Relativistic Effect of Cosmogenic Muons

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Abstract

Muons are 2nd generation leptons which have a mass of 105 MeV, 200 times more massive than an electron, with a negative charge. When cosmic rays hit earth's atmosphere, pions are created and decay into muons within 26 nanoseconds. Muons interact electromagnetically with other particles and therefore can travel a relatively long distance while losing energy in the process. The lifetime of muons is about 2.197 microseconds and sometimes travel at near the speed of light. According to Classical Mechanics, muons travelling at nearly the speed of light, 2.998×10^{8}m/s, will take approximately 50 microseconds to reach sea level which is 25 times longer than muon lifetimes. Muons can however, be detected at sea level at a rate far greater than classical predictions. This is due to time dilation, a modern physics prediction made by Albert Einstein for objects travelling near the speed of light [2]. When taking a relativistic approach detection becomes possible and the predictions become reliable [1].

Keywords: muon, relativity, time dilation

Introduction

When cosmic rays collide with the upper atmosphere, an air shower is produced. An air shower is a cascade of ionized particles and electromagnetic radiation. When a particle strikes a nucleus in the air from the primary cosmic rays it produces energetic particles like pions that decay in the air into other particles like muons which then travel toward earth to be detected.

Einstein's Special Relativity is based on two principles. Light in a vacuum is the same speed for all observers and the laws of physics are the same for all observers in uniform motion relative to one another. This has great implications for objects that are moving at near the speed of light. In the case of this research that object is a muon particle. Time dilation is a product of Special Relativity that explains how muons could be detected at elevations where their lifetime would not allow. In terms of muons, time dilation is when a muon that is traveling at the speed of light experiences a slower time rate than that of an observer that is not moving at all. This makes it possible for muons to reach sea-level because to us as observers, we see a longer muon lifetime that is true of the muon.

Methods

To test the Relativistic Effect of Muons there is a few things needed. A detector, a way of recording data, and a portable way to house all the equipment. The detector is a cylindrical scintillator that interacts with charged particles as they pass through and produce scintillation light, also known as photons. By measuring the intensity of the scintillation light, we can infer the amount of energy a particle left behind. A photomultiplier tube can produce a pulse output whose height is proportional to the energy that was left in the scintillator by the charged particle. What is measured is a voltage produced by the photomultiplier tube that is converted to digital signal and counted by a counting device. The photomultiplier tube used required a period of normalization. This is mainly due to temperature. Depending on the temperature the high voltage inside the PMT would change. To compliment the PMT an Analog to Digital Binary Counter (ADBC) was built to increase the portability of the experiment. A signal from the PMT was input to the ADBC and stored in binary code on the ADBC without the need of a computer.

The signal produced from the PMT is inverted and somewhat weak. This signal also includes unwanted background that needs to be filtered through. The ADBC serves two purposes. The first is to filter through all the signals and keep the desired signals. This is done by first amplifying the signal then cutting off the undesired signals. The left-over signals are now seen as digital signals recognized by the counter and registered. Once counted the signal is cut off from the PMT and can be seen on the LED display in Binary. The LED displays 8-bit increments of data and can be switched with the switch buttons connected to it. The first button displays the first 8 bits, the second shows the second set of 8 bits

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and so on. The fifth button is used to reset the counter to be used again. This counter can display a total of 32 bits, counting up to 4,294,967,296. The Schematics can be seen In Figure 1 and the actual counter in Figure 2.

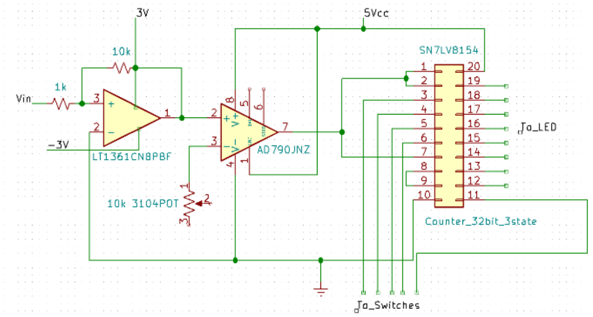

Figure 1: Switches number 1-5 from left to right. Switch number five is the reset switch

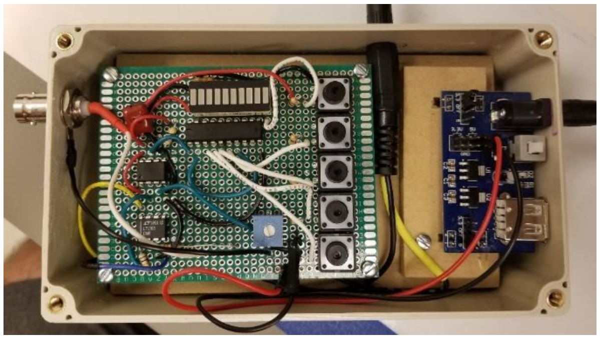

Figure 2: Switches number 1-5 from bottom to top. LED displays on-off as 1 or 0 respectively from left to right. The leftmost bit being the 1s place from the first 8 bits. Device is powered by D-Cell Batteries at different voltages.

Using this equipment, the muon flux was tested for five hours at a time at different elevations. To calibrate the device, it was first tested at around 100 ft. Knowing the rate of muons at this elevation we could calibrate the equipment to read around 3.6 muons per second. Once tested, the muon detector will be transported to different elevations to acquire data. The reason is that the flux of muons needs to be recorded at different elevations to extrapolate the exponential effect it has. The location at sea- level is Stanislaus State University – 100 ft (31 meters). Data acquisitions at different altitudes will be conducted at Yosemite National Park in the following locations. Hodgdon Meadow - 4200 ft (1402 meters), Crane Flat Campground-6200 ft (1890 meters), and Tuolumne Meadows Campground-8600 ft (2621 meters). To see the effect of Relativity we need to find out the length the muon has traveled in its lifetime.

Expected Results

At 100 ft, we expect to detect 3.6 muon per second. Given this and the life time of the muon of 2.2 μs, we can extrapolate what the expected behavior of the muons will be at different heights. 2.2 μs is the lifetime at the rest frame of the muon and is the non-relativistic lifetime that would not allow the muons to be detected at sea-level. Note that this is the proper lifetime for a muon, and if it was not moving at the speed of light it would hold. The relativistic lifetime is what we as observers see. The relativistic lifetime is expected to be around 16 μs [3]. To relate the non-relativistic and relativistic lifetimes we must find the gamma factor predicted by Einstein. This gamma factor can be calculated through the following equation.

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} \tag{1}$$

Where v is the speed of the muon given to be 0.99 times the speed of light and c is the speed of light given to be 2.998×10^8 m/s. Here the gamma factor is calculated to be 7.08. With this information we can create two graphs shown in figures 3 and 4 showing how the flux is expected to be affected with altitude with and without involving the gamma factor.

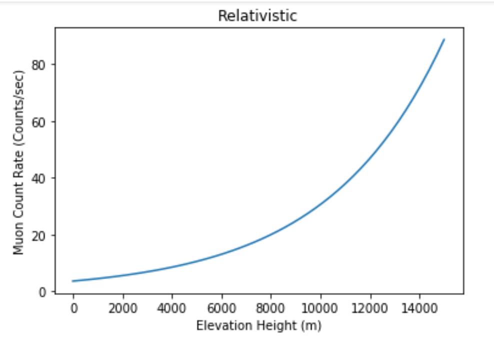

Figure 3: Counts/sec (Muons Rate) vs Elevation Change Considering Time Dilation

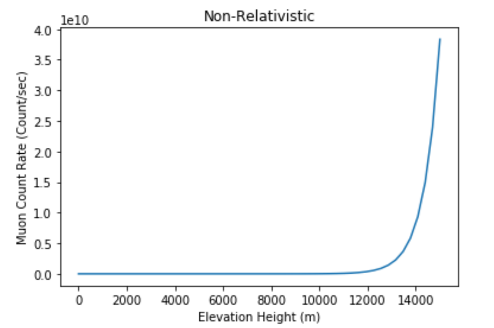

Figure 4: Counts/sec (Muon Rate) vs Elevation Change Not Considering Time Dilation

Notice the difference in muon production at 50000ft(15km). In Figure 4 the number of muons per second being created in a 175 cm^2 area would be around 3.5×10^{10} muons. There is not enough atmosphere at that height to harbor that number of muons. The expected number of muons at their production height match better with Figure 3 where around 75 muons are produced per 175 cm^2 per second.

Results

Elevation (m)	Counts	Time (s)	Measured Muon Rate(counts/s)
32	66864	18000	3.72 ± 0.014
1402	84646	18000	4.70 ± 0.016
1890	101041	18000	5.61 ± 0.018
2621	121532	18000	6.75 ± 0.019

Table 1: Raw Data taken from various elevations

From this data the experimental gamma factor was calculated to be 6.254 giving the muons an average velocity of 2.959×10^8 m/s which is 0.987c. The majority of the error suspected is with the temperature the device was run in. The temperature was about 10 degrees Celsius colder in Yosemite National Park which changed the calibration slightly. The temperature at night changed by 20 degrees Celsius which had the biggest effect. It is not easy to tell how much effect on the data this had but due to the nature of the equipment the calibration could not be changed. This data can be overlaid on the graphs in Figures 3 and 4 to see which fit better. Figure 6 shows the results of the data on the relativistic and non-relativistic expected graphs.

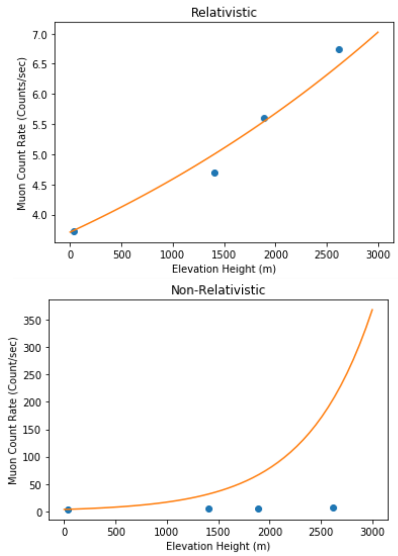

Figure 6: Comparing Relativistic and Nonrelativistic Graphs.

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References

[1] Coan, T.E., Ye, J.Y, Muon Physics, https://web.phys.ntu.edu.tw/asc/FunPhysExp/ModernPhys/exp/muonphysics.pdf
[2] Einstein, A. (1905). On the Electrodynamics of Moving Bodies, *The Principle of Relativity*
[3] Serway, R.A., Clement, J.M, Curt, A.M., (2005). *Modern Physics* (3rd ed.). Delhi, India: Cenage Learning