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Muon Decay Experiment

Introduction

Cosmic rays are extremely high energy particles that bombard the Earth from space. Primary particles, usually protons and light nuclei, strike atoms in the upper atmosphere and begin a chain of collisions that result in a shower of thousands of particles. In rare occasions the primary particle can have in excess of 10^{20} eV of kinetic energy. This is five orders of magnitude higher than the most energetic particles accelerated at man made facilities. The weakest cosmic rays still possess kinetic energies around a GeV. Within the showers started by the primary particles, a host of different particles are made including electrons, pions, muons, and gamma rays. Pions are extremely unstable particles made out of two quarks. They decay after several nanoseconds into combinations of muons and muon neutrinos. The majority of particles that reach the ground during a shower fall relatively straight. This is because particles that strike the atmosphere at an angle have to travel through more of it to reach the ground. In doing so the lose more of their energy.

Cosmic ray muons are often introduced in introductory college courses on modern physics as an example of how Einstein's theory of special relativity is evident in nature. Muons are unstable particles with lifetime of 2.2 μs. With the help of the CROP program, this experiment has been designed to provide you with an opportunity to detect these particles and measure their lifetime.

Equipment

-CROP scintillation detectors
-CROP Data acquisition (DAQ) card w/manual
-2 CROP high voltage power supplies
-Labview software

The scintillation detectors consist of plates of plastic scintillator attached to photomultiplier tubes. The plates fluoresce any time ionizing radiation (charged particles, EM waves, etc.) pass through them. They are wrapped in black plastic to shield them from ambient light. **The PMT's on the two thin detectors should operate at 1350 Volts and the PMT on the thick detector should operate at 1100 Volts.**

The DAQ card is specifically made for cosmic ray experiments by a company called Quarknet. The detailed operations of the card are explained in the manual and you should familiarize yourself with them before using the card. Essentially, it receives, digitizes, and amplifies signals from up to four channels and has programmable coincidence settings which it uses to identify events. The timing structure is of special importance as the goal of this lab is to calculate muon lifetimes. There are two main aspects of the timing called the TMC Delay and the Gate width. Read about what these are and how to set them in the manual.

Objectives

1. Use the Threshold Scan function of CROP DAQ 4.0 to determine the correct discriminator (find out what discriminators are in the manual) voltages for each of the three detectors. The program will write the data to a spreadsheet file. When the counts column is graphed against the voltage column the graph should look exponential. Set the y scale to logarithmic and find the voltage at which the slope changes. For an example of this see the CROP website at http://crop.unl.edu/. Click on the Tech Info link and Setting Thresholds: Notes section. After the thresholds are found for each counter set the discriminators to the correct values and do a short (a couple of minutes) Singles Rate Scan using the same program. The rates should be in the hundreds of hertz. If they are not close that range, notify your instructor as they may need some troubleshooting.

2. With the proper discriminator settings you may begin collecting muon decay data. First make sure the detectors are in a vertical stack with the thick one in the middle. Plug the top detector into channel one, the middle detector into channel two and the bottom on into channel three. Use the Labview program Muon Decay Data Collection. If you have some experience with Labview look at the block diagram and try to understand what the program does. It will create a data file that will be analyzed later. To make sure that the analysis program is able to read the file make sure to stop collecting data before the file reaches 100 megabytes in size. This will probably require you to stop the program after a few days. The file should be at least 30 megabytes to provide good statistics. Before leaving the lab you should check to make sure the program is actually writing data to the file.

3. Analyze the Muon decay files using the Muon Decay Data Analyzer program. Depending on how large your file is this may take a while. On average the program will go through about 3 MB per minute. The program will save a file that contains the histogram data. This data should be used to verify whether or not the decay matches the exponential decay model

$$N = N_0\exp[-\lambda t].$$

4. Devise an experiment that will yield different results. The average decay time should not be an artifact of the computer analysis so an attempt to falsify a result should be made .

Sample Lab Write-Up

Introduction

The University of Nebraska has been home to the Cosmic Ray Observatory Project (CROP) for almost 12 years. In the early going, an attempt was made by the project's researchers to measure muon decays using the same materials they use to detect cosmic ray showers. This attempt failed to yield any conclusive results and was more or less forgotten about until a twist of fortune resulted in CROP acquiring new scintillating material that was better suited to such an experiment. Professor Daniel Claes suggested that if a successful measurement could be made with the new material, it might make a good experiment for students to do in the advanced lab. Labview software was used in conjunction with the data acquisition card used by CROP to detect particles and then analyze data files looking for events with signatures that matched those expected for muon decays.

Theory

Cosmic rays are extremely high energy particles that bombard the Earth from space. Primary particles, usually protons and light nuclei, strike atoms in the upper atmosphere and begin a chain of collisions that result in a shower of thousands of particles. In rare occasions the primary particle can have in excess of 10^{20} eV of kinetic energy. This is five orders of magnitude higher than the most energetic particles accelerated at man made facilities. The weakest cosmic rays still possess kinetic energies around a GeV. Within the showers started by the primary particles, a host of different particles are made including electrons, pions, muons, and gamma rays. Pions are extremely unstable particles made out of two quarks. They decay after several nanoseconds into combinations of muons and muon neutrinos. The majority of particles that reach the ground during a shower fall relatively normal to the Earth's surface. This is because particles that strike the atmosphere at an angle have to travel through more of it to reach the ground. In doing so they lose more of their energy.

Muons are the second heaviest member of the lepton family of particles. The other members are the electron, and the tau, and the neutrinos that correspond to each of the three. The muon and the tau have the same -1 charge as the electron, but are much heavier. Muons are about 207 times as massive and taus are almost twice as massive as protons. Because of their large masses, these two particles are unstable and decay a short time after they form. The decay equation for muons is as follows,

$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu. \qquad (1)$$

The average lifetime of a muon is 2.2 μs. Their decay, just like any ordinary nuclear decay, is exponential in nature. A group of muons detected at some time will follow this exponential decay pattern such that on average after a certain half life, half of the muons will have decayed and the remainder will still be exist. The generic exponential decay equation is sufficient to model the decay process

$$A = A_0\exp[-\lambda t]. \qquad (2)$$

In the above equation, λ is the decay constant with units 1/s. This constant determines the half life from the relation

$$t_{1/2} = \ln(2)/\lambda. \qquad (3)$$

For an exponential decay, the relation between average time and half life time is

$$t_{average} = t_{1/2} / \ln(2). \qquad (4)$$

With this knowledge, all that is needed is sufficient statistical data to form such an exponential decay plot. Once plotted, the data can be fitted with equation (2) and the average and half life times can be calculated. The idea behind the data collection is to detect a relativistic muon, stop it so that it exists in the laboratory's rest frame, and then detect the electron it decays into.

a

Experimental Apparatus and Procedures

Because muons and electrons are charged they are easily detected using various means. The CROP program uses plates made out of plastic doped with an agent that fluoresces when charged particles and electromagnetic radiation pass through it. These plates, in conjunction with photomultiplier tubes, allow impacts to be detected. Because the material is sensitive to electromagnetic radiation above a certain energy the plates must be wrapped in black plastic for light tightness. The wrapping does nothing to protect against x-ray and gamma ray radiation, but fortunately the presence of these is limited on the Earth's surface. Photomultiplier tubes are attached to the plates to measure the light given off by the detectors during particle hits. The complete detectors must be tested for their optimum threshold setting and high voltage input.

The plates that CROP uses for their data collection are a half inch thick and cut in squares that are 24 inch by 24 inch squares. Evidently they were ill suited for a muon decay experiment as the previous attempt using them did not work. In the last six months however, CROP acquired fourteen plates of scintillating plastic that were four inches thick and similar in length and width to the existing pieces. The added thickness greatly increased the likelihood that a muon decay experiment could be successful. This is because the muons would now have to travel through eight times as much material and the probability that they would stop inside of it is therefore higher. Once stopped inside the plastic, the muon then lives out its life and decays according to equation (1). At this point the electron is detected and the decay time is calculated.

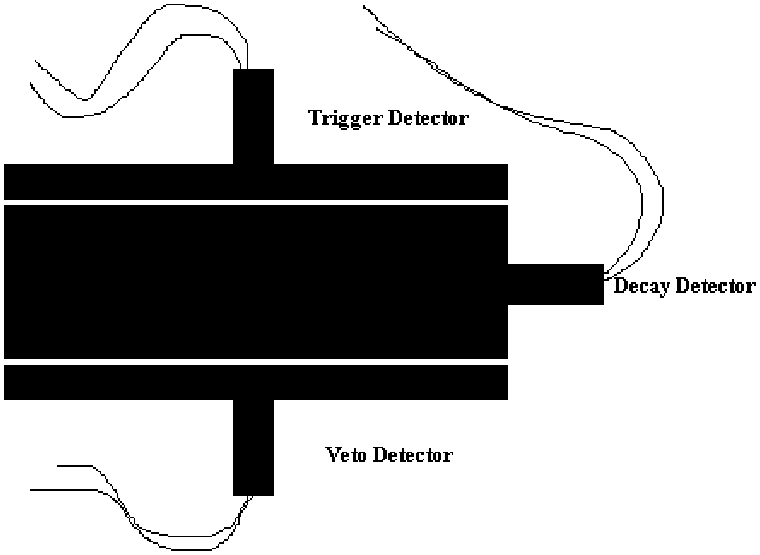


Figure 1. The detector arrangement used to measure muon decays. The top detector serves a trigger, the middle detector measures the decay and the bottom detector provides a veto.

To achieve efficient event detection a group of detectors needed to be arranged as illustrated in Figure (1). Two detectors where built to match the length and width dimensions of the thick panel. These two where then stacked, one on top of and one beneath, the thick detector. This arrangement allows a number of things to be done. First the two thin detectors provide a control mechanism to filter out accidental counts from the decay detector. If the middle detector records a particle hit but the top one does not then the event can be thrown out because there is a good chance that the signal may not have been a cosmic ray particle. If, however, the top and middle detector record hits in sequence then it is most likely due to an incident particle. The bottom detector can be used then as a veto detector. If it records something as well then it can be reasonably assumed that the particle did not stop in the thick detector and instead passed through all three. I this case, the event is thrown out as well since it would not provide any useful decay data. This system is not failsafe as noise can trigger PMT signals and a coincidence between the top and middle detectors without a signal from the bottom detector can happen accidentally. It is also possible that this method filters out good events as well. Perhaps a muon does stop in the middle detector but goes unseen by the top detector. In this case the event would go unnoticed and the potential data lost.

All of the coincidence and timing of these events was taken care of by a data acquisition card made specifically for cosmic ray detection by a company called Quarknet. The card has programmable fast logic circuitry that allows various coincidence settings to compare up to four independently amplified and discriminated channels. At the core of the card's design is the timing mechanism. There is a clock tick supplied by an RC circuit with a time constant of 24 ns. This allows 24 ns resolution on the two settings the card uses for event timing.

The first time setting is the data delay. This setting is the time after a signal reaches the card from an active channel during which the card will wait for more signals to come in to meet the coincidence criteria. For example, consider a card set to record two fold coincidences (events that register hits on two different detectors) with a delay time of 48 ns. This means that after a signal comes in, the card will wait 48 ns, or two clock ticks, for a signal from another channel. If another signal comes in then a new event is started. If a signal does not come in then the first signal is disregarded and the process starts over again when the next signal reaches the card. A related timing setting is the veto delay. This is the length of time after the first signal that a signal on a veto detector will veto the event

The second aspect of timing is called the gate width. This setting determines what happens once an event has been identified. The gate width is a window during which any new signals that come in get assigned to the event. Consider again the previous example now with the card having a gate width of 1 μs. Any new signals received by the card up to a microsecond after the event was identified will be appended to that event.

The card is controlled by a computer which also serves as the output destination for the data that the card collects. The connection is made via a serial port. The interface used to communicate with the card for this experiment was the Labview software that CROP uses. It provides a user friendly means to communicate with the card even for those with limited programming experience. Two programs were written, one which programs all of the proper card settings and collects the data, and another that analyzes the data and creates a histogram of decay times. Three runs were taken that took significant amounts of data. For each the settings were:

Coincidence – 2 Fold (with veto on Channel 3)
Data Delay – 48 ns (2 clock ticks)
Veto Delay – 96 ns (4 clock ticks)
Gate Width – 9600 ns (400 clock ticks)

Also worth noting is the fact that the card has a GPS timing and positioning capability that was not used in this experiment and had to be turned off. With all of these settings being assigned by Labview all that is required to start data collection is to name a file to which the program writes the data that it receives. The data collection program does nothing to filter the data, it simply gives the card the proper settings and writes the data from the card to a file.

The data from the card has the following appearance:

```
06AE9E0D    AC  30    00  01    23  35    00  01
06AE9E0E    00  01    00  01    28  2B    00  01
06B11B43    80  01    00  01    00  01    00  01
06C00118    A4  36    22  01    2E  3A    00  01
```

There are nine columns in each line and each corresponds to a particular value. The first column is the clock tick value. Anything that happened during a particular clock tick (24 ns) is recorded on the same line as its clock tick. The next two numbers are the rise and fall times of the signal on channel one in units of 0.75 ns. The next three pairs are the rise and fall times of channels two, three, and four respectively. All of the numbers are in hexadecimal. When the hexadecimal numbers are converted to binary each digit has a meaning. The digit with the most immediate significance is in the rise time for channel one. The seventh binary digit is the delimiter that separates events. On a new event this digit is 1 and on data that is part of an old event the digit is 2. This allows lines to be sorted into events.

The data analysis program reads in the file that is filled with lines similar to the ones above. It reads the file line by line organizing it into events using the channel one rise time discussed above. These events are then analyzed one by one. In a given event, the program looks for one rise time and one fall time in channel one. This corresponds to a particle entering and exiting the top detector. It then looks for a rise time and a fall time in channel two. This corresponds to a particle entering and either exiting or stopping in channel two. Next the program verifies that there are no rise or fall times in channels three or four because three is the veto detector and four is not active. Finally, it looks for a second rise time in channel two. Because the program limits channel one to one rise and fall time and a second rise time in channel two suggests that the new particle originated inside the second detector. If a second rise time is present, the program immediately subtracts the clock tick at the beginning of the event from the clock tick that the second rise time is a part of. The result of this subtraction is the muon decay time. Each decay time is fed into a Labview histogram VI that prints the results on a graph as well as the average decay time and the standard deviation of the times. The results of the histogram are also saved so that they can be opened using Microsoft Excel or a data analysis program such as Microcal Origin without running the Labview program again.

Results

Using the data collection program three runs were taken over the course of a week. Each run spanned a different amount of time. The first run lasted about a day and a half and created a file that was a little over 50 megabytes. From this file the analysis program found 1780 valid events. The histogram is shown in Figure (2) below.

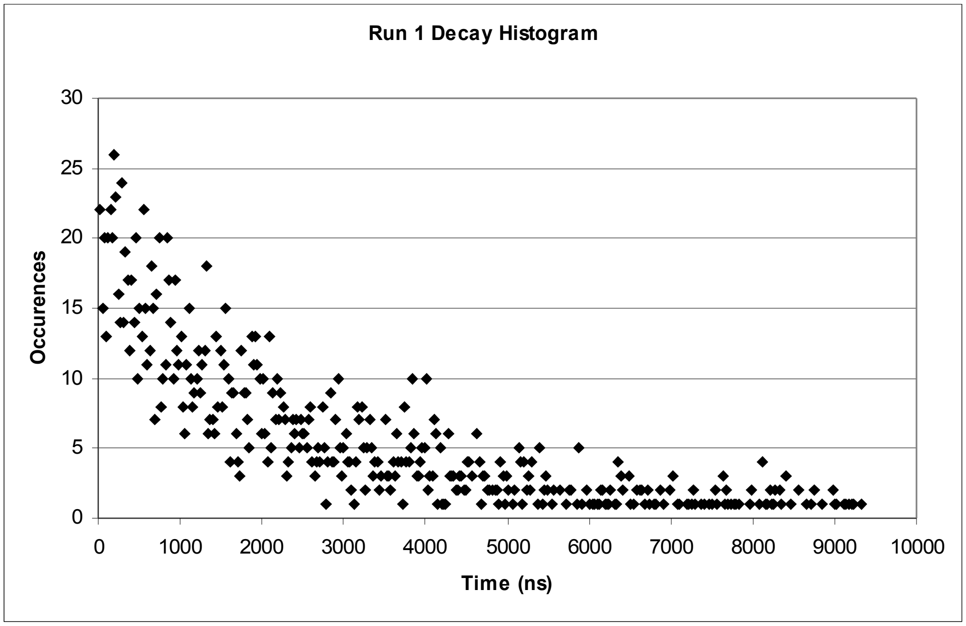


Figure 2. The histogram from the first run. A quasi-exponential behavior is seen.

The average time calculated by the program was 2.176 µs. The spreadsheet file consists of decay times and the number of times a decay was detected after that amount of time. Using this data the total number of events measured can be calculated by simply summing the

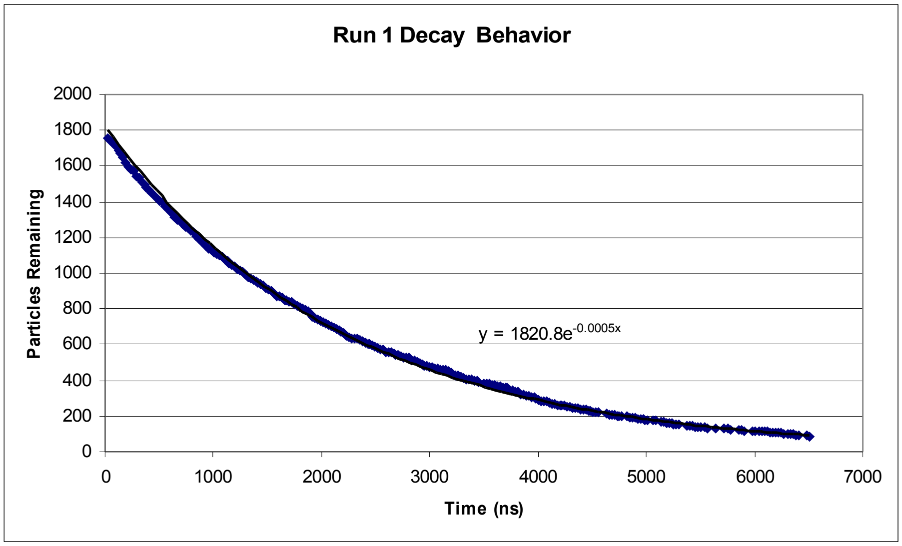
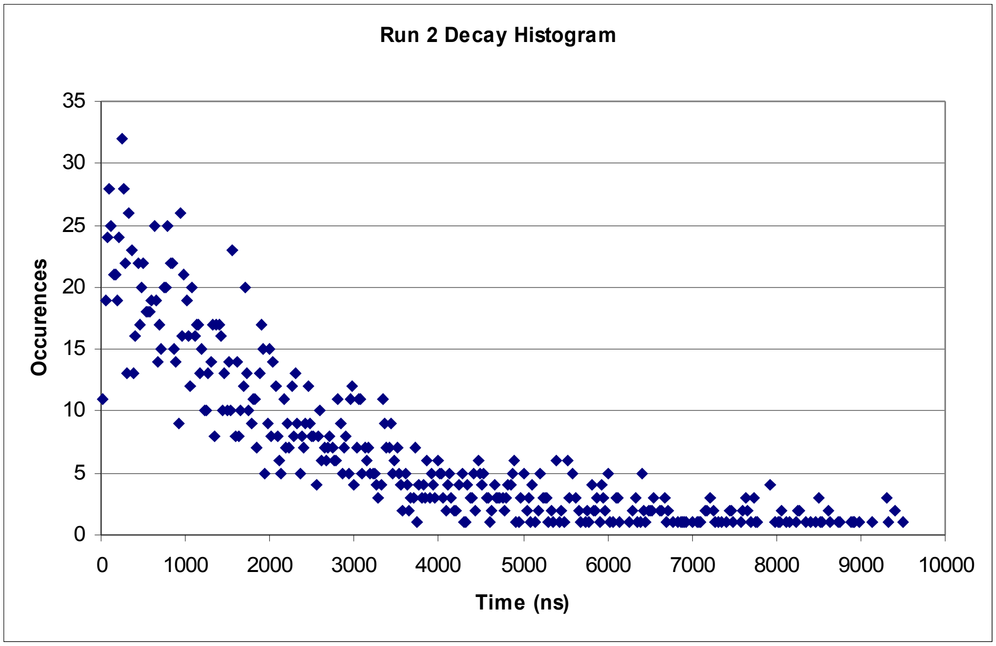


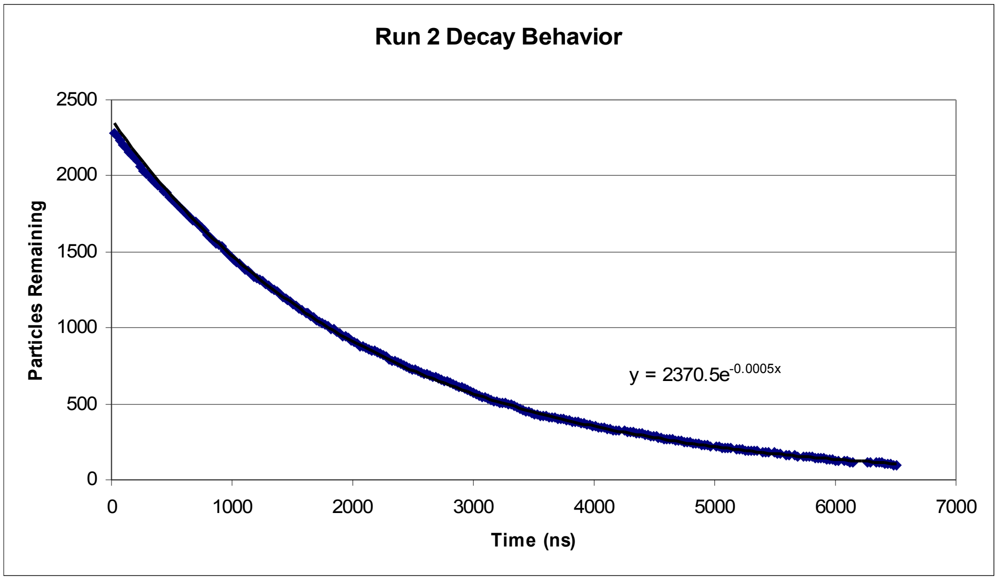
Figure 3. The exponential character of the muon decay as seen in run 1.Decay constant λ=0.0005 ns^{-1}

"Occurrences" column. This can be used to create a plot of particles remaining from the total amount after a certain time. This is seen in figure (3).

The second run lasted about two days and resulted in a file that was about 64 MB and included 2289 events. The average decay time calculated from run 2 was 2.130 µs. The histogram and decay behavior is seen below in Figure (4) a-b.



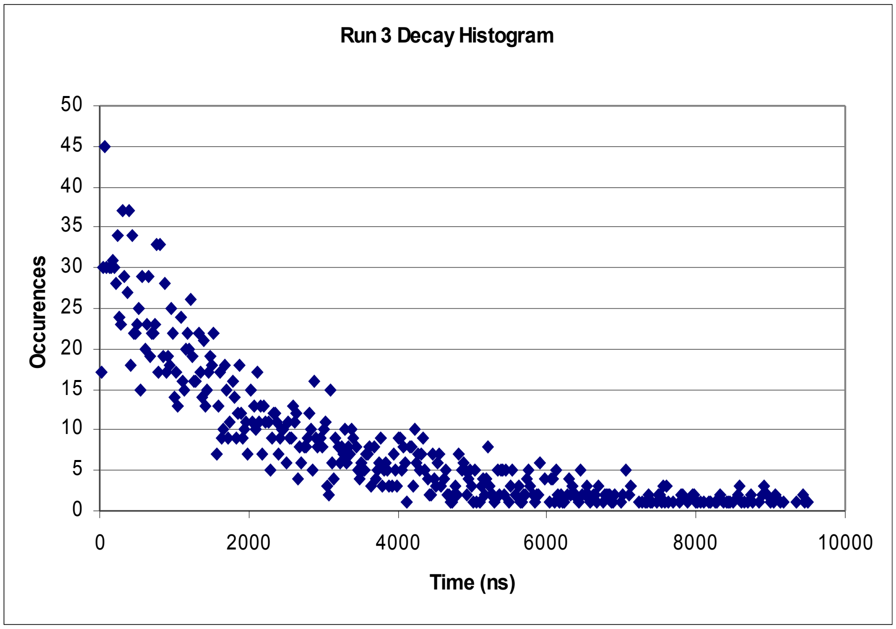
(a)



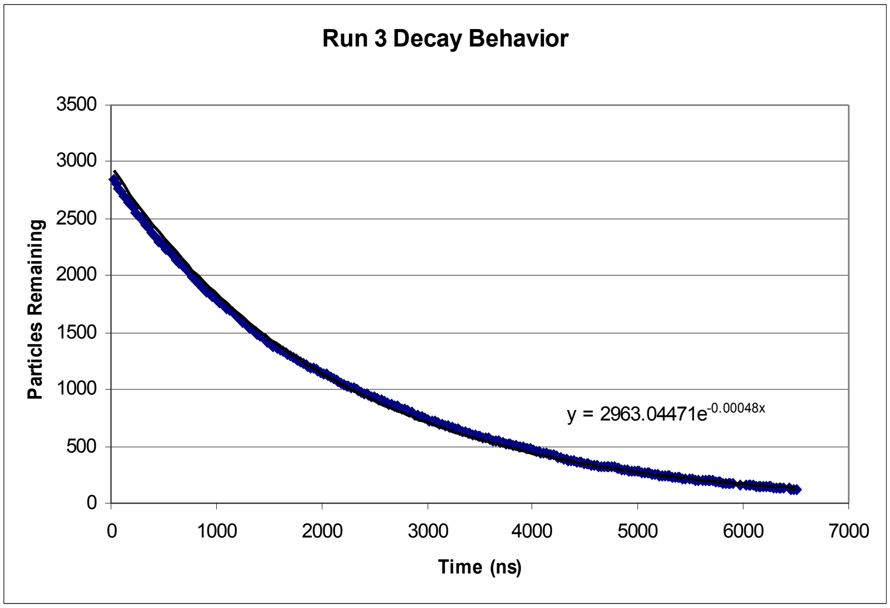
(b)

Figure 4. The histogram (a) and decay behavior (b) of run 2. The patterns for both plots are the same as in run 1. Again $\lambda=0.0005\ \mathrm{ns}^{-1}$

The third run was the longest at about two and a half days. Its file was just over 80 MB and took about 35 minutes for the program to analyze. It had 2857 valid events and an average decay time of 2.125 μs. The data for run 3 is shown in Figure (5) a-b.



(a)



(b)

Figure 5 (a-b). The data for run 3 shows the same behavior as in the first two runs. The exponential character of the second plot is similar with λ=0.00048 ns^{-1}

The important data from these three runs are summed up in Table (1) below. These numbers were calculated using equations (2), (3),and (4) above.

	Events	Average Decay Time (ns)	λ (ns-1)	Half Life (ns)	Average from Half Life (ns)
Run 1	1780	2176	0.00050	1386	2000

Run 2	2289	2130	0.00050	1386	2000
Run 3	2857	2125	0.00048	1444	2083
Average	2309	2144	0.00049	1406	2028

Table 1. The results from each of the three runs.

The average of the decay times calculated for each of these runs was 2.144 μs which has a percent difference of 2.5% from the accepted value. This is very close considering the failed attempt CROP experienced previously. In an effort to verify that the numbers being spit out of the program were true reflections of a natural phenomenon and not an artifact of the programming, several regular CROP data files were run through the analysis program. These files were taken with regular CROP detectors spaced several meters apart on a high school rooftop. The results were distinctly different from those seen above. This is not terribly convincing however since the CROP data files are taken with a gate width one quarter of the duration the above files were taken at. This only allows times of less than 2400 ns to be recorded. Despite this fact, there was no noticeable decay pattern in the three files analyzed. Another data file was created for the express purpose of performing this test in which there was no veto condition, but the delay and gate times were left at 48 ns and 9600 ns. For an unknown reason the analysis program crashes when trying to read this file. More attempts should be made to verify the validity of the results as well as debugging the programs.

Discussion

This lab shows that a compact system can be used to accurately measure the average decay time of muons. The behavior observed matches the expected behavior very well and is fitted nicely with an exponential decay graph. The decay time measured was 2.144 microseconds which is within 2.5% of the actual value of 2.212 microseconds. More effort needs to be made though to determine if this number is indeed coming from muon decays or from some other process. This is difficult however because the analysis program is so specific in what it looks for. It only counts events that exactly match the pattern for muon decays. Specifically, it requires that the top detector have only one signal, the middle counter have one whole signal and a second signal rise, and finally it requires that there be no signals from channels three and four. This combination of coincidences would be quite odd for detector arrangement other than the one used. This may be why the program has trouble analyzing data that was taken under different conditions. It may simply be that it does not find any coincidences that match the pattern.

The equipment assembled in the last few weeks should provide an excellent learning opportunity for students who attempt this lab in the future. It provides a useful and practical introduction to topics in particle and nuclear physics. The lab will also be a nice compliment to the Geiger-Mueller Tube lab as it involves many similar principles.