Cosmic Ray Investigations

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Background

The subject of relativity captivated my imagination since I was a high school student. Deep down I wanted to conduct my own experiments to see relativistic time dilation or length contraction first hand. At some point I learned that cosmic rays, fast moving particles from outer space, could be used to demonstrate relativistic effects so I was excited two years ago when I had a chance to use a simple portable cosmic ray detector.

In July 2001, I had the good fortune of being among a group of high school teachers gathered in Snowmass, Colorado to take part in the QuarkNet particle physics education program. An informal activity there took advantage of a cosmic ray detector (CRD) built at Lawrence Berkeley National Laboratory. Teachers used this detector to measure the flux of cosmic rays at various altitudes and it quickly became apparent that there were greater numbers of cosmic rays at higher altitudes.

The majority of cosmic rays that penetrate far into Earth's atmosphere are muons. Muons are unstable and have half-lives of just a few microseconds. This explains the difference in the number of muons at different elevations: some of the muons detected at high elevations will decay before they reach lower elevations.

Special relativity predicts that fast moving muons will have longer half-lives than muons at rest because of time dilation. By measuring the fluxes of muons at various elevations, one might determine the average lifetime of moving muons, but to demonstrate relativity one would also have to measure the lifetime of muons at rest.

In November 2001, I attended a QuarkNet reunion meeting at Fermilab. In one activity, teachers were given the opportunity to perform experiments with a different model of cosmic ray detector. Like the Berkeley CRD, this one could count muons that passed through it. Occasionally, however, a muon would be slowed to a stop while it was inside the detector. This new CRD could measure the time between when the muon entered the detector and when it subsequently decayed. In this way, the detector could measure the lifetimes of muons that were practically at rest.

Naturally, I was excited. I clearly saw how a pair of experiments would allow me to observe relativistic time dilation. Much of my spare time during November, December, and January were spent poring over data from the Fermilab CRD to find a way to calculate the half-life of muons at rest. While I succeeded in developing a method of data analysis, the data itself appeared to be dominated by noise, so I did not trust the result.

In June 2002, a Fermilab CRD was sent to LBNL for local teachers to use. After repairing some damage that occurred during shipping I brought the CRD to my high school. A handful of students and I set up the detector. In December, we gathered a few data sets that appeared to be reliable. I used this data to determine the half-life of a muon at rest.

In March 2003, a group of students joined me on a trip up Mt. Diablo. We brought with us a Berkeley CRD so that we could measure the flux of muons at the mountain's summit and at an elevation of 2000 feet. By comparing these results with those from the Fermilab CRD, students and I concluded that the fast moving muons had half-lives that were more than six times as long as the half-lives of muons at rest. With this result, my high school dream was fulfilled: I was observing a direct consequence of special relativity.

Experiment 1: The lifetime of muons at rest

Abstract

Plastic scintillators were used to detect atmospheric muons, the products of cosmic rays. Some of these muons are stopped within the plastic of the detector and the electronics are designed to measure the time between their arrival and their subsequent decay. The amount of time that a muon existed before it reached the detector had no effect on how long it continued to live once it entered the detector. Therefore, the decay times measured by the detector gave an accurate value of the muon's lifetime. After two kinds of noise were subtracted from the data, the results from three data sets yielded an average lifetime of 2.07×10^{-6}s, in good agreement with the accepted value of 2.20×10^{-6}s.

Overview of the Fermilab Cosmic Ray Detector (CRD)

The Fermilab CRDs consist of two or three scintillator paddles and a circuit board for analog to digital conversion, pulse coincidence determination, counting and timing. (Figure 1.)

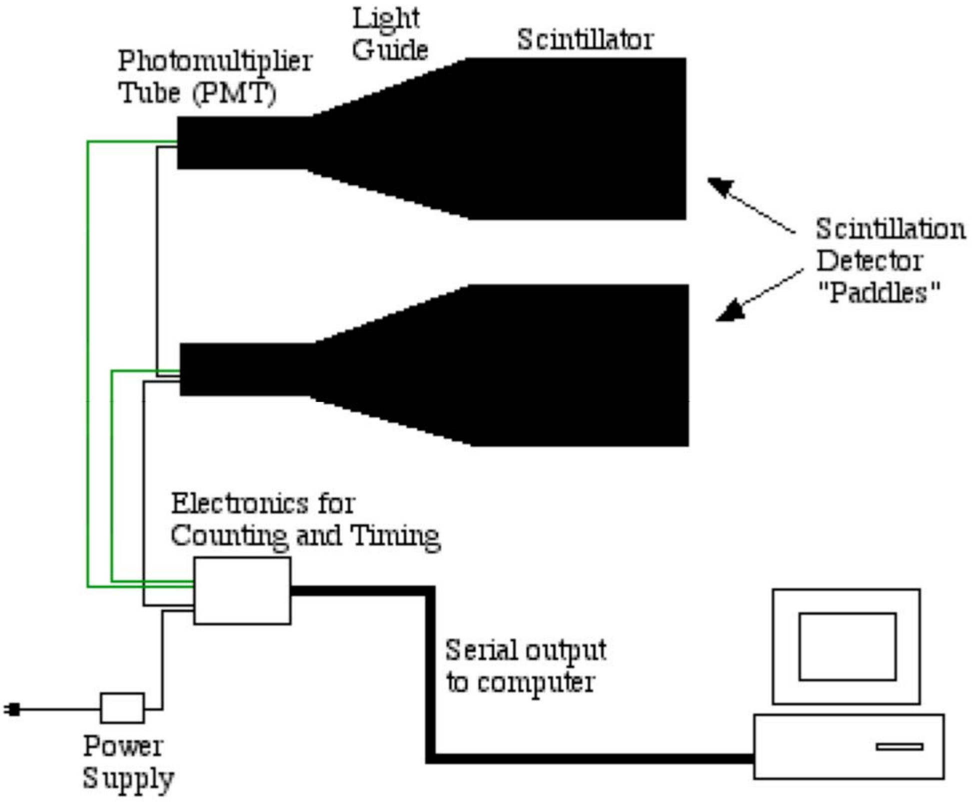

Figure 1

During normal operation one paddle would be placed above the other. When a charged particle passes through one of the plastic scintillators, the plastic atoms emit light which is then guided to a photomultiplier tube. By photoelectric effect, light hitting the photocathode of the PMT knocks out electrons. These electrons are then electrically attracted through a cascade of dynodes. Upon each collision with a dynode additional electrons are knocked free. Thus the original pulse of light is converted into a measurable electric pulse.

Most of the secondary cosmic rays that reach Earth's surface are muons. High energy (fast moving) muons are able to penetrate a long distance even through dense materials. Thus many muons will travel through both scintillator paddles. (Figure 2.) The circuit board looks for pulses arriving from different paddles at nearly the same time: a coincidence. These coincidences act as triggers that increment a counter on the circuit board and output the time at which the coincidence occurred to a computer where data is recorded for subsequent analysis.

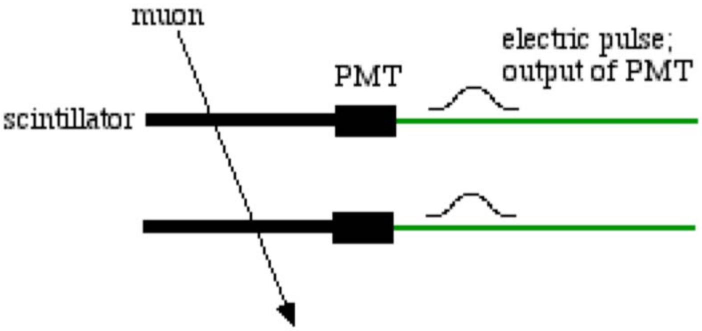

Figure 2

Occasionally a muon of lower energy will not penetrate all the way through the scintillator paddle. Because muons are unstable and have fairly short half-lives (on the order of microseconds), muons that stop within a paddle will subsequently decay. The decay products move at high speeds so they, too, will cause the plastic to scintillate. (Figure 3.) Some of these events can be recognized in the following manner: suppose a muon passes through the top paddle but is stopped within the lower paddle. First this will generate a coincidence, because the muon has moved within both paddles. Shortly thereafter a second pulse will come from the lower paddle due to the motion of the muon's decay products.

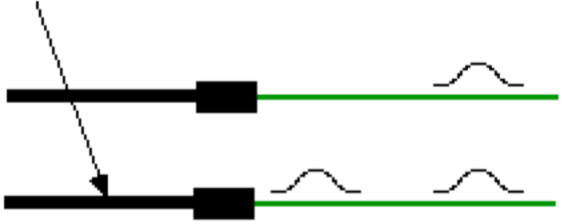

Figure 3: Time delay between the two pulses from the lower scintillator shows the time for the muon to decay.

The circuitry identifies these decay events by starting a 20 microsecond clock after each coincidence. If there is a pulse from either paddle during that 20 microsecond interval, the circuitry gives a distinctive output that includes the amount of time between the coincidence and subsequent decay.

Data

A brief description of the data follows. A more thorough tutorial on interpreting data from the Fermilab CRD can be found at http://quarknet.fnal.gov/cosmics.

The computer interface was set to record only those events that were potential muon decays. The second column of numbers in the sample data at right (Figure 4) always begins with a "5", indicating that a second pulse from one of the PMTs occurred within 20 microseconds of the original coincidence.

The third column of data indicates the paddle in which the second pulse was observed. In this experiment, paddle "1" was placed on top of paddle "4". We are interested in events where muons from the atmosphere pass through the top paddle and then decay in the bottom paddle. Thus the one event in which the second pulse occurred in paddle "1" is not of interest.

00256F52	55	4	2
00180ACB	55	4	03D6
00368D30	55	4	2
003234F6	55	4	2
0086FBD5	55	4	2
000D15A4	55	4	2
0068C615	55	4	1
004F52DB	55	4	2
000E8F3E	55	4	136
00265BEE	55	4	1
007CF81E	55	1	2
0003ABAA	55	4	03DA
0019E8A1	55	4	1
0027D8AF	55	4	2
0020ECE5	55	4	1

Figure 4

The fourth column gives the number of 20 ns clock cycles between the coincidence and the decay. This number is given in hexadecimal. By converting to decimal and multiplying by 20, one obtains the time in nanoseconds for each of the stopped muons to decay.

Analysis

The accompanying Excel spreadsheets display the three raw data sets and calculations. A few points are worthy of special attention:

First, in the sample data of Figure 4 there are many events with decay times of one or two cycles. The detector recorded 4333 decay events in the lower paddle in the data set begun on 12/5/02. Of these, 3940 showed decay times of just one or two cycles. By contrast, there were seven events that decayed in three cycles; two events that decayed in four cycles; 30 that decayed in five cycles, and so forth. This large disparity makes the shortest decay times (one or two clock cycles) suspicious. Perhaps they are an artifact of the apparatus and electronics. For this reason, these events were not included in the muon lifetime analysis.

Even if these events were real, removing them from the analysis would have no effect on the result. Just as the amount of time that the muons existed before they reached the detector has no effect on how long they will continue to live after their arrival, so too neglecting muons that may have decayed during the first few nanoseconds will have no effect on how long the remaining muons live. After excluding all of the decays that occurred in one or two clock cycles, the shortest decay time would appear to be 3 cycles instead of one. To avoid biasing the remaining data set towards longer decay times, two clock cycles were subtracted from all of the decay times.

The same pattern is seen in the raw data collected starting on 1/7/03. Here there are thousands of events with decay times up to 9 cycles. Thus 9 cycles were subtracted from all events with decay times of 10 or more cycles, and events with decay times of 9 or fewer cycles were ignored. The same procedure was followed with data collected beginning on 1/6/03.

The second important point about the data becomes apparent by looking at a histogram of decay times. (Figure 5.)

Decay Time(ns)	Frequency
1000	168
2000	64
3000	39
4000	25
5000	23
6000	13
7000	13
8000	7
9000	3
10000	5
11000	2
12000	5
13000	3
14000	2
15000	7
16000	2
17000	2
18000	3
19000	3
20000	4

Figure 5

Initially there is the expected exponential drop in frequency of muons with longer decay times, but after 7000 or 8000 nanoseconds, the frequencies level off. One can interpret this as a background noise. A possible explanation is that the photocathode of the photomultiplier tube is boiling off electrons which then are accelerated through the dynode chain and create a signal at random times. If one of these false signals occurs within 20 microseconds of a muon passing through both paddles, it would leave a signature identical to a muon getting stopped within the detector and decaying. Because this background appears roughly even across all of the time bins, subtracting the average background from all of the time bins should remove any bias in the data.

The frequencies in this histogram appear to show an exponential decline. This exponential decline is consistent with the nature of particle decay. Given a population of muons, a given percentage should decay during the first 1000ns. During the next 1000ns the same percentage of muons should decay, but because there are now fewer to begin with, there will be a smaller absolute number of decays during this second interval. In this way, the number that decay in any interval is proportional to the total number at the beginning of that interval. This property defines an exponential relationship.

The "lifetime" (t) of a particle is defined as the amount of time before a population of those particles is reduced to 1/e of its original number. Thus if one starts with N particles, the number (y) at any subsequent time should be given by

$$y = Ne^{-\frac{t}{\tau}}$$

(When t = t, for example, then y = Ne^{-1}.)

The histogram of Figure 5 does not actually show the total number of muons remaining at any time; instead it gives the number that decay during each interval, or

$$\frac{dy}{dt} = N\left(-\frac{1}{\tau}\right)e^{-\frac{t}{\tau}}$$

where t is the lifetime that is sought. Plotting the natural log of the frequencies versus the decay time should yield a straight line with slope -1/t:

$$\ln\left(\frac{dy}{dt}\right) = \ln\left(-\frac{N}{\tau}\right) + \left(\frac{-1}{\tau}\right)t$$

One such plot taken from the data of 12/5/02 is shown below. (Figure 6.)

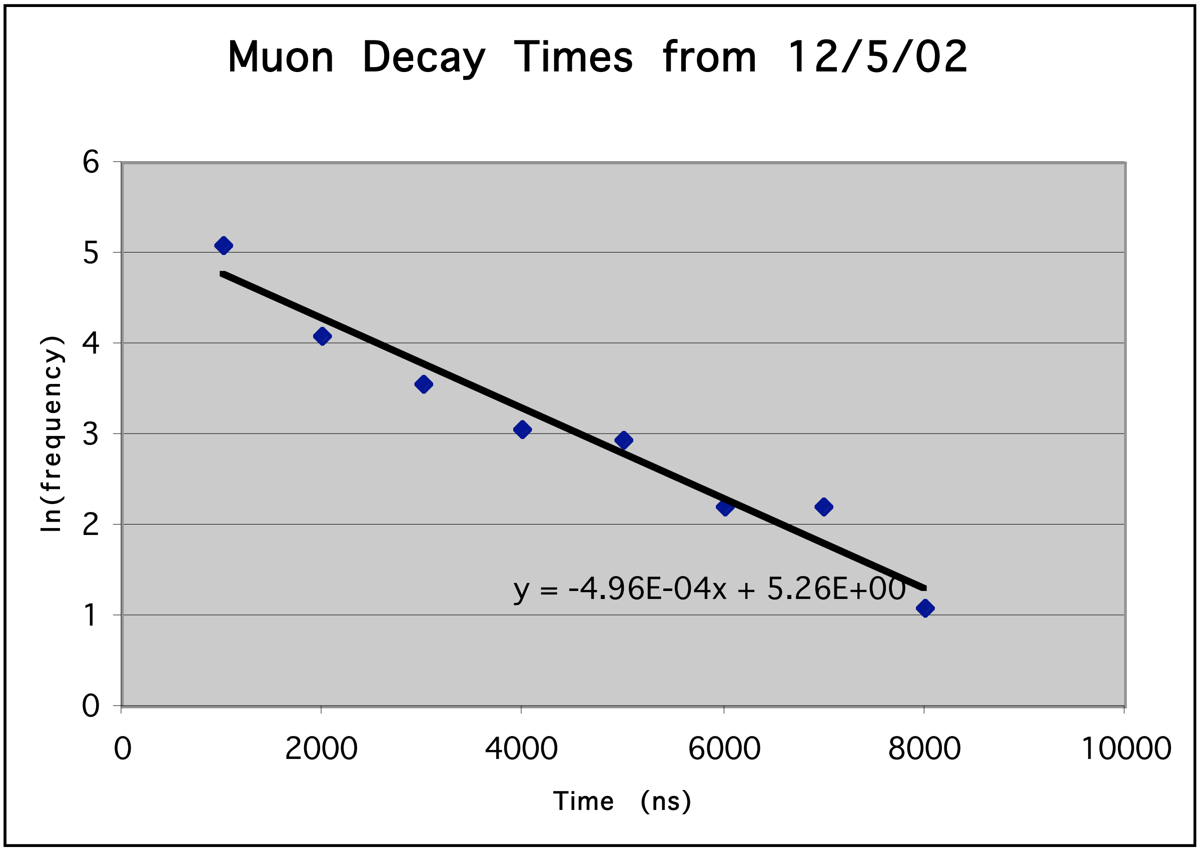

Figure 6

$$\tau = -\frac{1}{slope} = -\frac{1}{-4.96 \text{ x } 10^{-4}}$$

$$\tau = 2016ns$$

Similar calculations can be found in the spreadsheets for 1/6/03 and 1/7/03.

Results and Conclusions

Results from the three data sets yielded an average muon lifetime of 2.07 x 10^{-6}s. This agrees fairly well with the accepted lifetime of 2.197 x 10^{-6}s.

Perhaps the largest source of error comes from determining the appropriate background noise to subtract from the frequencies. Changing the background from 4 false decays per 1000ns to 3 false decays per 1000ns changes the calculated muon lifetime by 7% (using data from 12/5/02.) Acquiring a larger number of data points can improve the signal to noise ratio. For example, the data set collected beginning 1/7/03 has nearly twice as many events, and a similar change in background noise yielded a 4% change in the muon lifetime. Other factors which may reduce the noise and improve detection efficiency are related to the detector paddles themselves. The joints between the light guides and the PMTs were not rigid. As a result, some light is probably lost at these junctions.

Furthermore, the PMTs were not behaving reliably. Bumping the wires gently often resulted in radically different count rates. Also, the dynode voltages were not adjusted to attain maximum efficiency. Members of the Berkeley QuarkNet center are currently re-glueing the light guide junctions and plan to conduct a systematic debugging and adjustment to the PMTs. These adjustments may allow future measurements of muon lifetimes with greater precision and greater ease.

Experiment 2: The lifetime of energetic muons

Abstract

A portable cosmic ray detector built by Howard Matis at LBNL was used to measure cosmic ray fluxes at two different elevations. Cosmic ray muons are produced in the upper atmosphere and many decay while traveling toward earth. Thus the cosmic ray flux is greater at higher elevations than at lower elevations. The muon's time of flight from the higher elevation to the lower elevation was calculated by assuming that the muons move at approximately light speed. The lifetime of the muon (t) was then found by substituting the flux measurements and time of flight (*t)* into the equation: $Flux_2 = (Flux_1)e^{-\frac{t}{\tau}}$. Results from counting 2000 muons at elevations separated by 564 meters yielded a lifetime of 1.4 x 10^{-5}s, more than six times longer than the lifetime of the muon at rest.

Overview of the Berkeley Cosmic Ray Detector (CRD)

The Berkeley CRDs consist of two plastic scintillator paddles with a fixed separation distance of about 11.5 cm. The scinctillators are joined to photomulitplier tubes (PMTs) via plastic light guides. Output from the PMTs is routed to a circuit board with a digital counter. Switches enable the user to count pulses on either paddle or to count coincidences between the two paddles. In coincidence mode the detector effectively counts cosmic ray muons that pass through the paddles. More details concerning the LBNL CRDs can be found online at: http://www.lbl.gov/abc/cosmic

Data

On March 1, 2003, Berkeley CRD #6 was taken to Mt. Diablo for cosmic ray flux measurements. The CRD was placed on the hood of a Honda Civic in the summit parking lot of Mount Diablo where the elevation sign reads 3849 feet. Subsequently the detector was driven downhill and placed on the Honda's hood adjacent to a "2000 feet" elevation sign.

In each trial the time was measured for the detector to record 1000 events. (Figure 7.)

Altitude: 3849 ft.	
Trial Number	Time for 1000 events
1	443 s
2	473 s
3	455 s
Altitude 2000 ft.	
Trial Number	Time for 1000 events
1	518 s
2	526 s

Figure 7

Analysis

As can be seen in Figure 7, less time is required for 1000 events on the cosmic ray detector at higher elevations. In other words, there is a higher cosmic ray flux at higher elevations. One reason for this difference in flux is that muons are created high in the atmosphere and their short lifetimes cause many to decay on their way down toward Earth. So the lower the elevation, the fewer muons remain to pass through the detector.

The average lifetime of fast moving cosmic ray muons can be estimated by assuming that muon decay is the only reason for the dependence of flux on elevation. (There are other factors that may also affect the cosmic ray fluxes and some of these will be discussed in the "Results" section below.)

Most cosmic ray muons are moving close to the speed of light, so the time for them to travel from 3849 ft. to 2000 ft. is approximately:

$$t = \frac{d}{v} = \frac{1849 ft}{c} = \frac{563.6m}{2.998 \times 10^8 m/s} = 1.880 \times 10^{-6} s$$

The number of muons passing through the detector each second at 3849 ft. is:

$$Flux_1 = \frac{3000 \text{ muons}}{443s + 473s + 455s} = 2.188 \text{ muons/s}$$

At 2000 ft:

$$Flux_2 = \frac{2000 \text{ muons}}{518s + 526s} = 1.916 \text{ muons/s}$$

Because the decay of a population over time is exponential, $Flux_2 = (Flux_1)e^{-\frac{t}{\tau}}$, where t is the time of flight from 3849 ft. to 2000 ft. and t is the lifetime of the muon. Solving for t gives:

$$\frac{Flux_2}{Flux_1} = e^{-\frac{t}{\tau}}$$

$$\ln\left(\frac{Flux_2}{Flux_1}\right) = -\frac{t}{\tau}$$

$$\tau = \frac{t}{\ln\left(\frac{Flux_1}{Flux_2}\right)} = \frac{1.879 \times 10^{-6} s}{\ln\left(\frac{2.188 \text{ muons/s}}{1.916 \text{ muons/s}}\right)} = 1.41 \times 10^{-5} s$$

Results and Conclusions

An average lifetime of 1.41 x 10^{-5}s for these high speed muons is about 6.4 times longer than the muon's lifetime at rest, 2.197 x 10^{-6}s. This appears to be a direct result of relativistic time dilation.

More recent experiments using the Berkeley CRD on Mount Diablo have yielded average lifetimes of 1.35 x 10^{-5} s and 1.55 x 10^{-5} s.

As mentioned previously, muon decay is not the only factor that affects the count rate at different elevations. Another significant factor may be the stopping power of the atmosphere. As muons move through hundreds of meters of air, some may be slowed or stopped by collisions with air molecules. Additional experiments or data about the cross section of muons would be necessary to determine the magnitude of this effect. Because the stopping power of the air would create a larger difference in muon flux at different elevations, this effect would make it appear that the muon lifetime is less than it actually is. In other words, energetic cosmic ray muons really live longer than 1.4 x 10^{-5} s on average, so relativity is still clearly at work.

Another assumption is that the detector is seeing only muons. In fact, at sea level there should also be a small flux of primary cosmic rays (mostly protons) and also secondary cosmic ray electrons. If the flux of either of these is significant, then the muon lifetime measurement will be skewed. How it would be skewed would depend on how fast the flux of these other particles decreases with altitude.

A third potential source of error arises if more muons are formed between the top of Mt. Diablo and the lower elevation. For example if a cosmic ray proton collided with an air molecule below 3849 feet, an air shower of pions and subsequently muons might be detected in the lower detector while nothing (or only the primary particle) was detected in the upper detector.