Cosmic Ray Muon Detection

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Our goal was to observe and record the flux of Muons as they enter our atmosphere. Using a scintillating bar, two photomultipliers, Labview and an oscilloscope, we were able to calculate the lifetime of a muon \((2.09 \pm 0.46 \mu s \ (95\% \ CI))\). We report an attenuation length of \(a = 8.86 \pm 0.20\) m \((95\% \ CI)\). We will then provide a plan to construct a four bar system in order to get the coincidence angle.
I. INTRODUCTION

As cosmic rays hit the Earth’s atmosphere, secondary particles are produced. Some of these secondary charged particles will not make it through the atmosphere, as they mainly collide with the nuclei of the air. However, some of these particles will make it through, and because they travel at relativistic speeds, we can detect them at the Earth’s surface [4]. This phenomenon is referred to as cosmic ray showers. About 90% of the nuclear cosmic rays are protons, 9% is helium nuclei and the remaining 1% is heavier nuclei [7]. One result of the interaction between incoming protons and nuclei is pions. These pions decay into muons, and the muons decay into neutrinos and electrons (Fig. 1). The muons travel with relativistic speeds approximately in the same direction as the incoming protons. Although mouns are unstable due to their large mass, mouns have high penetrating power [2]. As muons enter a scintillating bar, there is a small chance that the muons will collide with an electron or a nucleus in the scintillating bar, causing them to come to a stop [2]. The resulting photons travel down our bar, and using the time differences provided by photomultiplier tube (PMT) readings, we can get an insight of the lifetime of the mouns and their incoming flux direction.

II. MODEL

Muons are a part of the elementary particle family and are similar to electrons. A muon has a $-e$ charge and has a $\frac{1}{2}\hbar$ spin. Many of the muons that are observed in Earth’s atmosphere are due to cosmic radiation; these muons travel at relativistic speeds and carry relatively high energy. In order to detect the muons, a scintillating material is used. When a muon interacts with the scintillating material, it will excite particles in the material. These atoms will then drop back down to a non excited state, releasing photons. These photons are then detected with a Photo Multiplier Tube(PMT). In order to find the relative position of the muon within the scintillating bar, a time difference in signals can be used between two PMTs on opposite sides of a scintillating bar. Interestingly enough, some muons hit electrons inside the bar; conservation of momentum then leaves very little momentum for the muon to exit the bar [6]. These muons stay inside the bar and eventually decay (FIG 1). The decay states release photons which can be detected by the PMTs. The average lifetime of a muons is about $2\ \mu s$, which is long enough for the PMT to capture the decay events.
The decay of a muon follows the basic exponential decay form,

\[ N(t) = N_0 e^{-\frac{t}{\tau}} \]

where \(\tau\) is the lifetime of the muon. We can also integrate the light pulses going to either side of a scintillating bar and plot the log of the ratios against the position of the muon on the scintillating bar in order to get an attenuation length. We see that

\[ \ln\left(\frac{Q_1}{Q_2}\right) = \frac{-2x}{a} \]

where \(Q_2\) and \(Q_2\) are the integral of the light pulses, and \(a\) is the attenuation length, and \(x\) is the distance from the middle of the bar.

\[ \text{Attenuation} = \frac{-c}{\text{slope} \times n} \]

In this case, \(c/n\) is the speed of light in a vacuum, which converts our slope from seconds to meters, and \(n\) is the refractive index of our scintillating bar, which is 1.5. In our case, we plot the log of the ratios vs. the difference in time of pulses, which explains the negative in the slope. We find the difference of time in the pulses using a software version of a Constant Fraction Discriminator.

\[ \mu^- \rightarrow e^- + \nu_e + \nu_\mu \text{ or } \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

FIG. 1. The muons that stay in our bar will quickly decay according to one of the two muon decay modes shown above. In the first model (left), our muon decays into an electron, an electron antineutrino, and a muon neutrino. In the second mode (right) the muon decays to a positron, an electron neutrino, and a muon antineutrino. Both forms of decay induce the plastic to emit photons that can be detected by the PMTs.

III. SETUP

A simple schematic diagram of our setup can be seen in Fig. 2. Each end of a 1-meter long scintillating bar is attached to an 8 cm diameter coupling plastic base. This plastic base, which was 3D printed specifically for our setup, works like a coupling piece, keeping the PMTs attached to the ends of our bar. Before the PMTs, couplings, and scintillating bar
were glued together, the bar was wrapped in a reflective material (wrinkled aluminum foil) in order to maximize the reflection of decaying particles inside the bar [2]. Once the bar was completely wrapped in foil, we attached our coupling pieces at the ends of the bar and glued them using black caulking. In order to keep any light from coming into the bar, we wrapped the bar once again but this time we used black electrical tape.

Before attaching the PMTs to the couplers, we applied a small amount of optical couplant to the front part of our PMTs. Optical coupling compounds are used to bridge the gap or boundary for light signals traveling between different media. The couplant grease maximizes light transmission by matching the refractive index of our plastic scintillating bar with that of the glass in the front part of our PMTs. The PMTs were also glued with black caulk and electrical tape in order to make the inside of our bar the most light-tight possible. We also connected a truss system that connects both the PMT tubes in order to keep them from drooping off of the end of the scintillating bar, making sure that the connection between the couplant and the PMT was light-tight.

The PMTs are attached to high voltage and the anode output runs into an oscilloscope through a 50Ω terminator for impedance matching. The resulting photons from the decaying muons are captured by the PMT and then converted into electrical signals to be read by the oscilloscope.

IV. DATA ANALYSIS

First, we trigger the data using a 100 mV trigger so that we are generally dealing with cosmic radiation. We then tell our oscilloscope to collect when two events occur. From our LabVIEW program, we were able to obtain the area under the curves of our voltage vs. time graphs for each individual event (Fig. 3). We then proceeded to plot the log of the ratio of the areas vs. the time difference of the peaks in the event. The result is shown in Fig. 4. We expect a linear dependency of the ratio of the areas with respect to the time difference; however, our data shows a much wider spread than we expect. We report an attenuation length of $\alpha = 8.86 \pm 0.20 \text{m} (95\% \text{ CI})$, which is reasonable.
FIG. 1. Our setup consists of a completely sealed scintillating bar sitting on a flat surface with two photomultipliers (PMTs) attached at each end. We provide a voltage of about 1.7 kV to each PMT. When a muon decays in our bar, the resulting photons travel through the bar until they hit our PMTs, creating a cascade of electrons, a sharp current pulse that can easily be detected in an oscilloscope.

FIG. 2. This graphic shows a muon impacting the scintillating bar as received by the two PMTs at either end of the bar. Note how Channel 1 receives a much more intense pulse slightly earlier than Channel 2. This is the result of the muon impacting the bar closer to the Ch. 1 PMT.
FIG. 3. Here we report a 2-Dimensional histogram of $\log(q_1/q_2)$ vs $\Delta t$, or position, where $q_1$ and $q_2$ are the integrals of the signals taken from the PMT tubes. We expect the distribution of $\log(q_1/q_2)$ to be less Gaussian like. The $\Delta t$ data was found using a software version of a Constant Fraction Discriminator. We fit the data to a linear fit and find the attenuation length to $a = 8.86 \pm 0.20$ m (95% CI). This does not make sense to us and therefore draws red flags for us.

V. PROPOSED TWO BAR SYSTEM

We include a proposed plan for a two bar, four PMT system. This system would be set up with four channels running to an oscilloscope. First, the PMT pulses are noted to be 100 mV. In order to trigger TTL, we need the signal to be 1V. Therefore, all signals must run through a fast amplifier in order to raise the voltage of each pulse to a high enough level. We propose using a LF411 for our fast amplification (Fig 5). Following the amplification, we also realize that each data piece must be stored until the logic circuit is finished. We propose using D flip flops in order to accomplish this piece. After going through flip flops, the signals are propagated through 2 AND gates, whilst the reset is delayed 100ns by an
OR gate, allowing enough time for all events to happen. We propose to use a 555 to delay the reset signal, or a HEX not gate. If all signals produce a YES, then the circuit has the system write the data to a file. After 100ns of delay time, all the flip flops will be reset (Fig. 6).

![Figure 4](image_url)

**FIG. 4.** Here we show the proposed fast amplifier, a non inverting LF411. We use $R_f = 1.2k\Omega$ and $R_g = 100\Omega$ so that the gain, $\frac{R_f}{R_g}$, is equal to about 12. This circuit, however, is slow for our needs.

VI. CONCLUSION

We present a decay constant for the lifetime of a muon that agrees with the previous group [6]. Their reported value for $\tau$ is $2.05 \pm 0.14 \mu s$ (95% CI), while our value for $\tau$ was $2.09 \pm 0.46 \mu s$ (95% CI). These values clearly overlap, but notice that our uncertainty is a bit bigger. The reason behind this is that our group collected fewer samples. We also report an attenuation length of $a = 80 \pm 1mm$ (95% CI). We note that normal attenuation lengths are on the order of 400cm and recognize that we have messed up somewhere in our calculations or our bar is bad. We then move on to propose a TTL circuit for a two bar, four PMT system with a main goal of mapping the coincidence angle of incoming muons.
FIG. 5. Here we show the proposed TTL circuit. Each amplified signal is denoted by the boxes surrounding numbers. Each signal then passes through the set option of an D flip flop. The reset option is taken from a four way OR gate that is connected to the output of the flip flops. The reset is delayed 100 ns by the first OR gate it passes through, allowing enough time for all 4 events to happen. This can be achieved through a 555. The signals then pass through 2 AND gates. If all four signals are a GO, than the two AND gates will give a TRUE output and follow onto the last AND gate.

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