Cosmic Ray Muons

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Abstract

Measuring particles from cosmic ray sources, we report measurements for muon lifetimes as they stop in a detector in the form of a one foot cube of doped polystyrene scintillator, as well as calculations of ground level fluxes of particles passing through this detector. We found that the muons' effective lifetime when stopped in the scintillating material is $2.125 \pm 0.038 \mu s$, while the flux of stopped muons is found to be $(1.604 \pm 0.054) \times 10^-6$ muons per second per cm^2 per steradian per (gm/cm^2)), and the flux of all particles is found to be $(2.10 \pm 0.006) \times 10^{-2} \frac{1}{cm^2 s}$.

1 Introduction

1.1 Cosmic Rays

Cosmic rays are high-energy protons and other light nuclei that originate from outside of the solar system. When they reach the earth's outer atmosphere, at roughly 15 km above sea level, they interact with nuclei in the air and produce a cascade of secondary particles. Of these, it's primarily muons and electrons that reach ground level. The accepted value for the rate at which muons arrive at ground level is 1 muon per cm^2 per minute.

Muons are electrically charged and therefore as they pass through matter they lose their kinetic energy to Coulomb scattering. In order to study these muons, we use a detector in the form of a large block of dense scintillating material, and as cosmic ray muons pass through and deposit their energy, the scintillating material re-emits this energy as light.

1.2 Muon Decays

The muons that reach ground level have a broad spectrum of kinetic energies. The majority of muons have enough energy to pass through our detector, but those with sufficiently low kinetic energy (less than 150 MeV) lose all their energy ionizing the scintillating material and stop in the detector. Muons eventually decay by the weak force into electrons and neutrinos,

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu \text{ and } \mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e, \tag{1}$$

with a mean lifetime that is currently accepted as $2.197019 \pm 0.000021 \mu s$. The neutrinos escape our scintillator undetected, but the electrons proceed to ionize the scintillating material as well. This gives a characteristic way to detect stopped muons, since pulses of light from muons should be immediately followed by another pulse from the decay electrons, assuming that uncorrelated muons arriving within a few microseconds of each other is negligible. The mean lifetimes of these muons may then be inferred from how much time is between the muon arrival and electron arrival. With particle decay being a random process with constant probability of decaying in any differential time interval, repeated measurements of the muon lifetime should obey the Poisson distribution. Letting τ denote the decay lifetime, the probability of observing n decay events in a time interval t is

$$P(t,n) = \frac{1}{n!}(t/\tau)^n e^{-t/\tau}. \tag{2}$$

Of course, the only physically meaningful values for n in this scenario are 0 and 1, the muon decays or it doesn't. The probability that 0 events are observed in this interval, i.e. that the muon does not decay in this interval, is

$$P(t,0) = e^{-t/\tau}. \tag{3}$$

Measurements of the time intervals between muon arrival and muon decay therefore gives a histogram showing exponential decay in how frequently the muons are measured to have lived for increasing amounts of time, and the muon's mean lifetime can be found from fitting an exponential to this histogram and extracting the constant τ.

The ground level fluxes of positive and negative charged muons are not necessarily the same for all energies, but for energies on the order of 100 MeV, the fluxes are approximately equal. This implies that equal numbers of positive and negative muons decay in our detector. However, it should be noted that negative muons have a chance of being captured early by nuclei in their stopping material, and hence the negative muons have a shorter mean lifetime than the positive muons, $2.028 \pm 0.002\mu s$ for our scintillator. Given this, we expect to measure an effective mean lifetime of $2.11\mu s$.

1.3 Particle Fluxes

With our detector being sensitive to all charged particles that pass through it, it is capable of measuring two different fluxes. First, the total particle flux, which is a simple count of all scintillator pulses. These may be from all kinds of particles, including all the muons that pass through without stopping, including all the muons that stop in the detector and including their decay electrons.

Second is the flux of stopping muons. Muon flux as it reaches the detector at ground level has some angular dependence, as muons that arrive from some angle

θ from the vertical will have travelled a pathlength that is proportional to $\cos\theta$, giving those muons more chance to decay prematurely and therefore attenuating their flux from those angles. Empirically, the flux angular dependence is

$$F(\theta) = F_o \cos^2\theta, \tag{4}$$

where F_o is the flux at zenith. In particular, the stopping muon flux can be written as a function of zenith angle, muon momentum, muon stopping range, and the detector thickness, as

$$F(\theta) = \frac{\text{Muons at zenith angle } \theta}{[\text{Horizontal area } A][\text{Stopping range } R][\text{Solid Angle } \Omega][\text{Time } t]} \tag{5}$$

Assuming that the number of stopping muons per unit volume in the scintillator is independent of position, the total number of stopped muons can be written in terms of flux using eq 5 as

$$N_{TOT} = \int F(\theta) dA dR d\Omega dt. \tag{6}$$

Integrating this leads to

$$N_{TOT} = F_o \frac{2\pi}{3} \rho V T, \tag{7}$$

where V is the volume of the detector, ρ is the density of the scintillating material, and T is the total time of counting. Rearranging gives an expression for the vertical muon flux from the number of stopped muon decay events and physical properties of the detector,

$$F_o = \frac{3N_{TOT}}{2\pi\rho V T}. \tag{8}$$

Section 2 will describe our apparatus and procedures for studying cosmic ray muon lifetimes and fluxes, in two parts; Section 2.1 will describe in detail the scintillator detector and how it acquires data, section 2.2 will describe our procedures for extracting measurements of the muon lifetime and particle fluxes from this data. Section 3 will present the results of this data, and section 4 will conclude by reporting values for the muon lifetime, total particle flux, and vertical muon flux.

2 Procedures

2.1 Apparatus

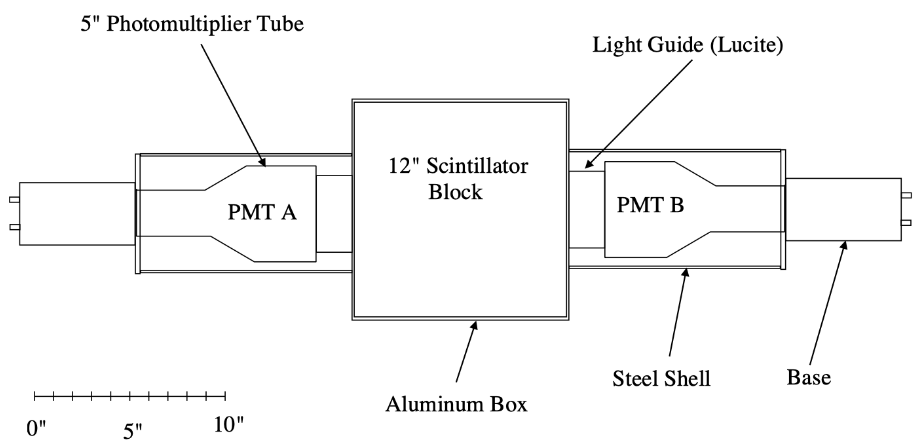

Figure 1: A simplified diagram of the experimental setup.

Figure 1 shows a diagram of our detector, a 12" scintillator cube viewed from opposite sides by two photomultiplier tubes (PMTs). The scintillator is made of doped polystyrene with density 1.032 gm/cm^3. For every charged particle that passes through the scintillator and deposit kinetic energy, the scintillator releases a small burst of light which is detectable by both PMTs. Having two

PMTs is necessary for this experiment because it is the coincidence of both PMTs receiving signals at the same time which confirms that the detector has most likely seen a real particle rather than electronic noise.

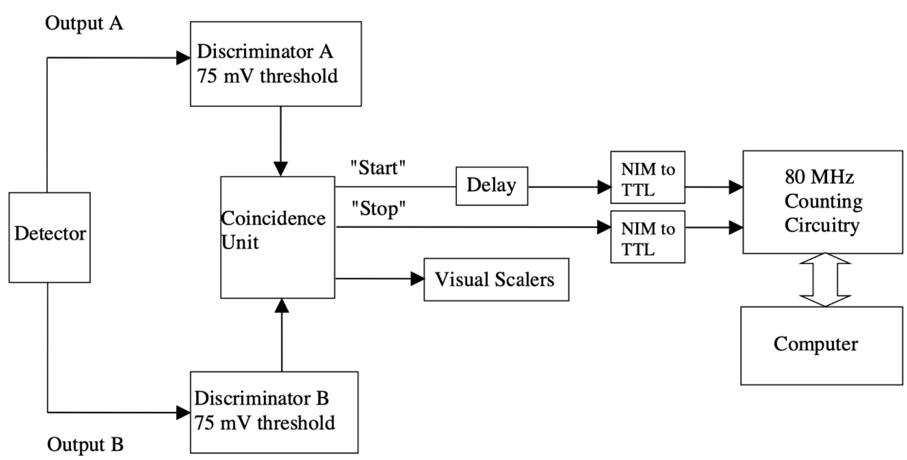

Figure 2: A simplified diagram of the electronics that process PMT data and pass them to a computer for analysis.

Figure 2 shows the path that the signals from each PMT follow on their way to the computer. These electronic devices are configured to avoid background electronic noise and measure the time between signals.

Signals from each of PMT A and B are first sent to separate discriminators. These are devices that check whether their input voltage exceeds a particular threshold, and if so outputs a signal of consistent voltage. This is to block noise caused by triggerings of the PMTs for low energies. Each PMT is powered by a high voltage supply, where the higher the voltage to the PMTs is, the larger is their gain as they amplify the light pulses in the scintillator. Highly amplified pulses are desirable as it means the detector triggers on weaker signals and the experiment can get statistical results more efficiently, but this comes at a risk of amplifying electronic noise above the discriminator threshold. We found that to get clean data, it was sufficient to keep the high voltage power supplies to both PMTs set to 2100V.

To further reduce background noise, each discriminator then feeds into a coincidence unit, a device that outputs a signal only if the inputs from A and B overlapped in time. The output signals from the discriminator units are adjustable and on the order of 20 nanoseconds wide. With some space to accommodate for the finite speed of light in the detector, the overlap between these signals enforces that the output signal most likely corresponds to a particle in the detector. The coincidence unit outputs two identical signals which go toward measuring time between events, along with a third output that goes to a visual scaler, allowing us to view a running total of particles passing through the detector.

In sending signals from the coincidence unit to the counting circuitry, a time-to-digital converter (TDC), the following logic is used to ensure that signals are processed in the correct order. The coincidence unit outputs two identical signals for every particle, labelled by "Start" and "Stop" in figure 2. "Start" is delayed by a few nanoseconds, which is long enough to ensure that the "Stop" signal arrives at the TDC first. The TDC has two inputs corresponding to start and stop, it starts counting on an 80 MHz clock when it receives an input at start and stops counting when it receives an input at stop. When the "Stop" signal arrives at the stop input while the TDC is not counting, the TDC does nothing. A few nanoseconds later, it receives the delayed "Start" signal at start, and starts counting. At this point, it counts time until the next particle is detected and sends another set of "Stop" and "Start" signals. The "Stop" signal arrives first again, and the TDC stops counting time and sends its result to the computer. While it does so, the TDC does not accept any start input for long enough that the "Start" signal is ignored. The computer only keeps data for time intervals shorter than 20 microseconds. Assuming that uncorrelated particles arrive within 20 microseconds of each other negligibly often, the data that is kept corresponds to the TDC starting when it receives a muon decay and stopping when it receives the decay electron. This is the lifetime of that muon. Note that the TDC runs on an 80 MHz counter, so its finest resolution is 12.5 nanoseconds, and therefore the delayed start does not largely impact the muon lifetime measurements, especially not the mean lifetime.

2.2 Analysis Procedures

As previously mentioned, the muon mean lifetime is measured from a histogram of muon lifetime measurements by the TDC by fitting to it equation 3, plus a constant background to account for pairs of uncorrelated random muons:

$$N(t) = N_o e^{-t/\tau}. \tag{9}$$

As for flux calculations, the total number of muons detected can be measured statistically from this fit by

$$N_{TOT} = N_o \frac{\tau}{\Delta t}. \tag{10}$$

One complication with the data is that the TDC stop input does not consistently trigger on short pulses like those that come from the discriminator unit, so the "Stop" signals are lengthened to 800 ns. This becomes a blind spot where muon lifetimes shorter than 800 nanoseconds cannot be measured, and due to statistical uncertainty the first couple of nonzero histogram bins are often unreliable due to crossovers into and out from the 800 nanosecond region. For this reason we exclude the first few bins when fitting.

As for the total particle flux, we measure this directly from the visual scaler output from the coincidence unit, by simply counting how many particles it detects in ten one-minute trials.

3 Results

Over a total of 502 hours, we allowed the detector to make measurements of particles passing through. We collected data four times, each time modifying voltage supplied to the photomultiplier tubes and adjusting the discriminator in an attempt to minimize random noise and find superior statistics from one of these trials. The parameters of these four trials are listed in table 1.

Table 1: Detector Runtimes and Parameters

Duration Dates	Duration	HVA (V)	HVB (V)	Discriminator (mV)
3/1/22 (~3:20PM) to 3/3/22 (~10:00AM)	~43 hours	2100	2100	75
3/3/22 (~10:30AM) to 3/15/22 (~9:30AM)	~287 hours	2200	2100	75
3/15/22 (~9:45AM) to 3/17/22 (~1:30PM)	~52 hours	2200	2100	50
3/17/22 (~2:15PM) to 3/22/22 (~2:30PM)	~120 hours	2200	2100	100

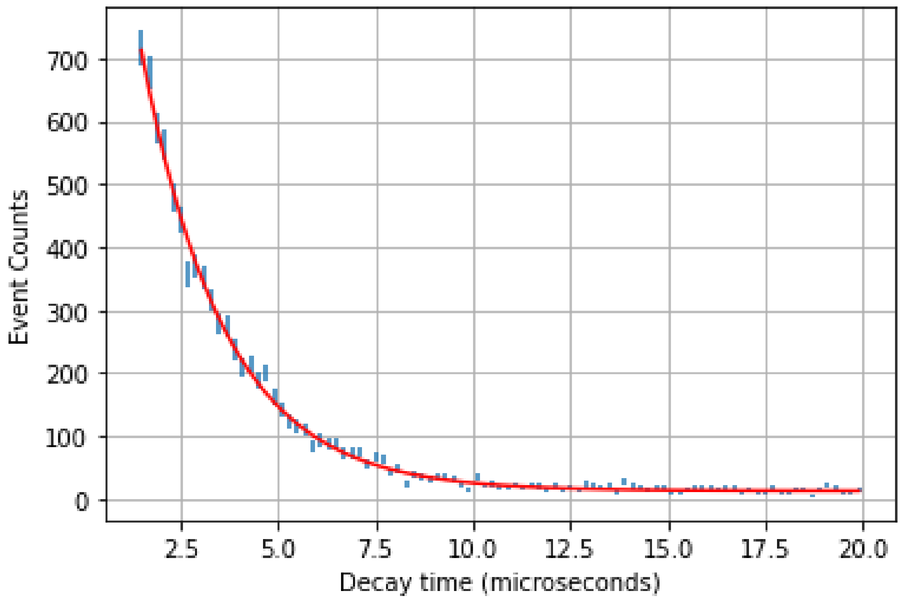

Figure 3: Histogram plus exponential fit for the first muon decay dataset, 43 hours of detector runtime. Bin width is 200 nanoseconds.

Table 2: Stopped Muon Lifetime Data

Data Run	Mean Lifetime (μs)	Goodness of Fit (χ^2/ν)
1	2.125 ± 0.038	1.216 ± 0.149
2	2.090 ± 0.015	1.934 ± 0.149
3	2.062 ± 0.029	1.427 ± 0.105
4	2.092 ± 0.024	1.449 ± 0.105

Figure 3 shows the stopped muon decay histogram from the first of these four datasets. Fitting exponential curves to these histograms, we get the results in table 2. All errors come from fitting with scipy.optimize.curve_fit, a least-squares fitting technique using the default Levenberg-Marquardt algorithm.

We find that the best fit, and the closest lifetime value to the expected value of $2.11 \mu s$, is from the first dataset, seeing as its χ^2 value is closest to unity. This is not surprising, as it had the lowest PMT voltage settings, as well as a high discriminator threshold, allowing it to effectively filter out noisy data during runtime.

Table 3: Stopped Muon Flux

Data Run	Stopped Muons Flux (10^{-6} muons per sec per cm^2 per steradian per (gm/cm^2))
1	1.604 ± 0.054
2	2.392 ± 0.033
3	2.456 ± 0.067
4	1.606 ± 0.036

Table 3 shows the results of stopped muon flux from each of the four datasets, calculated according to equations 8 and 10. The accepted value is 5×10^{-6} muons per sec per cm^2 per steradian per (gm/cm^2), which all of these estimates fall short of. This undercounting might be due to an inability for the detector to count all muons, between the short time scale blindness and the discriminator thresholds. In particular, there could be muons that enter the scintillator block from the edges/corners and fail to trigger the more distant PMT to sufficient threshold, and it's possible that electrons can even escape the block undetected at these boundaries. Therefore it appears likely that, unlike our assumption, the effective cross-section of the detector is not the scintillator's full area. Uncertainty on the flux values are again calculated from the fitting parameters.

Finally, we measured the total particle flux as $(2.10\pm0.006)\times10^{-2}\frac{1}{cm^2 s}$. This again falls short of the accepted value $2.4\times10^{-2}\frac{1}{cm^2 s}$, by the same reasoning as above.

4 Conclusions

We conclude that the effective mean lifetime of cosmic ray muons stopped in carbon is $2.125\pm0.038\mu s$, which agrees with the expected lifetime of $2.11\mu s$. The flux of stopped muons in the detector is estimated as $(1.604 \pm 0.054) \times 10^-6$ muons per second per cm^2 per steradian per (gm/cm^2)), and the flux of all particles passing through the detector is estimated as $(2.10\pm0.006)\times10^{-2}\frac{1}{cm^2 s}$. These fluxes do not agree with expected values to satisfaction, likely due to overestimates of the detector's effective cross-section.

5 References

Cosmic Ray Muons, R. A. Schumacher