Measurement of the Lifetime of Cosmic Ray Muons

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We attempted to experimentally measure the lifetime of cosmic ray muons. After repeated attempts, we unfortunately were unable to produce any thing but spurious results. We measured an average lifetime of 2.2 μsec, which agrees with the expected lifetime. However, the variance in the lifetime data was on the order of 0.1 μsec which disagrees with the expected exponential probability distribution. Additionally, the lifetime data was shown to fit to a bimodal Gaussian distribution which also disagrees with the expected exponential distribution.

BACKGROUND

Muons are elementary subatomic particles carrying one negative unit of elementary charge and with a mass of 105.7 MeV/c^2 [3]. They carry spin 1/2 and are therefore fermions [3]. In addition, they are classified as leptons and closely resemble electrons (except in mass) [3]. Muons constitute the majority of radiation at sea level [3] and were discovered by J. C. Street and E. C. Stevenson using a cloud chamber in 1937 [4, 5]. The muon was the first elementary particle to be discovered that was not a constituent of the atom [5].

Since radioactive decay, nuclear fission, and nuclear fusion processes are not energetic enough to produce muons, the question, once one has detected the existence of muons, then occurs as to how muons are produced in the first place. Cosmic rays - particles from space that impinge on the upper atmosphere - consist primarily of high energy protons. When these protons impinge on the atmosphere, they react with nuclei and produce pions. Those pions are unstable and within a few meters produce muons and neutrinos (see figure 1). However, the muons are also unstable and decay into an electron, an electron neutrino, and a muon neutrino:

$\mu^- \rightarrow e^- + \nu_e + \upsilon_\mu$

Historically, measurement of the lifetime of cosmic ray muons was pivotal in providing experimental evidence for the special theory of relativity. At rest, muons are known to have a lifetime of ~2.2 μsec [1] which, under Newtonian mechanics, would make it impossible for muons produced in the high atmosphere to be, on average, observed at sea level (the atmosphere is ~15km in thickness [2] but with an average lifetime of 2.2 μsec, even at a speed of c, we expect muons to travel an average of ~660 meters [2].) Due to the effects of time dilation, however, the muons' average lifetime is considerably lengthened from the Earth's reference frame and, due to length contraction, the height of the atmosphere is considerably shortened shortened from the muons' frame relative to the Earth [2].

One question that can be raised in this context is as to how many muons actually survive at sea level. If special relativity is not taken into account, then trivially the time and the length traveled is the same in both reference frames. In that case, $\sim 2.7 * 10^{-5}$of the original muon population survives, or approx 0.3 out of a million [7]. This, of course, does not correspond to the distribution that is actually observed. The muons are, in fact, traveling at close to the speed of light, and therefore, special relativity needs to be taken into account as follows (assuming the muons travel at 0.98c):

$(lifetime) = \frac{(lifetime)_0}{\sqrt{1-v^2/c^2}} = \frac{2.2\mu s}{\sqrt{1-(0.98)^2}} \simeq 11.06\mu s$

$t = \frac{h}{v} = \frac{15km}{0.98\times 3\times 10^8 m/s} \simeq 50\mu s$

$(\#lifetimes) \simeq \frac{50\mu s}{11.06\mu s} \simeq 4.52$

But after a period of 4.52 lifetimes, approx 4% of the original population will survive. Due to the large population of cosmic ray muons, one would expect to see counts on the order of one per second.

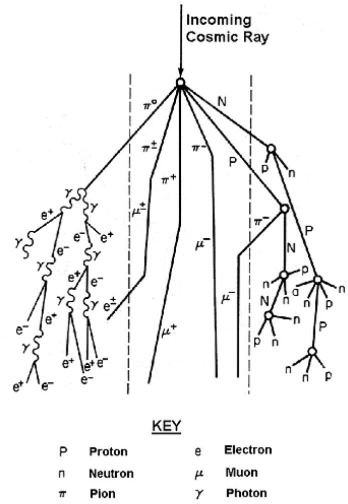

Figure 1: Cosmic ray decay chains, beginning in the upper atmosphere with an incoming cosmic ray - usually a proton - and terminating in electrons, positrons, muons, anti-muons, and protons. The electrons and positrons are collectively unstable and will annihilate with each other producing gamma rays. The muons are unstable because they have a particular lifetime. The neutrons are stable on the time scales of interest, and the protons are stable. Graphic from [6].

In our experiment, we attempted to reproduce the historic measurement of the cosmic ray muon. Due to what

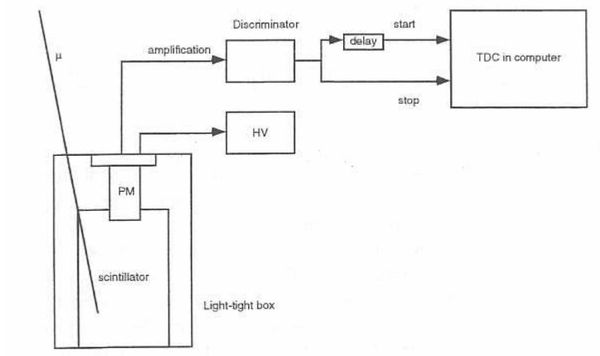

Figure 2. Schematic of muon lifetime set-up.

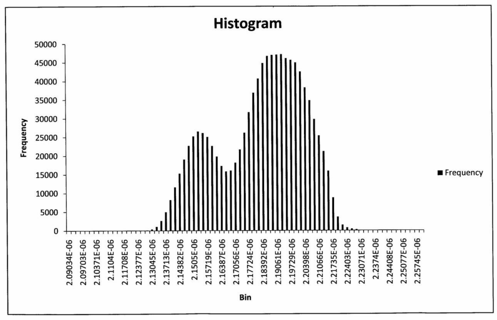

Figure 3: The distribution of spurious data. It appears to be a bimodal Gaussian distribution, but its origin is unclear.

was presumably a malfunction in our equipment, however, we were unable to successfully reproduce the aforementioned results.

METHODS

Our setup consisted of several different components - a scintillator, a photomultiplier tube, a high voltage source, a discriminator, delay line, and a computer equipped with a Time to Digital Converter (TDC).

The scintillator is a fluid which scintillates upon exposure to radiation. Therefore, when muons, or other particles, impinge on the scintillator, the material releases photons which then proceed to strike the photomultiplier tube. When the muon decays, one of its decay products is an electron, and when that electron travels out into the scintillator, it also causes photons to be released. Therefore, the photomultiplier tube will see two successive bursts of photons for each muon event. The photomultiplier tube uses a high voltage source to amplify the signal from the scintillator and to translate the two bursts of photons into an electronic signal. That signal is then amplified and passed to the discriminator. The discriminator passes that signal to the TDC through a set of delay lines. The first signal to arrive stops the previous run, and the second signal starts the new run (as in the diagram, the delay line leads to 'start' and a short cable leads to 'stop'.)

The discriminator has some characteristic cut off voltage, which, when set properly, sets apart the noise from actual muon events (only events with voltages above that of the cutoff voltage are recorded.) Therefore, due to the presence of gamma rays and other particles, when the threshold voltage is set too low, spurious results may be obtained.

BATCH PROGRAM

Early on, it became clear that the program had a limit on the number of data points that it could output and that every time the program was run, information had to be manually entered. Not having the original source code, we needed a work around so that the program could be run continuously over the course of several days (allowing us to gather an extremely large amount of data.) The solution that we arrived at was to use a batch script that would automatically enter input.

'Batch' is a scripting language for automating DOS commands. Since the software we used to gather muon lifetime data ran in a DOS environment, it seemed natural to use a Batch script as an appropriate way in which to automate input. The script we wrote also had the capability to repeatedly call the appropriate software, so that we could run continuously over an indefinite period of time. The batch script, perhaps unfortunately, was the only part of our project which succeeded in operating correctly.

RESULTS AND DISCUSSION

The computer contained several programs, and it was unclear as to which program actually produced good results. We believe that the output of the program was supposed to be lifetime data in microseconds. However, it was clear that every program we tested consistently produced results centered on 2.2 microseconds with a variance of ~0.1 microseconds. Running over a period of several days, we produced the data set shown in figure 3. This is clearly a bimodal Gaussian distribution. Note that this is also clearly not an exponential decay, as it should be.

Several possibilities occurred to us as to what could have possibly gone wrong. The first idea is that something could have gone wrong with the threshold voltage on the discriminator. Lowering the threshold voltage increases the frequency of detections, as expected. However, the variance did not change in an observable fashion when the threshold voltage was lowered. In addition, we set the threshold voltage so that the observed frequency of detection was on the same order of magnitude as we expected. Setting the threshold in this manner produced the graph shown in figure 2. We also tried other discriminators and these produced the same results as well.

Another possibility is that something could have gone wrong with the cables leading from the discriminator into the computer. We tried switching out these cables as well as changing their lengths. One cable produced poor results which we attribute to the oxidation that was present on the outer part of its connector. The other cables produced zero results but had negative total run times, which we can attribute to the reversal of the 'start' and 'stop' commands. Regardless, to whatever the negative times can be attributed to, they are obviously non-physical.

Yet another possibility is that the amplifier could have been malfunctioning. To test this idea, we switched out the amplifier and used an identical setup as before. We noted that one of the amplifiers was completely malfunctioning (and therefore was not producing data at all). The other amplifier, however, seemed to be working correctly. We tried to adjust the calibration on the amplifier using the plastic screw driver, but we were not convinced that the screw driver was actually making contact with the screw at all. Regardless, attempting to change the amplification appeared to have little effect (if any at all) on the data output by the computer.

There exist several other possibilities as to the source of the error. Note that our methodology for checking errors depended highly on the assumption that a single component was malfunctioning. However, we did some minimal checking for combinations of problems. Having said that, given that the system contains seven systems and numerous subsystems, the number of possible combinations of problem systems is enormous. In addition, there were a few systems that we were unable to verify as operating correctly. These systems are the computer's TDC card, the PMT, and the scintillator. A problem could have also occurred in the software though this seems unlikely given that we were using the same software as previous groups had used. However, it also seems unlikely that there could have been a problem in the scintillator or the PMT. Therefore, if one of those four had a problem, it was probably in the computer's TDC card. We did attempt to test this by passing signals from a function generator into the discriminator and then into the computer. The computer output was what we interpreted to be the correct results in that the results were highly consistent (as one would expect from signals produced by a function generator.) We also attempted to test the TDC by using the 'virt' program as instructed in the lab manual. According to the 'virt' program, the card was operating correctly, though we have no information as to how the 'virt' program operates internally.

CONCLUSION

Though we were unable to find the problem in our apparatus, we did successfully create a batch script to automate data gathering which was successful in gathering data over a period of several days. Through a careful process of elimination, we tested all of our equipment and were inconclusive as to what the possible source of the malfunction could be. Our data shows a lifetime distribution which is inconsistent with previous results and had a significantly low variance. However, we believe that due to the creation of the batch script, future groups will be in a better position due to the fact that, unlike in previous years, their data gathering efforts will be automated.

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