Muon Decay

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Abstract

We used a scintillator apparatus to monitor muon decay at sea-level from atmospheric sources. By Accumulating a Poisson distribution of muon decay times and accounting for background events, we obtained the mean muon lifetime to be 2.184 ± 0.030ms from an exponential fit. Comparison to other data sets from groups that used our apparatus in a different location, one year ago, yielded interesting results regarding the systematic and random errors associated with our apparatus.

1 Introduction

Many forms of particle radiation are present in our atmosphere. Radiation entering our atmosphere has basically two possible sources: our Sun and other cosmic sources. The various forms of radiation, i.e. types of particles, can be unique to a specific range of altitudes; they may have characteristic decay times that terminate at a given altitude, or they get absorbed at sufficient densities. For example, alpha radiation (helium nuclei) enters our atmosphere and will interact with air molecules, such as ozone. The interaction will produce pions π^+ or π^-, which subsequently decay into muons and their corresponding muon neutrinos:

$$\pi^+ \to \mu^+ + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

A third decay mode yields electron-positron pairs and gamma radiation:

$$\pi^0 \to e^- + e^+ + \gamma$$

The other common decay modes are shown in Figure 1.

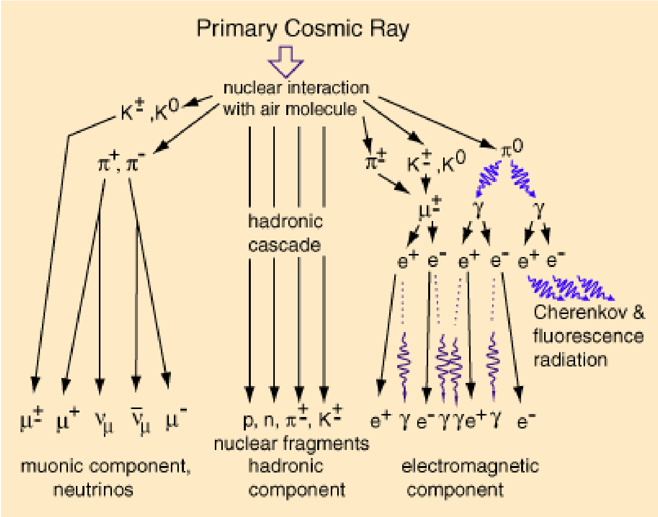

Figure 1: [2]

Most of these particles don't make it to sea level; they get absorbed at higher altitudes or they are like the pions which have very short lifetimes. The particle radiation from cosmic sources at sea level mostly consists of the products of pion decay; photons (particularly gamma radiation), neutrinos, and muons. Electrons and positrons are easily absorbed at higher altitudes. The The neutrinos are extremely hard to detect and will pass right through much of the Earth's bulk before being stopped. So, the remaining particles of interest are gamma rays and muons; in these experiments we focused on the muons.

Our goal in these experiments was to determine the mean muon lifetime by following the experimental methods in [1]. We then used this lifetime to calculate the value of the Fermi coupling constant G_F;

$$G_F = \sqrt{\frac{192\pi^3\hbar^7}{\tau_\mu m^5 c^4}} \tag{1}$$

2 Methods

Our apparatus featured a scintillator coupled to a photomultiplier tube (PMT), each connected to a HV power supply; their purpose was to detect particles and amplify their electronic pulses. Scintillators are designed to emit light when excited by incoming particles. When coupled with a PMT, the light emitted by a scintillator generates electric current in the PMT via the photoelectric effect. If the signal is to be good, the generated current will take on sharp pulse shapes which then feed into an exterior apparatus.

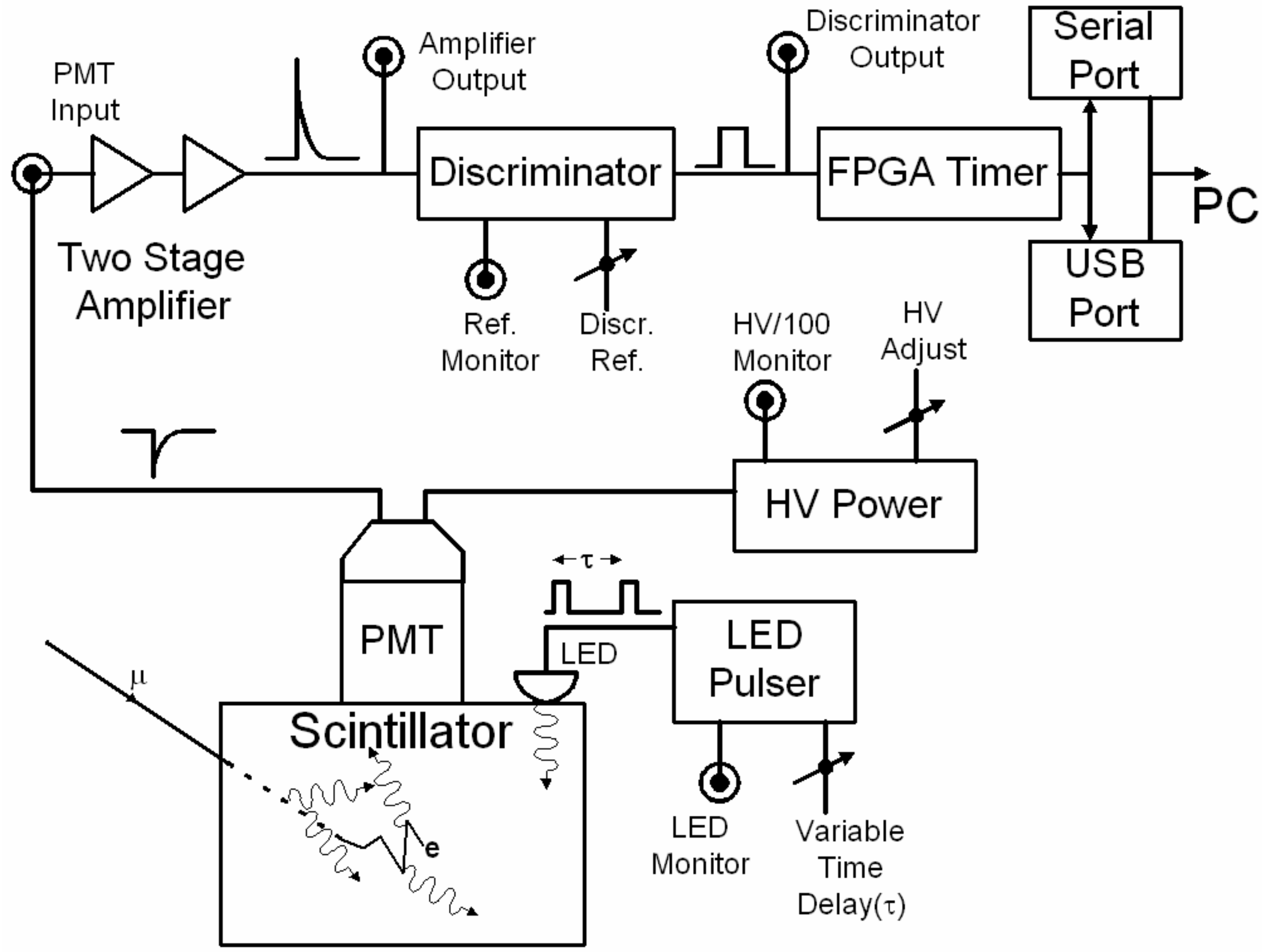

Figure 2: The full block diagram for our apparatus [1]. The PMT, scintillator, LED pulser, and HV power are all coupled in the same casing. The two stage amp, discriminator and FPGA timer are in a separate casing which we refer to as the electronics box.

The block diagram of our apparatus is shown in Figure 2. As seen in the figure, the signal from the PMT runs through an amplifier chain to a discriminator. The discriminator provides a threshold voltage and PMT pulses below this threshold will be thrown away. This function provides a lower bound on particle energies.

Muons entering the scintillator may pass straight through if they have high enough momentum. If they do get stopped, they may be trapped by an atom in the scintillator lattice and act as a heavy electron in a bound state. They also impinge momentum into the scintillator lattice and generate scintillator light; this gives an initial pulse. Muons have no memory for their internal decay mechanism, and therefore, will decay with equal probability once inside the scintillator. Their decay produces electrons which create a secondary pulse. The FPGA timer marks the first pulse and waits for the second pulse; delay times larger than a predetermined interval get thrown away later in software to reduce background. Pairs of γ photons and pairs of muons that pass straight through the scintillator can still accidentally pass the FPGA timer's requirements, thus "faking" a muon decay. Setting a proper threshold voltage to reduce gamma events can eliminate some of these fake muons.

From here, the discriminated pulses set off a muon decay trigger and get sent to a PC via USB and recorded as data. We used several pieces of software to monitor, plot, and analyze the collected data.

2.1 Software

We used a program called Muon.exe to record and automatically histogram muon decay events. Muon.exe saves data in a raw format with all the FPGA timer information. The program sift.exe "sifted" through the raw data files and threw away decay events that had bad FPGA delay times. The binned data was then taken into *Gnuplot* and histogrammed. χ^2 fits were done with *Gnuplot*'s Marquardt algorithm and P-values (error function results of the χ^2) were calculated using [3].

2.2 Calibration

Two main parameters needed to be calibrated on our apparatus; the first was the HV adjust voltage and the second was the threshold voltage. The HV adjust was controlled by a knob on the scintillator control panel and monitored using a multimeter in parallel with the HV/100 Monitor in/out.
In order to eliminate pulses from gamma radiation, we needed to set the muon detector threshold above the radiative energy of the gamma rays. Since the total count rate is inversely proportional to the threshold setting, we lowered the threshold until the count rate approached a constant. This region of constancy is seen in Figure 3.

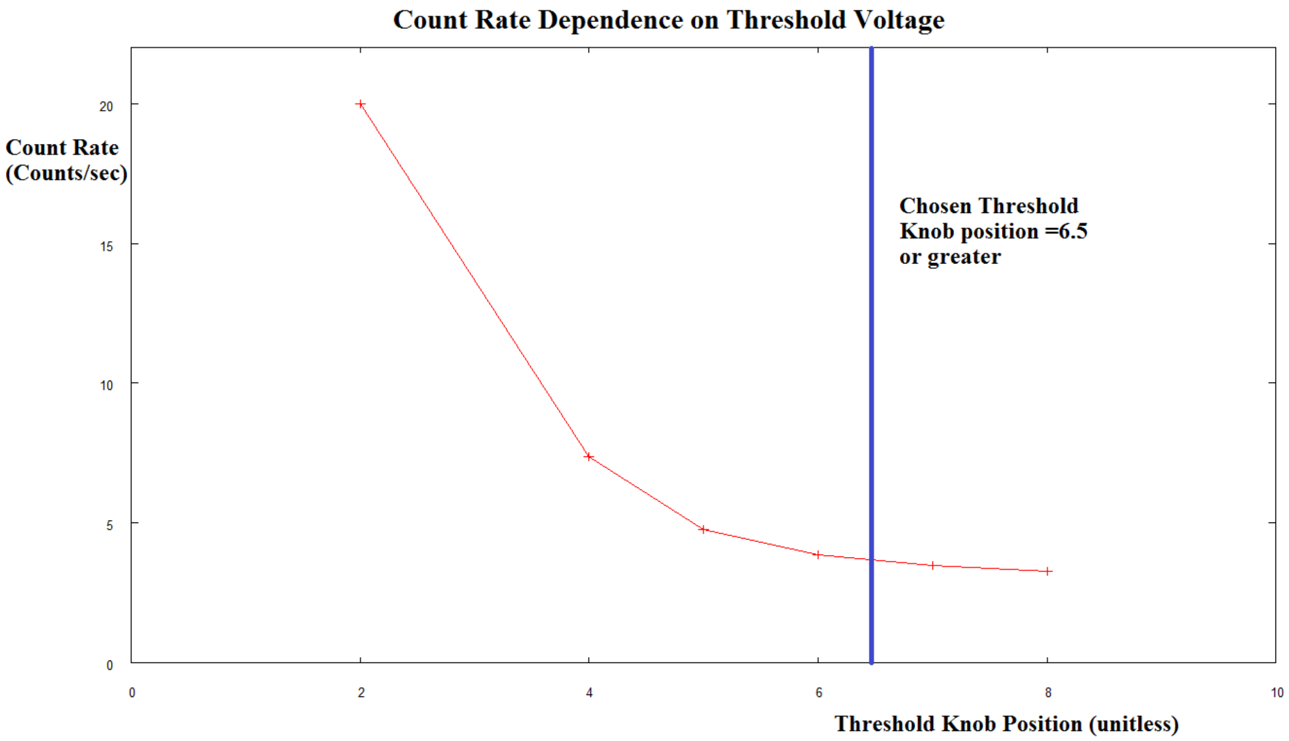

Figure 3: We plotted the muon count rate as a function of the threshold voltage. Here, we took the knob position to be proportional to the threshold voltage, which was unnecessary to measure.

We then chose a knob position of 6.5 to be the threshold used for the rest of the experiments. The second parameter, the HV adjust, was chosen to
After calibration, our muon count rate hovered around 3 Muons per second, with an average decay rate of 0.5 muon decays per minute. This necessitated long data taking periods, lasting up to a week on average.

2.3 Extracting the Muon Lifetime, τ_μ

We hypothesized that the data filling each decay time bin obeys Poisson statistics. With this in mind, we performed exponential fits to our histograms taking $\sqrt{N+1}$ to be the vertical error on each bin where N is the number of counts in the bin. We hypothesized a functional form of

$$N(x) = a \cdot e^{\frac{-x}{T}} + b$$

Where a is an amplitude, T is the mean muon decay time, and b is a background offset. *Gnuplot*'s fitting algorithm gave us a value of T or τ_μ for each trial.

3 Results

Below, we tabulated the aggregate of data we took. Table 1 features our best trial result in the first row; in the subsequent rows, other groups' data has been summarized using our own fits.

Trial	$\frac{\chi^2}{\nu}$	χ^2	P-value	Muon Lifetime (ns)	Background	Time Lapsed (Days)
Adrian and Spencer '14	1.25614	46.47718	0.1366	2184.11 ± 29.54	3.43 ± 0.7352	6.9814
March '14	2.89188	106.99956	0	2104.47 ± 61.8	5.2024 ± 1.264	4.8693
Feb '14	2.20248	81.49176	0	2201.9 ± 43.69	9.35563 ± 1.331	4.9598
May '13	1.81255	67.06435	0.0017	2242.74 ± 41.07	11.2962 ± 1.294	7.0076
May '13	1.82706	67.60122	0.0015	2180.77 ± 39.72	8.37187 ± 1.07	4.896
May '13	2.27004	83.99148	0	2235.34 ± 39.35	14.7676 ± 1.623	6.9896

Table 1

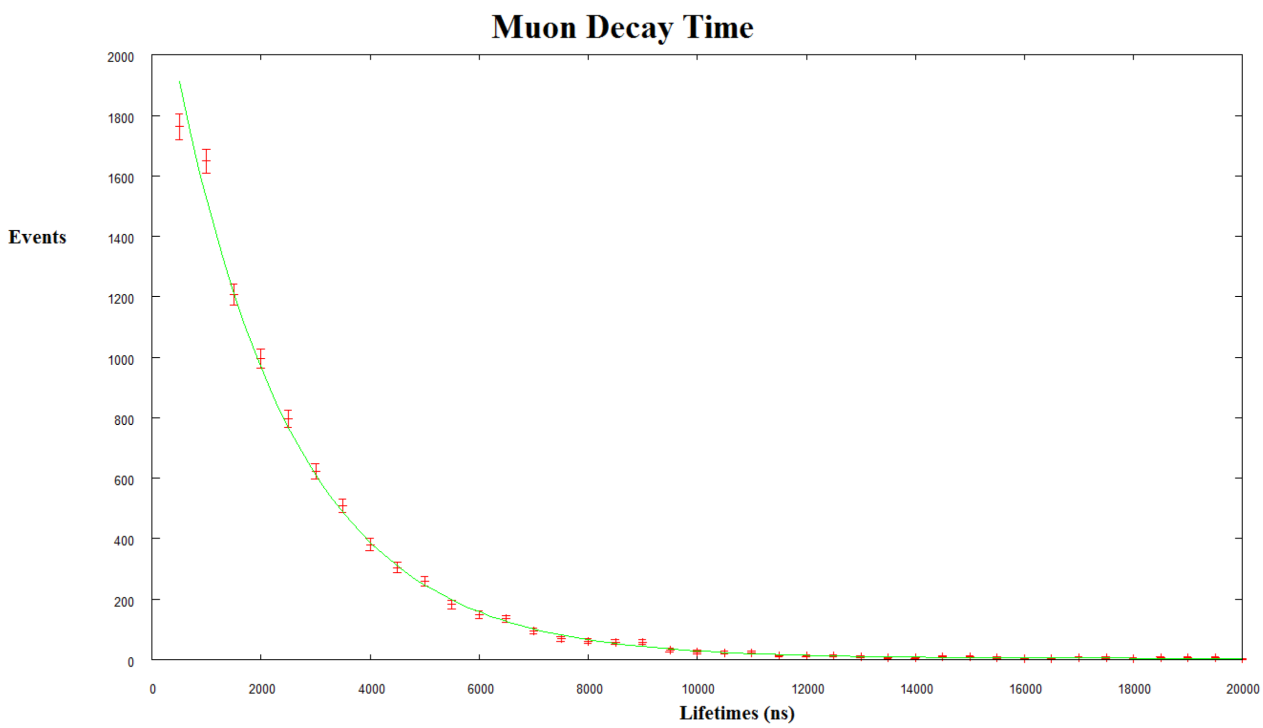

Figure 4: The muon decay histogram.

As in Table 1, we found the mean muon lifetime to be 2184.11 ± 29.54 nanoseconds or 2.18 ± 0.030 μs after truncating significant figures. Our chi-square fit gave us a P-value of 0.1366, and so there is no reason to reject our result from the statistics. Comparing to the accepted value of 2.19μs, our result seems promising.

We compared our results with the results of past groups' data. This was done by using their sifted data files and doing the fitting ourselves. It should be noted that our apparatus was located in a different location (Thimann labs) on campus last year. From the fitting data in Table 1, it is evident that the other groups had much worse χ^2 fits than ours; those whose muon lifetime deviates significantly from the accepted value we believe are the result of systematic error in the devices. This may or may not be related to the change in location.

4 Summary

We found a value for the muon lifetime that is consistent with the accepted experimental value.

References

[1] Coan, Thomas E., and Jingbo Ye. "Muon Physics." *Southern Methodist University* Matphys LLC. Web. http://www.matphys.com/muon_manual.pdf.

[2] "Cosmic Rays." Hyperphysics. Web. 24 May 2014. http://hyperphysics.phy-astr.gsu.edu/hbase/astro/cosmic.html#c1.

[3] Walker, John. Z-Score Calculator. Fourmilab Switzerland. John Walker, n.d. Web. 26 Feb. 2014.
https://www.fourmilab.ch/rpkp/experiments/analysis/zCalc.html.