to find approximately 1000 coincident counts for each angle and distance.

0 degrees from the zeinth, 9.5 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1008	1094	1072
Time (s)	95.2	60.2	54.3

0 degrees from the zeinth, 21.0 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1059	1002	1069
Time (s)	62.8	99.3	56.6

-30 degrees from the zeinth, 12.0 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1041	1108	1036
Time (s)	31.08	26.2	40.7

-30 degrees from the zeinth, 22.5 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1009	1027	1043
Time (s)	45.2	119.8	96.5

-60 degrees from the zeinth, 9.0 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1048	1164	1018
Time (s)	45.2	40.9	47.4

-60 degrees from the zeinth, 20.0 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1020	1008	1019
Time (s)	170.4	145.6	115.3

30 degrees from the zeinth, 15.0 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1043	1026	1023
Time (s)	57.0	46.4	57.6

30 degrees from the zeinth, 22.5 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1032	1025	1020
Time (s)	74.6	83.0	98.0

60 degrees from the zeinth, 10 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1060	1112	1005
Time (s)	67.9	42.4	58.1

60 degrees from the zeinth, 21.5 cm between detectors

	Trial 1	Trial 2	Trial 3
Count	1006	1001	1006
Time (s)	134.0	164.5	137.2

III. RESULTS

We found the charge species-averaged muon lifetime inside the scintillator to be 2.06018 ± 0.11686 microseconds. This is consistent with what we would expect to find; the theoretical muon lifetime is about 2.2 microseconds and our measurement is slightly lower because the negative muons might interact with the protons in the scintillator and therefore be captured or absorbed.

We found the directional distribution of the local muon flux to be 0.73131 ± 0.0287 muons per minute per square centimeter at an angle of 28 ± 0.61451 degrees to the south of the zenith. We would expect the directional distribution to be optimal when in line with the sun, which changes position in the sky over the course of a lab period, which introduces error in the final measurement.

IV. DISCUSSION

Although our measurement setup allows us to detect muon lifetime and flux, we can also expect some level of noise or background. For example, the photomultiplier tube might detect background high energy photons such as gamma or ultraviolet radiation. Additionally, the bandwidth of the blue light is not a perfect delta function but rather a range with width, which introduces a source of additional PMT detections. The electronic equipment also introduces thermal noise since we operate our equipment at room temperature. We can adjust the discriminator to exclude detections above a certain threshold, excluding noise and including detections; we found the noise level is very close to the detection maximum, creating a finicky experience with the discriminator. In our software and analysis, we can exclude outliers and account for uncertainty due to noise using statistical methods.

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