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Muon Mean Lifetime Measurement in a High School Classroom

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Requirements for the Degree of
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by
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Abstract

This thesis describes a cosmic ray muon lifetime experiment that has been developed for use in a high school classroom. The detector consists of a scintillator that is coupled to a photomultiplier tube. A timing circuit discriminates against signals below a specified threshold voltage and measures the time from when a stopped muon entered the scintillator until it decays. Data acquisition is done using a Macintosh computer and Macintosh compatible software. This software is then used to generate the necessary plots and perform the mean lifetime calculation.

I. Introduction

A. Rationale

This thesis project comes as a result of my experience working at Fermi National Accelerator Laboratory during the summer of 1994 through the Teacher Research Associates (TRAC) program for teachers. As a conclusion to this experience, teachers were encouraged to develop a "follow-on project" that could be brought back to their classrooms. After my exposure to many of the aspects of a real high energy physics (HEP) experiment, I wanted to give my students a similar experience. Upon discussing the idea with Dane Skow, he suggested the idea of experimentally measuring the lifetime of cosmic ray muons. Such an experiment as this has all the components of a real HEP experiment. However, in order to study high energy physics, one needs particles of high energy! This experiment takes advantage of the fact that the universe serves as the accelerator of such particles rather than huge cyclotrons or synchrotrons. This idea was chosen as the follow-on project.

Over the past year and a half, a muon lifetime experiment has been developed and tested. This project was implemented into a high school classroom during the spring semesters of 1995 and 1996.

B. The Source of Cosmic Ray Muons

It has been known for many years that a charged electroscope, if left standing, will eventually discharge no matter how well it is insulated. Attributing this discharge to radioactive materials, Rutherford and Cooke in 1903 surrounded a charged electroscope with bricks in hopes of shielding out unwanted radiation. To their dismay, the discharge rate did not decrease significantly as they had anticipated. In 1912, Hess took an electroscope over five miles into the atmosphere by balloon in order to get away from the ground radiation that seemed to plague earlier experimenters. To the surprise of many, as his electroscope rose higher into the atmosphere, the discharge rate increased rather than decreased! In the November, 1912, issue of the German journal *Physikalische Zeitschrift*, Hess suggested:

> "The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."[1]

Because of this explanation, Hess is generally credited for the discovery of cosmic rays. In 1936 he was award the Nobel Prize in physics for this discovery. And so began the study of cosmic rays.

Although the existence of cosmic rays is unquestionably confirmed through countless experiments, the source of these cosmic rays is still a mystery. Many cosmologists believe that cosmic rays originate from or are in some way linked to supernovas. Many also believe they are extragalactic in origin. These cosmic rays, composed almost exclusively of positive nuclei, travel through space with energies up to hundreds of millions of times that of the highest energies produced in the large particle accelerators of the world today.

The cosmic rays that approach the earth from outside our atmosphere are called "primary particles." These primary particles that enter the upper part of our atmosphere are made up of roughly 90% protons and 10% heavier positive nuclei.[2] Once these energetic particles collide with another nuclear particle in our atmosphere, "secondary particles" are created. These secondary particles may in turn collide with other nucleons or decay before doing so. Such is the case for the creation of a cosmic ray muon.

In 1938, Anderson and Neddermeyer discovered the existence of particles called "mesons" in their study of these secondary cosmic rays. The meson was a particle that was predicted just a few years earlier by Yukawa. Yukawa had predicted these mesons, or "middle mass particles", to have a mass greater than that of the electron and yet not as large as the proton. Experiments confirmed that these secondary cosmic rays had masses in the $200m_e$ range, just as Yukawa predicted. (The muon, however, was not the "nuclear force mediator" that Yukawa was looking for, the pion was.)

When a high energy proton approaches the earth, the chances of it interacting with an atomic nucleus in our upper atmosphere is very great. One can define the probability of a 'collision' in terms of the interaction length of the absorber, which in this case is air. Because our atmosphere varies in density of molecules, it becomes inconvenient to express such interaction lengths in terms of length measurements. (This is even more difficult if you try comparing interaction lengths with solid absorbers which are thousands of times denser than air!) Instead, interaction lengths are measured in units of mass per unit area. To better understand this one might imagine a rectangular box with a width and length of 1 cm and a height h. See figure 1. If a particle has an interaction length of 80 g/cm^2, it will on average interact with matter in a volume equal to a box that is 1 cm x 1 cm x h, where h is determined so that the mass of the absorber enclosed is equal to 80 grams. One can imagine that the value of 'h' may be very large (over a kilometer for air in the upper atmosphere) or very small (7 cm for lead) depending on the density.

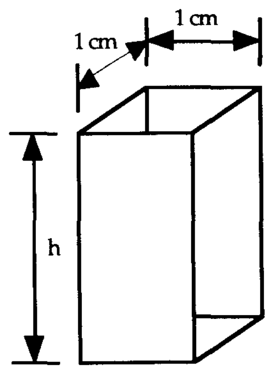


Figure 1 - Interaction Lengths

The primary cosmic rays have interaction lengths of about 80 g/cm^2. Since the total atmospheric depth is 1,003 g/cm^2 (about 30 km), the probability that they reach the earth's surface without a collision is on the order of 1 in 1,000,000. [2] From this interaction of primary particles with nucleons in the atmosphere, mainly pions and kaons are produced. In the collision that takes place, if most of the incoming momentum is transferred to an atmospheric proton, the following reactions are common,

$$p + p \rightarrow p + p + \pi^+ + \pi^\circ + \pi^-$$

and

$$p + p \rightarrow p + n + \pi^+ + \pi^+ + \pi^-$$

If most of the momentum transferred in this interaction is given to a neutron, then these reactions are common,

$$p + n \rightarrow p + p + \pi^+ + \pi^- + \pi^-$$

and

$$p + n \rightarrow p + n + \pi^+ + \pi^\circ + \pi^-$$

The charged pions that are created in the above collisions are very short lived (~10^{-8} s)[3] and will themselves most likely decay before reaching the earth's surface. These negative and positively charged pions decay into a muon (and neutrinos) via

$$\pi^- \rightarrow \mu^- + \nu_\mu$$

and

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Figure 2 shows a schematic diagram of how a typical secondary cosmic ray muon is produced by an incoming proton. (A progeny of secondary cosmic ray particles produced by an incoming proton is given in appendix A, while a complete listing of all possible decays that produce muons is recorded in appendix B.) It is the muon created in our atmosphere that is of interest to us in this experiment.

It might also be noted that the uncharged pion decays even more quickly (~10^{-16} s) into two γ rays which in turn create a shower of electrons and positrons that also make up a significant percentage of the secondary cosmic rays that make it to the earth's surface. Of the muons that are produced in the pion decays, the majority of them traverse the entire atmosphere and reach the earth's surface. Counting all the secondary cosmic rays detected at sea level, 70% are muons, 29% are electrons and positrons, and 1% are other heavier particles.[3]

C. Muon Flux & Intensity

The average muon vertical intensity at sea level is 1.1×10^{-2} muons/cm^2/sr/sec which corresponds to a flux through a horizontal area of 1.8×10^{-2} muons/cm^2/sec for magnetic latitudes above 45°.[4] This works out to a good rule of thumb of about 1 muon/cm^2/minute. At higher altitudes, up to about 25 km, the muon flux increases dramatically. This is seen in figure 3 which shows the total cosmic ray intensity (most of which is due to muons) at sea level, 2 km, and just over 4 km above sea level. One also notes from this figure that the intensity is somewhat

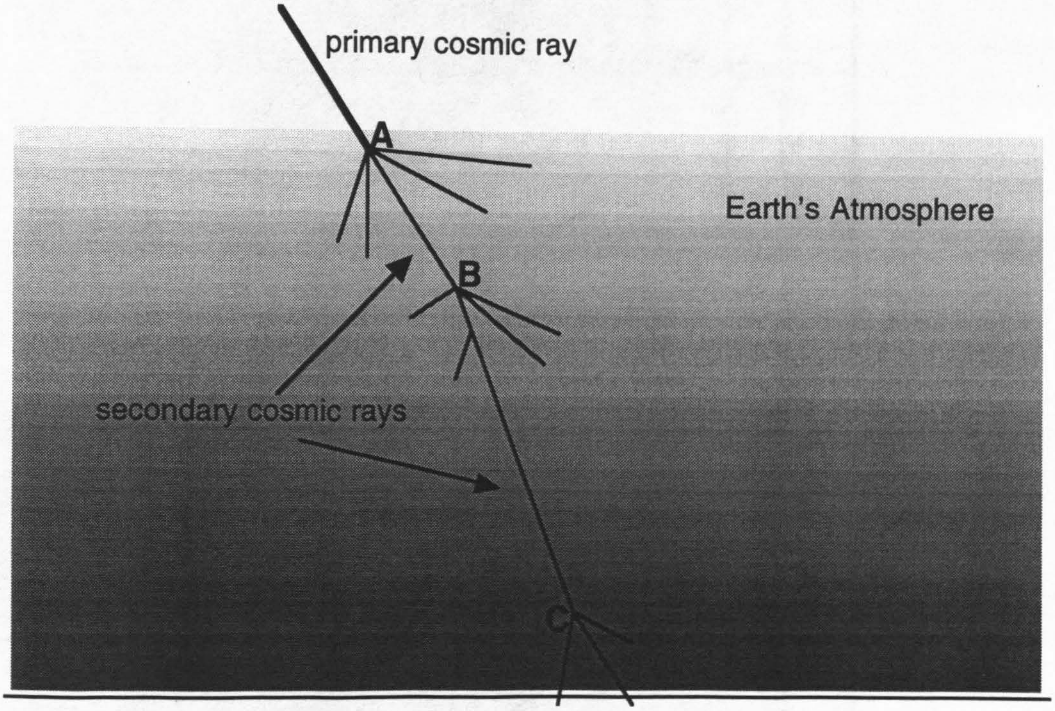


Figure 2 - Cosmic Ray Production Schematic

A primary cosmic ray proton enters the atmosphere and collides with another proton (A). A charged pion is a product of this interaction. It quickly decays (B) into a charged muon and neutrinos. The charged muon, which this experiment seeks to detect, will eventually decay (C) into an electron and two neutrinos.

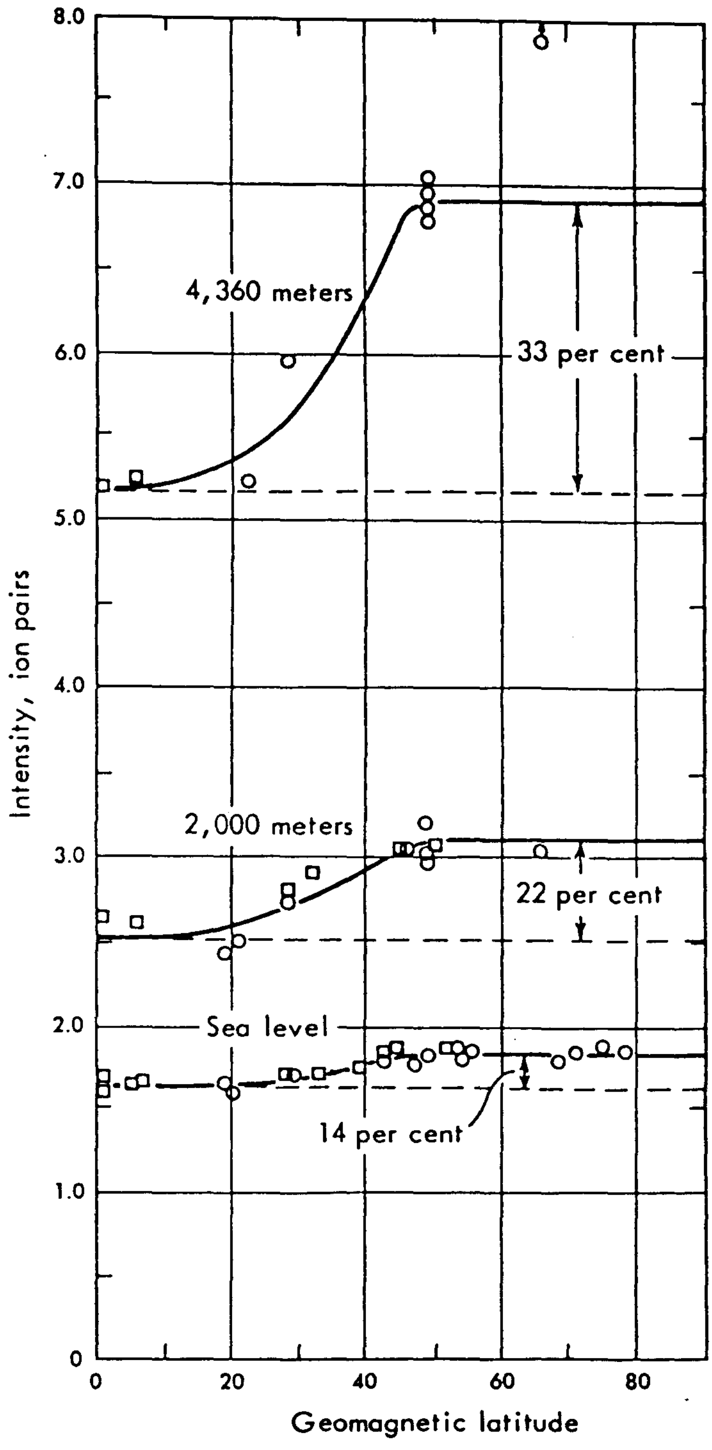


Figure 3 - Cosmic Ray Intensity as a Function of Geomagnetic Latitude
The intensity is measured for three different latitudes. It is determined by the number of ion pairs produced by cosmic rays in 1 cm^3 of air at standard temperature and pressure.[5]

latitude dependent. However, at sea level, the cosmic ray intensity is essentially constant above +45° latitude and below -45° latitude.

As the primary cosmic rays collide with particles in the atmosphere, a shower of secondary particles is created. These particles, however, will often interact with other particles creating still additional showers in the atmosphere before they have a chance to decay. Thus, one can understand the altitude dependence of the cosmic ray flux based on the fact that as one climbs to higher altitudes in the atmosphere, the density of particles created from these showers increases. At altitudes greater than 25 km, however, showers are less frequent since the density of the atmosphere has significantly decreased. This results in fewer cosmic rays above 25 km (most of which are primary particles at such heights).

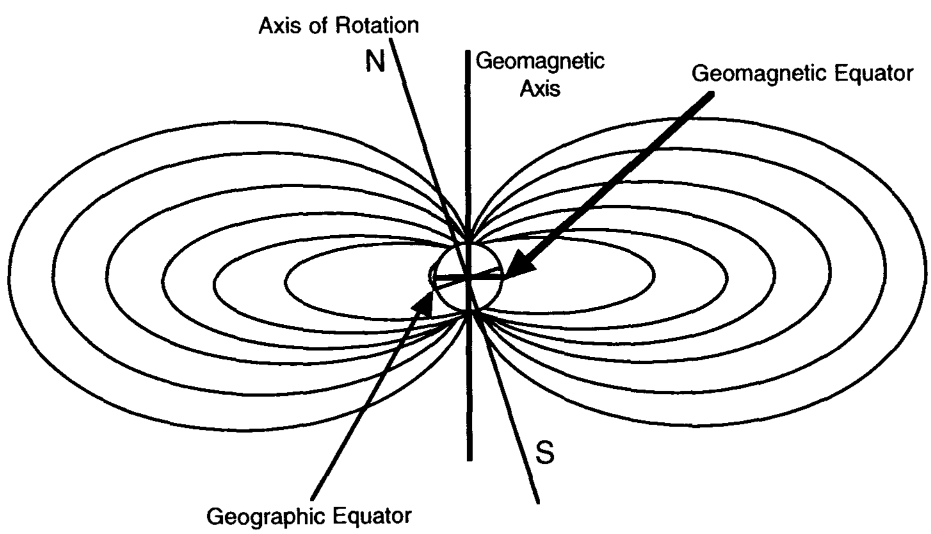


Figure 4 - Geomagnetic Latitudes
Geomagnetic latitudes are measured with respect to the geomagnetic axis.

The latitude dependence arises from two components: (1) the nature of the earth's magnetic field, and (2) temperature variations. It should be pointed out that the latitude dependence is "geomagnetic latitude" measured with respect to the magnetic equator as illustrated in figure 4 above. The 14% drop in intensity at the geomagnetic equator shown in figure 3 is mostly due to the magnetic field of the earth. Since the muons are charged, they and their parent pions both experience the Lorentz force when they enter the magnetic field of the earth. About two-thirds of the latitude dependence can be attributed to this effect. The remaining one-third of this latitude dependence can be attributed to the fact that it is warmer near the equator. Since warm air expands, the atmosphere expands and the secondary particles are created at higher altitudes. These particles now have a longer distance to travel and have a better chance of decaying before reaching the earth's surface. [1] To a first approximation, the flux is symmetric about the magnetic equator.

There also exists an east-west dependence of the flux. Since primary rays are mainly positive particles, and since the earth's magnetic field extends much farther out into space than the atmosphere, these primary particles arrive from the west more often than the east due to the earth's magnetic field. Intense solar activity also causes fluctuations in the cosmic ray intensity. These effects, however, account for variations of only a few percent. [1]

The energy spectrum of the incident muon flux at sea level peaks at just over 1 GeV.[6] These high energies are present even after muons have traveled through many kilometers of atmosphere (an atmospheric depth greater than 1,000 g/cm^2) and have collided with and ionized thousands of molecules. With such high energies, many muons not only make it to the earth's surface but travel through hundreds or even thousands of meters of earth. This fact is significant for an experiment such as this. Most of the incident muons will travel right though the detector used and will not decay until well within the earth. This experiment will pick out only those muons that have enough energy to make it all the way through the atmosphere but not enough to go through the detector. It is interesting to note that through various energy spectrum measurements made, Rossi and others were drawn to the conclusion of two distinct categories of muons: a soft component and a hard component. Figure 5 shows the incident cosmic ray flux for both muon components. It is only the soft muons that will be stopped by the detector in this experiment.

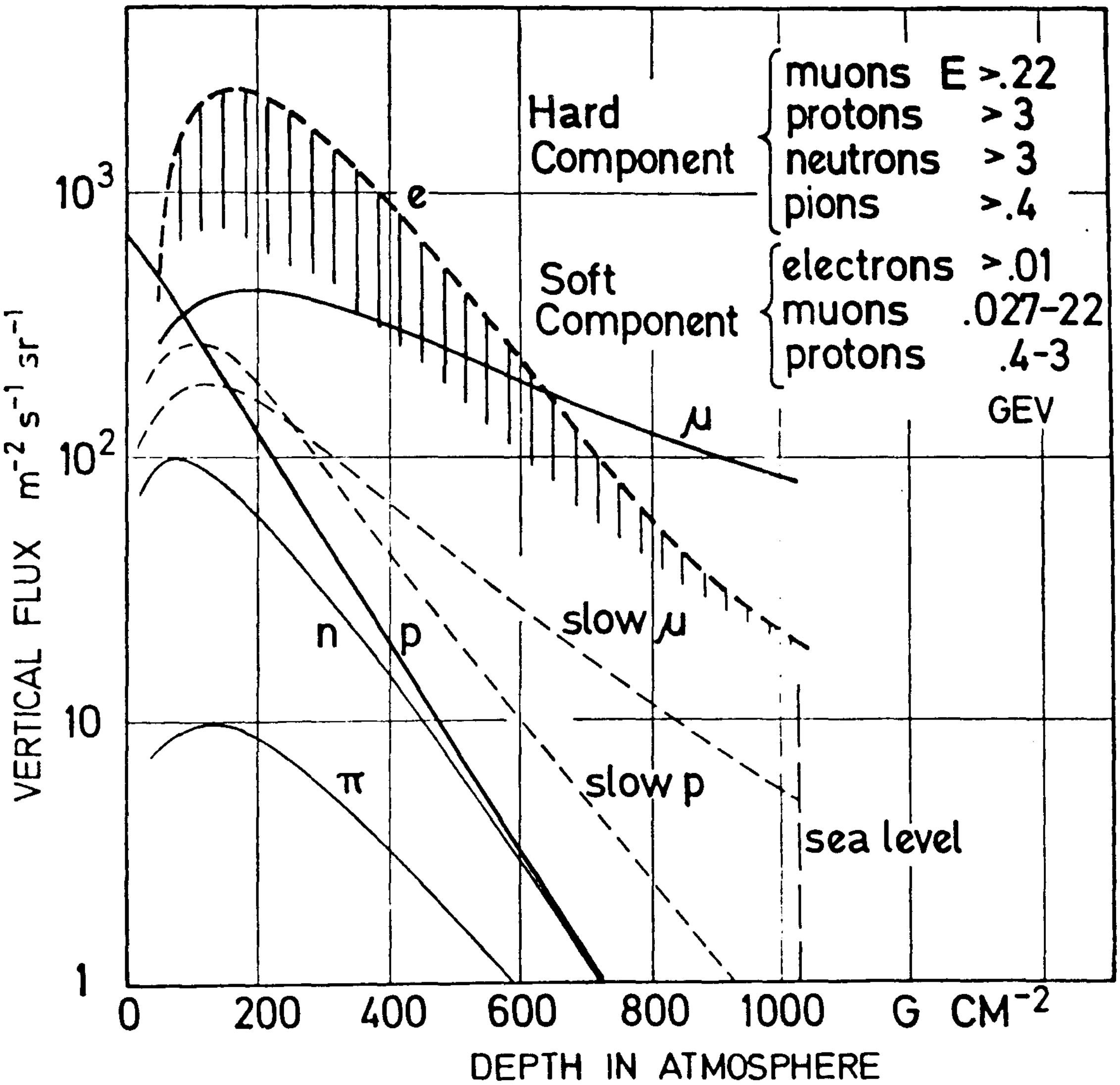


Figure 5- Flux of Cosmic Ray Components
Hard and soft components of cosmic ray radiation throughout the atmosphere. The total flux through our detector at sea level includes all these components.[7]

D. Making Muon Lifetime Measurements--Description of Experiment

The cosmic ray muon that is created in the upper atmosphere can itself decay. Due to their relativistic velocities and relatively long rest lifetimes, muons frequently make it to the surface of the earth, as stated earlier. It is this mean lifetime that this experiment seeks to measure. The charged cosmic ray muons will eventually decay via these processes:

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

and

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

The first experiment designed to measure muon lifetimes was performed by H. Euler and W. Heisenberg in 1938, but dozens followed in the next few years. This indirect method used the so-called absorption anomaly of the meson. It was found that the absorption of muons in air was considerably greater than it was in solid absorbers having the same mass per unit area. The explanation was that the time required for a muon to travel the layer of air involved was comparable to its lifetime. Therefore, a significant fraction of the muons were lost by decay without having to be stopped by ionization losses in some other absorber. For a solid absorber, however, the time to traverse this material was much shorter than the lifetime so that only muons which were stopped by the ionization losses failed to penetrate the absorber.[8] Though the results suggested μ-meson lifetimes of 2-3 μs, more accurate results required other techniques.

In 1941 Franco Rasetti performed the first experiment in which the muon lifetime was measured directly. In his experiment, a μ-meson discharged a Geiger-Muller counter and then stopped in an iron absorber. A short time later, the decay electron would discharge one of a series of other tubes. He used three different electric circuits to choose events that occurred within 1, 2, or 15 μs after the initial discharge. He concluded mean lifetimes of 1.5 ± 0.3 μs. More accurate results followed in 1943 by Rossi and Nereson using a similar technique giving results of 2.15 ± 0.1 μs. [1]

Quite recently a number of articles have been written discussing the use of scintillating material, photomultiplier tubes, and a timing circuit interfaced with a personal computer to aid in the data taking/analysis process. [6,9,10] Such a technique is the one used in this experiment.

Although the specifics of the detector operations are included in the next section, it may be helpful to have an overview of the process used to measure the muon mean lifetime in this experiment. If a muon is energetic enough to make it to the surface of the earth, but not too energetic (less than 25 MeV for this experiment)[9] so that it is captured by an atom within the scintillating material, a lifetime measurement is possible. For this scenario, scintillated light will be radiated at two different times. The first light pulse is emitted by the scintillator molecules when the muon gives some of its energy to the valence electrons which are excited and then fall back down into their ground state. Light is emitted a second time as an electron (or positron) from the muon decay leaves an ionization trail in the scintillating material. The data recorded should represent an exponential decay distribution of temporal spacing between the pairs of light pulses. The time between these two pulses is recorded for many decays. These time intervals are separated into 0.1 μs wide bins. Analysis of this data will lead to the determination of the muon mean lifetime.

II. Description of Apparatus

A. The Detector

1. Overview

This experiment was performed using two different detectors. Although the majority of this section focuses on the use of the second set-up, it is worthwhile to discuss briefly the apparent shortcomings of the first detector. Figures 6a and 6b show each of the detector set-ups. The main difference lies in the dimensions of the plastic scintillator used in each case. The reason for the change is discussed below.

2. Detector Components

Scintillating Block vs. Scintillating Tiles & Fibers. Since muon flux at sea level is $\sim 1 \times 10^{-2}$ muons/cm^2/sec, a detector of significant surface area is important to achieve a reasonable counting rate. Surface area, however, is only part of the equation. Counting rate for this experiment is also determined by the number of muons that enter and stop in the plastic scintillator. For this reason, it is important that the plastic be as thick as possible. Since the energy spectrum of the muon flux at sea level peaks just over 1 GeV,[6] the vast majority of incident muons will travel right through the detector.

The original detector used six scintillating tiles each having a surface area of 2700 cm^2 and a thickness of 0.32 cm. The tiles were stacked on top of each other so as to increase the thickness of the detector. Although the surface area was significant, this method offered a total thickness of just over 19 mm. Counting rates were very low. Related to this is the fact that the light output of the scintillator is linear to the energy lost by the particle traveling through it.[11] Thus, energies deposited into the detector were so small that it was difficult to 'see' the pulses. Perhaps even more significant is that fact that when scintillated light is directed into the attached fibers a second absorption/scintillation occurs. This, along with the larger distance that the light had to travel in the original detector, left room for many loses to occur.

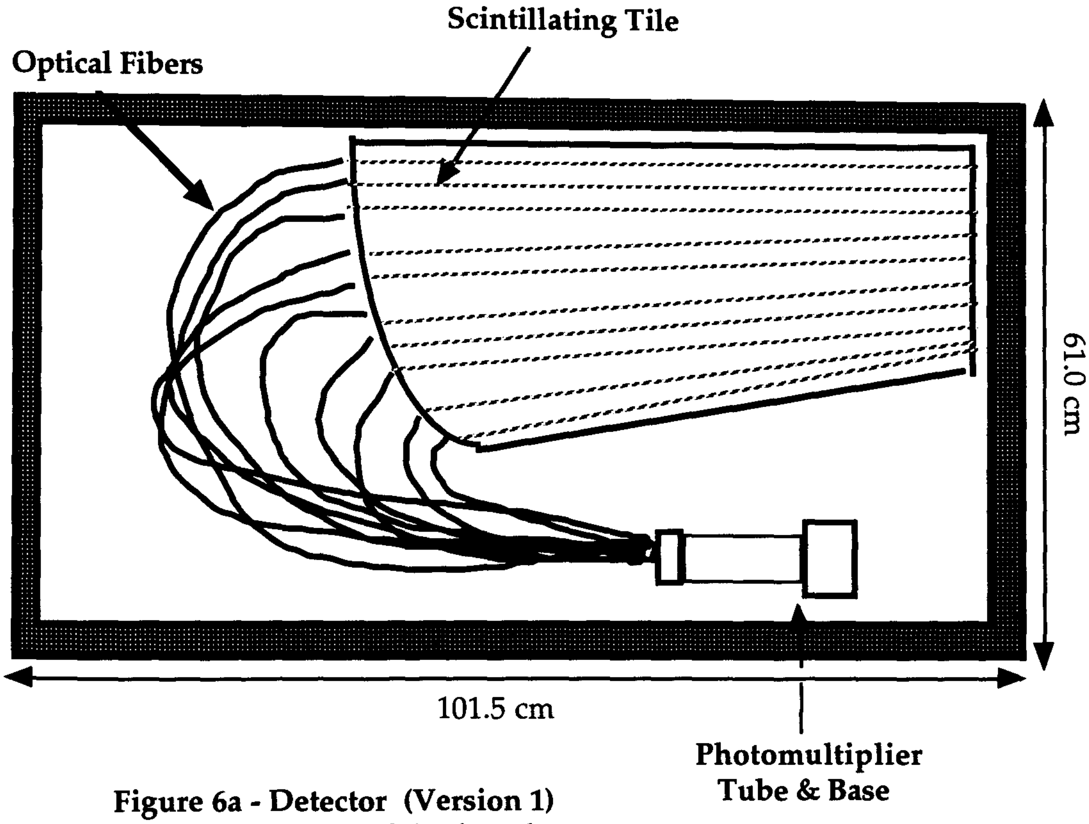


Figure 6a - Detector (Version 1)
This is a top view of the first detector. The detector was housed in a light tight box.

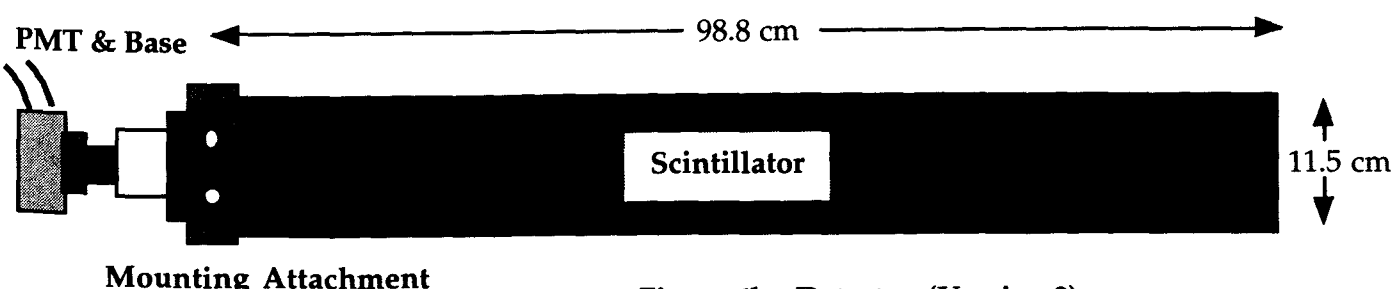


Figure 6b - Detector (Version 2)
This is a top view of the second detector.

The second detector used a plastic, rectangular block scintillator (98.0 cm x 11.4 cm x 11.4 cm). Such a block has under half the surface area (1120 cm^2) of the first version, but six times the thickness when compared to the tiles. This extra thickness seemed necessary to stop muons.

The scintillating block, which acts as a special kind of slab waveguide, is made of transparent polyvinyltoluene base and is doped with a proprietary dopant to make it fluoresce. This scintillator, NE 102, has a maximum emission wavelength around 423 nm. An emission spectrum for this scintillator is shown in figure 7. The scintillation process itself is the result of transitions made by the free valence electrons of the scintillator's molecules. Ionization produced by the muon excites these electrons. Although there are different modes of excitation, the simplest is illustrated in Figure 8. For this "singlet" excited states, a very quick decay (‹ 10 ps) called internal degradation occurs without the emission of radiation.[13] After this, the electron will fall back to its ground state giving off radiation in the form of visible light. This process, fluorescence, is responsible for the light that signals muon entrance and decay.

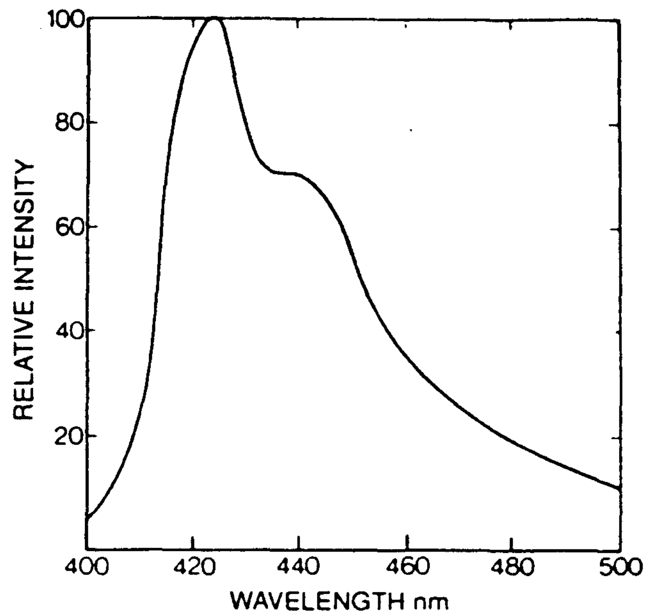


Figure 7 - Emission Spectra for the NE 102A Scintillator[12]

An item of concern in a timing experiment such as this is the time it takes the above process to occur compared to the mean lifetime of the muon. If the scintillation process above is fast compared to the decay time of the muon, then the above process is acceptable. However, if the time for the scintillation process to occur

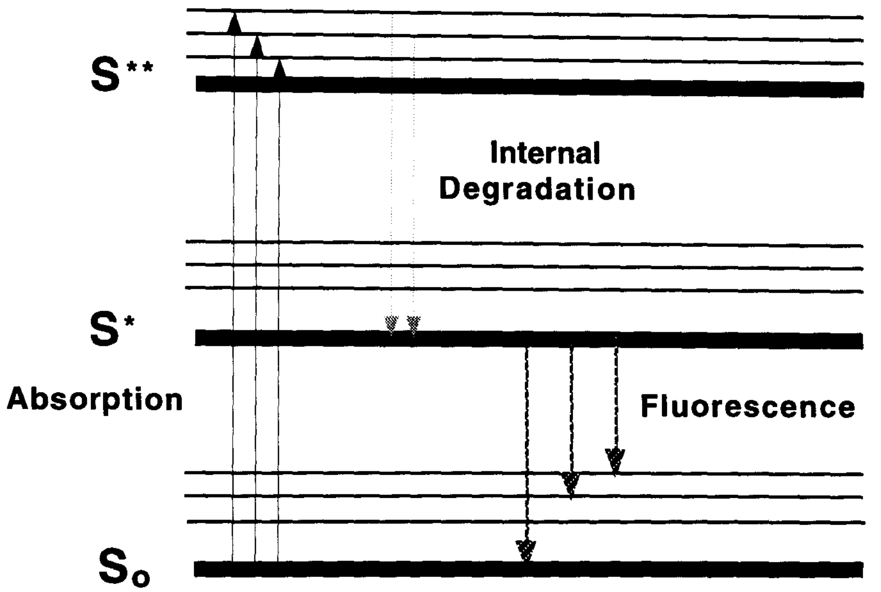


Figure 8 - Energy Level Diagram for Scintillator. The figure above shows the process by which light is emitted. As an electron falls back down into its ground state, fluorescence occurs. It is this process that gives the light pulse to be detected by the PMT.

cannot be ignored, then one must use an alternate method of measuring muon decays. For typical scintillating materials, like the one used here, the entire scintillation process occurs on the order of 10 ns.[13] The scintillator used in this experiment has a decay constant of 2.4 ns.[12] This means that within tens of nanoseconds essentially every excited electron has returned to the ground state. Since the mean lifetime of a muon is on the order of microseconds, the time required for the above process can be ignored.

Perhaps the greatest concern is not in timing but in the scintillator's ability to guide the light to the photomultiplier tube. Two types of losses may occur here: (1) absorption within the plastic, and (2) lack of transmission at the plastic-photomultiplier tube interface. Each is discussed briefly below.

1. *Absorption.* Light intensity is lost through absorption as a function of path length by the expression

$$I(x) = I_o e^{-x/a}$$

where 'I' is the intensity of the light after traversing a distance 'x' inside the scintillator, 'I_0' is the initial light intensity, and 'a' is the attenuation length--the distance that the light can travel before it drops to e^{-1} its original intensity. Since the actual path length inside the plastic is less than a meter, and since the attenuation length for this plastic scintillator is 2.5 m,[12] absorption will not decrease the light intensity very much.

2. *Lack of Transmission at Plastic-Tube interface.* If the scintillated light encounters any interface at an angle greater than the critical angle, transmission will not occur. Along with this, it is important that at interfaces where transmission is desired, the difference in the indices of refraction of the two media be small. To maximize the chance of transmission at the scintillator-phototube interface in this experiment, the two are joined by optical coupling fluid. This substance, used to encourage transmission, has an index of refraction very near that of the plastic scintillator and glass phototube. Everywhere else the plastic scintillator is surrounded with a reflective tape in an attempt to reflect any light that is transmitted (by encountering the side of the scintillator at an angle less that the critical angle) back into the plastic everywhere except where it joins the photomultiplier tube.

Photomultiplier Tube. The photomultiplier tube (PMT) used in this experiment is a RCA 6342A. Figure 9 shows the dynode structure of the phototube. This tube is connected to one end of the scintillator. Optical coupling grease was applied between the phototube and scintillator in an effort to allow for easy transmission of light. This tube is most sensitive to incident light in the 440 nm (blue) region of the spectrum,[14] a range that is compatible with the scintillator. The photomultiplier is used to multiply a light signal (probably of the order of a few photons) from the scintillator, and convert it to a readable output current. When incoming photons from the plastic strike the photocathode, an electron is "kicked off' via the photoelectric effect. Because of large potential differences, this electron accelerates toward the first dynode where it ejects more electrons. Each of the these electrons in turn create more free electrons as this cascade effect continues to the anode. At this point, the large number of the electrons constitute a measurable current.

Pin 1	Dynode #1
Pin 2	Dynode #2
Pin 3	Dynode #3
Pin 4	Dynode #4
Pin 5	Dynode #5
Pin 6	Dynode #6
Pin 7	Dynode #7
Pin 8	Dynode #8
Pin 9	Dynode #9
Pin 10	Dynode #10
Pin 11	Anode
Pin 12	Internal Connection
Pin 13	Focusing Electrode
Pin 14	Cathode

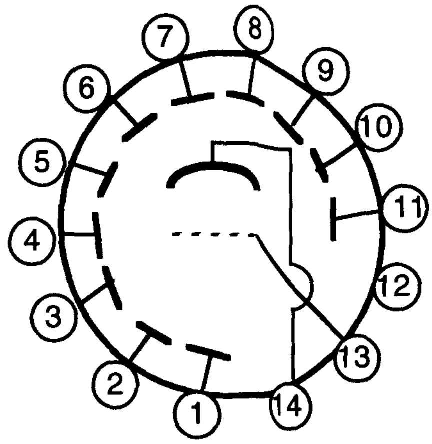


Figure 9 - Photomultiplier Tube Dynode Structure
Bottom view of PMT.

Experimentation has shown the rise time of the PMT pulse to be on the order of 10 ns, a time too short to fool the timing circuit to count a single pulse as two separate signals. This is important since we are concerned about measuring the temporal delay between two separate pulses.

In order to determine the proper operating voltage for the PMT, a scintillation-counter plateau test was done. In this test the number of counts/minute was measured as a function of HV. The reason for the so-called plateau test was to select a HV that will be large enough to generate a signal but not so large that regeneration effects (afterpulsing, discharges, etc.) may occur. The results of such a test will follow in the next section of this paper.

Since the light from the scintillator is a linear function of the energy deposited in the scintillator, the pulse height can only be varied by changing the high voltage--and thus the PMT gain. During the experimental runs, negative pulses of 5-45 mV where observed while operating at voltages of 1075 V.

It is the PMT that is a significant source of inefficiencies. Typically only about 20% of these photons will ever be detected.

B. The Electronics

1. Overview

The PMT generates a negative current pulse whose height is proportional to the light that entered the tube. This current pulse is fed into the input end of a timing circuit. Figure 10 shows a block diagram of the electronics for this experiment. A complete circuit diagram is included in appendix C.

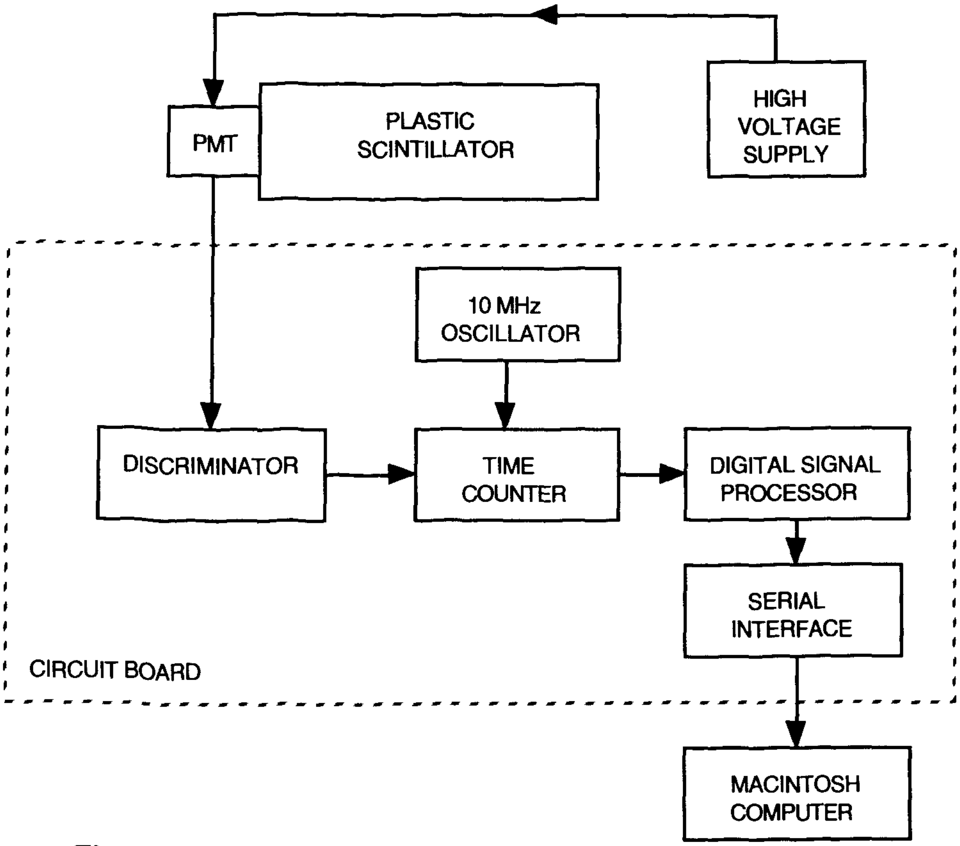


Figure 10 - Circuit Block Diagram

2. Description of Various Components

Due to the presence of noise in the circuit, a discriminator is used to set a threshold below which PMT output pulses and noise pulses are ignored. Because of the fact that PMT signals are typically on the order of a few mV, the circuit amplifies the input pulses by a factor of 11 before comparing them to threshold. If a pulse is above the threshold setting, a timing clock begins counting. The time interval between the initial pulse and the decay pulse is measured with the operation of a 10.0 MHz clock. If a second pulse follows within 25.8 μs, the interval time is sent to the computer as an 8 bit output word. To guard against electrical or optical reflections (ie. the first pulse being counted twice) a 0.4 μs delay is included. If the two pulses are detected within the 0.4 μs time interval, they are thrown out and the circuit is reset. The decision making of this circuit is done by an Analog Devices 2105 Digital Signal Processor (DSP) on the circuit board. Figure 11 shows a flow chart of the DSP logic.

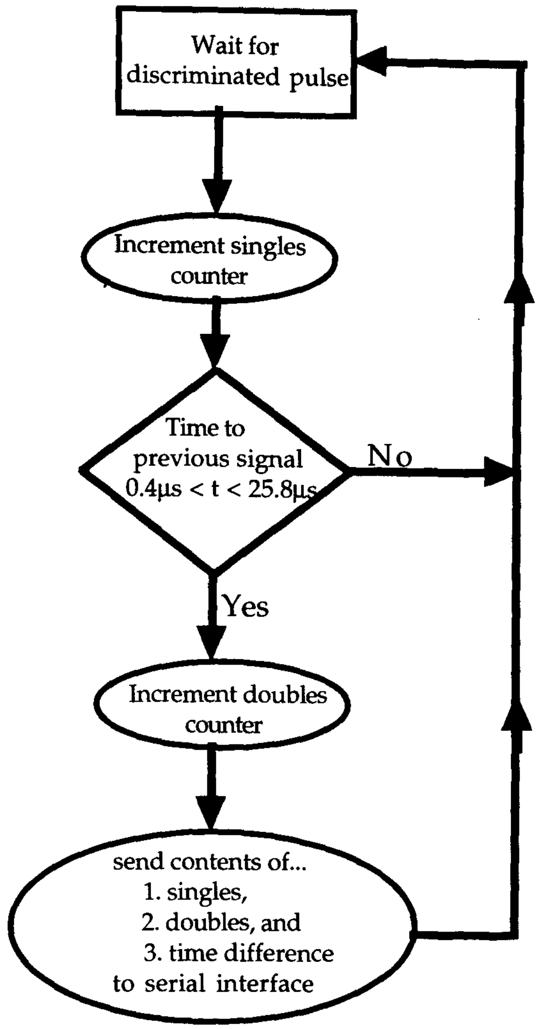


Figure 11 - DSP Logic Diagram

The programming of this signal processor was done by Sten Hansen[15] on a PC and written in "C" language. A compiler then converted this code to binary which was then burned into this chip. The DSP, which is set up to receive a digital signal, waits for a drop from the standard +5 V. When this occurs, a timer is started. If a second pulse occurs between 0.4 and 25.8 μs, the time between pulses is sent to the computer. Times are binned in 0.1 μs intervals.

C. Interfacing With Macintosh Computer

A 9-pin modem cable connects the circuit to the computer's modem port. The data is read into a Macintosh. Data comes in as a string of hex words. The computer monitor displays the data in real time with the help of a terminal emulation program called 'Z-term'. The data below serves as an example of what the display looks like. Each row represents a single muon candidate that decayed within the detector. The hex word in the first column tells the time interval between the two pulses. The second column represents a running total of the number of single pulses from the beginning of the run until the latest muon decay candidate. The final column is a running total of the number of double pulses that have occurred within the 0.4 - 25.8 μs interval.

0009	000401	0001
001D	000436	0002
000C	00044F	0003
0009	00048F	0004
0011	000786	0005
0023	000942	0006
0035	0009EB	0007

The terminal emulation program offers the option of storing the data to a text file where it can later be sorted and analyzed. Although the computer must be on for the duration of the experiment, the experiment can be left to run for a period of hours or days in order to gain good statistics.

III. Data Acquisition

A. Sorting Data into Files

The process of collecting and sorting in this experiment was a four stage process. As data came in it was stored in an "Unconverted Text File." After a run, these data were then saved as a ClarisWorks[16] "Converted Database File". At this point, the data needed to be converted from hex to decimal and to be sorted according to the time interval. A ClarisWorks spreadsheet program that I wrote was used to perform these functions. Finally, the number of counts in each bin was recorded in still another spreadsheet file according to run number, run time, HV, etc. Figure 12 illustrates this process.

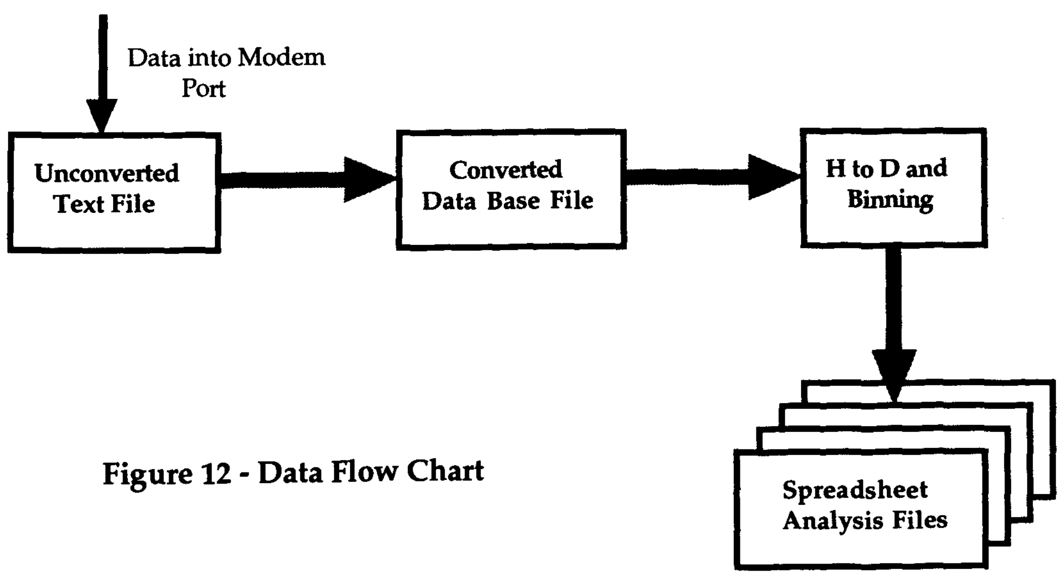


Figure 12 - Data Flow Chart

B. The Runs

1. Two Initial Investigations

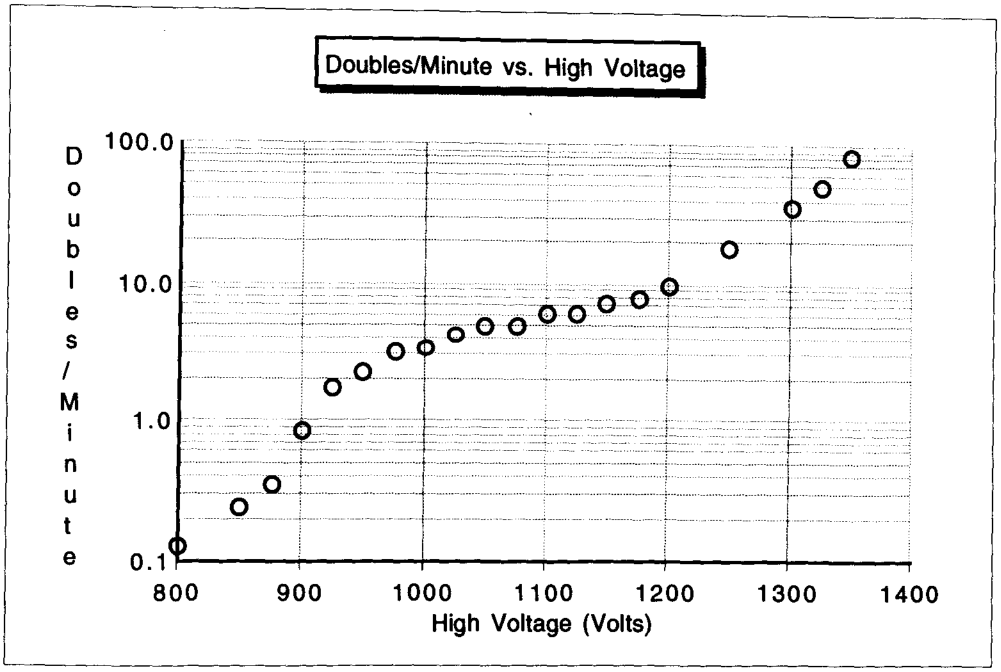
Operating High Voltage. Initially, two parameters were studied to determine the setting that would give the best results for the data collection runs. The first parameter was the operating high voltage of the phototube and base. As was mentioned in the previous section of this paper, the operating HV is an important part of the experiment. In order to determine the best PMT voltage, a scintillation-counter plateau test was done to determine the counting rate as a function of HV. A convenient threshold setting of 50 mV was used for this test. Plots of the counts/minute as a function of the PMT high voltage are shown in figure 13. By using a voltage near the center of this plateau, one can minimize the chances of counting variations due to drifts in the tube gain or high voltage.[13] The operating voltage chosen for the main runs of this experiment was 1075 V.

Operating Threshold. The second parameter varied was the threshold setting. In order for a pulse to be "accepted", it must be above a specified threshold. The importance of this is obvious when you consider that noise in an electrical circuit such as this is inevitable. Figure 14 is plot a of the number of doubles counts above threshold/minute as a function of threshold. It is important to note that the threshold value is compared to the analog signal after a multiplication of 11 from the PMT output. A huge counting rate was observed when operating at thresholds below 35 mV. Also, when operating at 1075 V, pulses above a 500 mV threshold were less than 1 per hour. To allow for the highest counting rate and yet be confident that counts were not primarily due to noise, a value of 50 mV was chosen for the threshold setting.

It is interesting to consider the counting rate of various threshold bins. Taking the values shown in figure 14, it is possible to determine the counting rate per 50 mV interval. Consider this example: If the threshold setting of 50 mV yields a counting rate of 5.0 doubles/minute, while the 100 mV threshold has a rate of 2.7 doubles/minute, we can assume that the difference (2.3 doubles/minute) is the rate that occurs between 50-100 mV. Figure 15 shows these results. Though somewhat crude, this may serve as an energy spectrum plot.

2. Lifetime Measurement Data

The two above investigations served in arriving at an operational high voltage and threshold. Once these settings were determined, many runs were performed at 1075 V and 50 mV for the high voltage and threshold settings respectively. Data from 16 separate runs totaling 156 hours of run time serve as the data base from which the



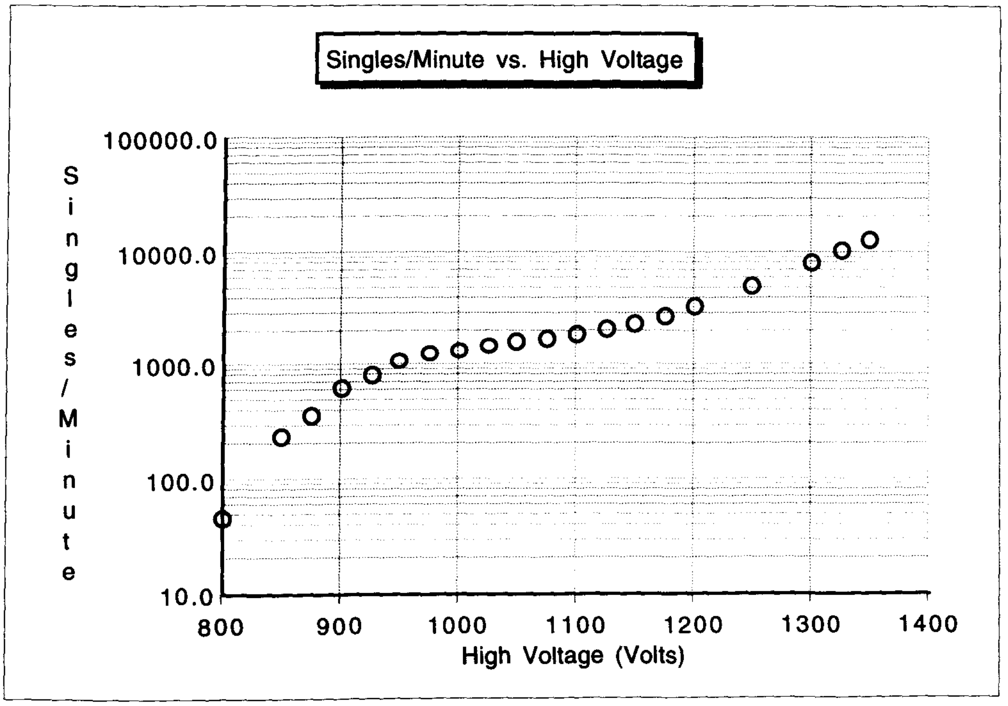


Figure 13 - High Voltage Plateau
The plots above show how both the singles counts and doubles counts plateau near 1075 V. This was chosen to be the operating voltage.

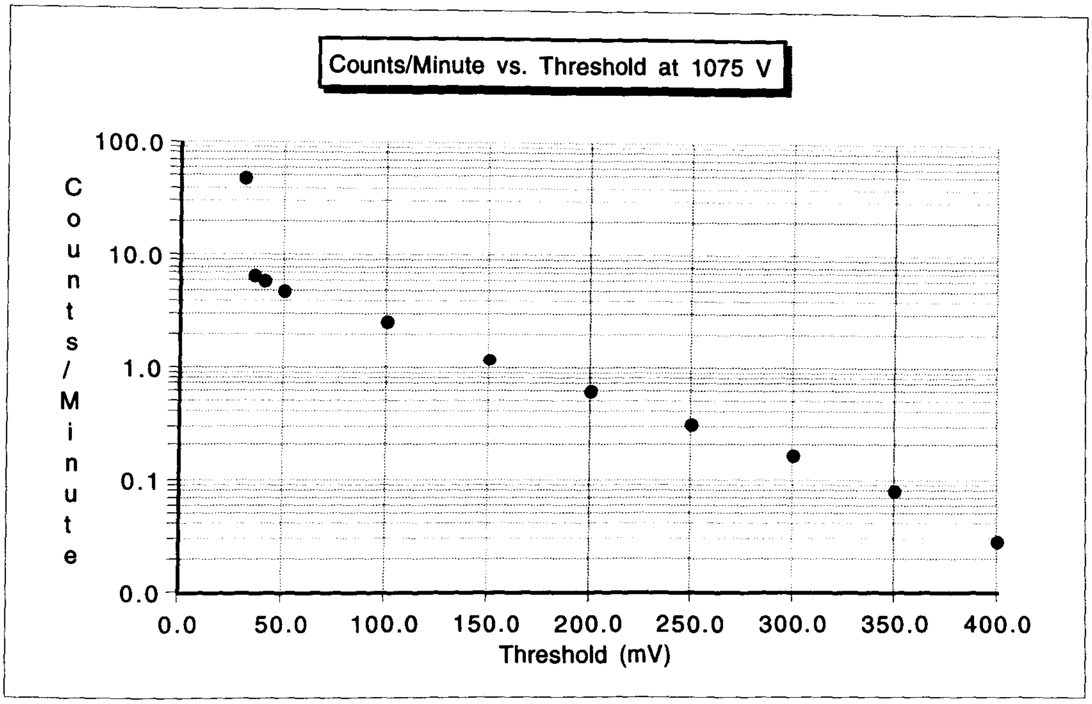


Figure 14 - Plot of Counting Rate as Function of Threshold

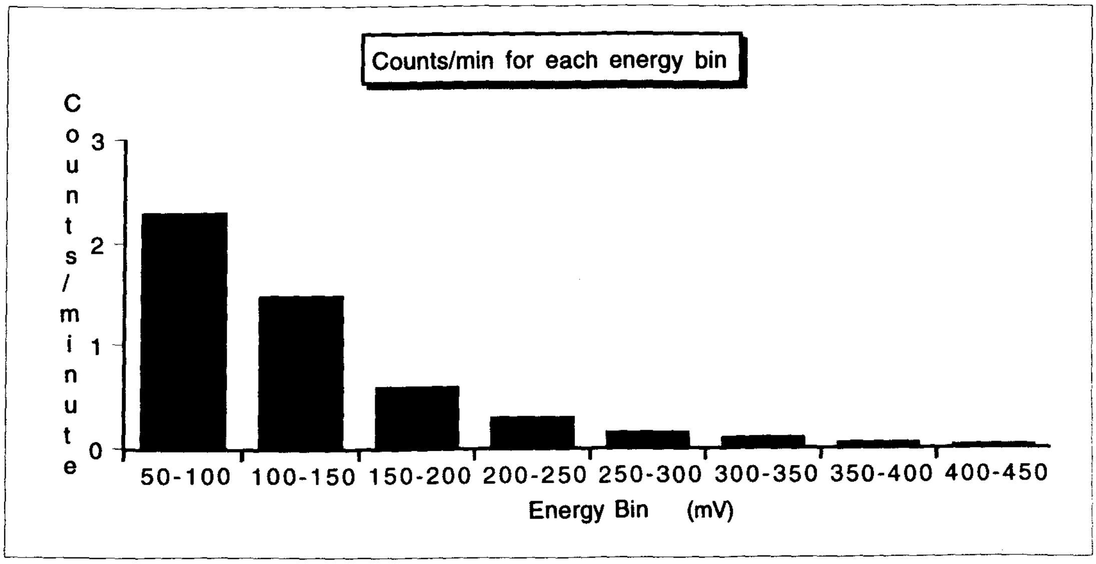


Figure 15 - Plot of Counting Rate for each Energy Bin

majority of the measurements in this experiment were made. It should be noted that small changes in HV and threshold settings offered no significant change in the lifetime measurement.

There was a criterion for data acceptance. It seemed reasonable to use the counting rate as an indicator of run reliability. Figure 16 shows the counting rate as a function of run number. It is interesting to note the large deviation of counting rate for run #5 compared to the other runs. Careful examination of this run showed some sort of strange loop occurring in the data. Such questionable data was dismissed.

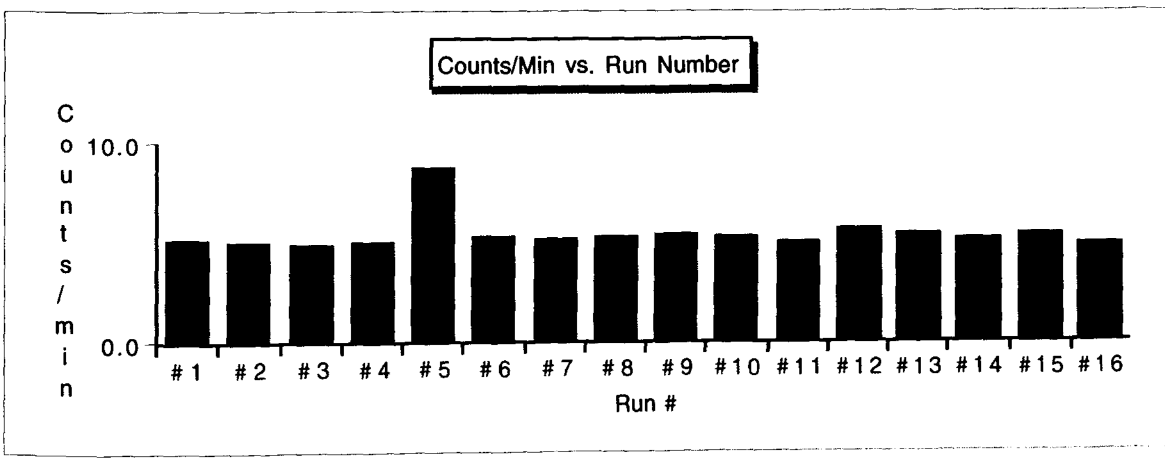


Figure 16 - Counting Rate as a Function of Run Number
This served as a check of run reliability.

IV. Analysis

A. Mean Lifetime Measurements

1. Justification of Exponential Decay

Theory suggests that the muon lifetime exhibits the characteristic exponential decay that is common to many physical phenomena, such as radioactive decay. In the case of radioactive materials, we know that the decay expression is

$$N(t) = N_o\, e^{-t/\tau}$$

where N_o is the initial population, N(t) is the population after time t, and τ is the mean lifetime. The fact that the muons in our experiment do not coexist, whereas they do in radioactive decays, does not change the decay expression. This does, however, give a slightly different meaning to N(t) and N_o. In this experiment, N_o is not the number of muons present at t=0, but instead represents the total number of muons that were captured and decayed within the detector. N(t) is then the number of muons that have decayed in time t, where t is the time between when a single muon entered the detector and decayed. With this in mind, we can generate plots as if all muons did coexist in our detector.

One might further be concerned with the fact that the wide range of velocities that the muons will have in their trip through the atmosphere and detector will clutter the time of flight issue since relativistic velocities must be considered for some of their flight but not all. It should be emphasized here that the times between entering and decay do not represent the entire lifetimes of the muons (which were most likely created in the upper atmosphere!). The common "zero time" that we can select will be when each muon *entered* the detector. And though this amount of time that the muon lived in the scintillator is not its entire lifetime, plotting of such data will yield the same exponential decay shape from which the lifetime can be found.

2. Binning

For each 0.1μs bin, we can expect that the number of data points in that bin is not necessarily the exact number that theory would suggest. For example, if we ran the exact same experiment numerous times, sometimes we would get the expected number of counts in a given bin, sometimes less, sometimes more. The number of counts in a given bin over many runs form a Gaussian distribution. Figure 17 illustrates this distribution of actual data quite nicely. This is a welcomed

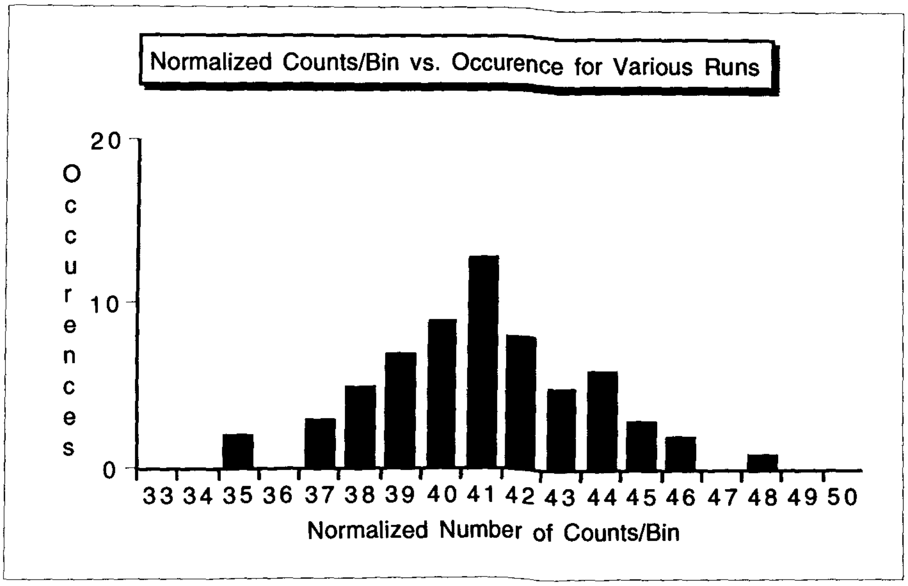


Figure 17 - Gaussian Distributed Data for a Single Bin

distribution since statistics tell us that for Gaussian distributed data the standard deviation (and thus the uncertainty) for some ith bin, σ_i, is simply expressed by

$$\sigma_i = (N_i)^{1/2}$$

where N_i is just the mean number of counts in that bin. For a single run this relationship can still be applied. The uncertainty in a bin is simply the square root of the number of counts in that bin. For example, if a bin contains 625 events, the uncertainty is ± 25 events. One can see that although the uncertainty increases with the number of events, the relative uncertainty decreases as one would expect.

To find the number of expected counts in each bin we need to know the decay rate,

$-dN/dt$, over the time interval of that bin (Δt_b). This value is not constant over the time of the bin, but we may assume that it is constant if Δt_b is small. We can further enhance our approximation by evaluating $- dN/dt$ at the center time of the bin. Thus, theory suggests that the number of counts in the ith bin is given by

$$N(t_i) = [- dN(t)/dt]_{ti} \ \Delta t_b$$

$$= (1/\tau) \ N_o e^{-(t_i/\tau)} \ \Delta t_b$$

$$= K e^{-(t_i/\tau)}$$

where $K = N_o (1/\tau) \Delta t_b$. The width of each bin is $\Delta t_b = 0.1$ μs for this experiment. Also, N_o represents the total number of muons that stopped in the detector. This equation expresses the theoretical number of counts in the ith bin as a function of the "initial" muon population and the mean lifetime, assuming that Δt_b is indeed known.

3. Determination of Mean Lifetime

Since we assume that our muon counts exhibit the characteristic exponential decay as a function of time, it would be useful to linearize this expression and then apply the least-squares method to determine the equation from which we may derive the mean lifetime.

Assume the form

$$N(t_i) = K e^{-(t_i/\tau)}$$

(Note that $N(t_i)$ represents the expected number of counts in each bin after any background has been subtracted.) Taking the natural log of both sides we get

$$\ln N(t_i) = \ln K - t/\tau$$

The least squares method[17] minimizes the value of χ^2 where χ^2 is given by

$$\chi^2 = \Sigma \{ [\ln N_i - \ln N(t_i)] / \sigma_i' \}^2$$

and where

$$\sigma_i' = [\, d/dN\, (\ln N_i)\,]\, \sigma_i = [\, 1 / N_i\,]\ \sigma_i$$

The σ_i' term arises from the fact that we must weight the 'linearized' uncertainties. After making the substitution for σ_i' we get

$$\chi^2 = \Sigma\, N_i\, [\, \ln N_i - \ln N(t_i)\,]^2$$

$$\chi^2 = \Sigma\, N_i\, [\, \ln N_i - \ln K + t/\tau\,]^2$$

After using a spreadsheet program to find values for τ and K that minimizes χ^2, one can arrive at the mean lifetime of the muon.

4. Background & Background Subtraction

As one might expect, reality does not always behave as the simple theory suggests. There are, however, some assumptions that may be made regarding the nature of the background that will allow us to expand our theory to include such background. It is this topic that will be developed next.

When a muon passes through the detector the timer is started. This muon should not be counted since its decay will not occur within the scintillator itself. There is a chance, however, that a second muon could be traversing the detector nearly simultaneously giving rise to a second pulse that is within the acceptable timing range. These double pulses constitute a "fake" event in the data since they are from two different muons. One could use additional scintillators stacked above or below to "veto" out these fakes. Such coincidence circuits for a muon lifetime experiment are discussed in Harthill and Melissinos.[9,11] I have chosen to use background subtraction techniques to save on hardware and to allow my students to "see" the random background. It should be noted that by using the voltage selected from the HV plateau curve and the threshold value selected, noise pulses from afterpulsing and discharging were reduced to less that one count per hour. Such a small noise rate is statistically insignificant for background considerations. We cannot, however, dismiss the fakes arising from two muons in coincidence.

Typical muon energy losses in scintillators like the one used in this experiment are on the order of 2 MeV/cm.[6] Given the thickness of our detector to be just under 11.4 cm, only those muons with less than about 23 MeV will stop. This constitutes a rather small fraction of the incident muon flux. In fact, I have found that approximately 1 in every 340 muons that enter the detector will stop. Therefore, most muons will traverse the detector without stopping. This, combined with the fact that the size of the PMT pulse is linear to the energy deposited in the scintillator, means that it is the more energetic muons that will have the highest probability of detection; these are the ones that will traverse the detector without stopping. Thus, perhaps the most significant source of background lies in the possibility that two nearly coincident muons traverse the detector within 25 μs of each other.

If one assumes that this background is completely random, then should the time between two non-related pulses be equally likely in any time interval? No! In fact, the time between two non-related pulses is itself an exponential decay! I do not want to belabor this point, but it is a very important in understanding why I will shortly make the approximation that the background IS constant.

Consider that 1725 muons pass <u>through</u> the detector per minute, each giving rise to a single pulse. (This is the average singles rate/minute detected for the experiment.) A computer program was written to simulate this. It generated 1725 random times within a one minute period and then plotted the time difference between two adjacent pulses. The distribution is shown in Figure 18.

Note that this is an exponential decay just like the stopped muons will generate! In theory one would have to fit the muon data to a function that is the sum of two exponential decays. It would be of the form:

$$N(t_i) = K\, e^{-(t_i / \tau_\mu)} + C\, e^{-(t_i / \tau_b)}$$

where K and C are constants, τ_μ is the muon mean lifetime, and τ_b is the average time between background pulses. For the example at hand, where 1725 random pulses occur each minute, τ_b = 580 μs. Since this decay takes hundreds of times longer that the muon decay, over the short time periods of 25.8 μs (the maximum

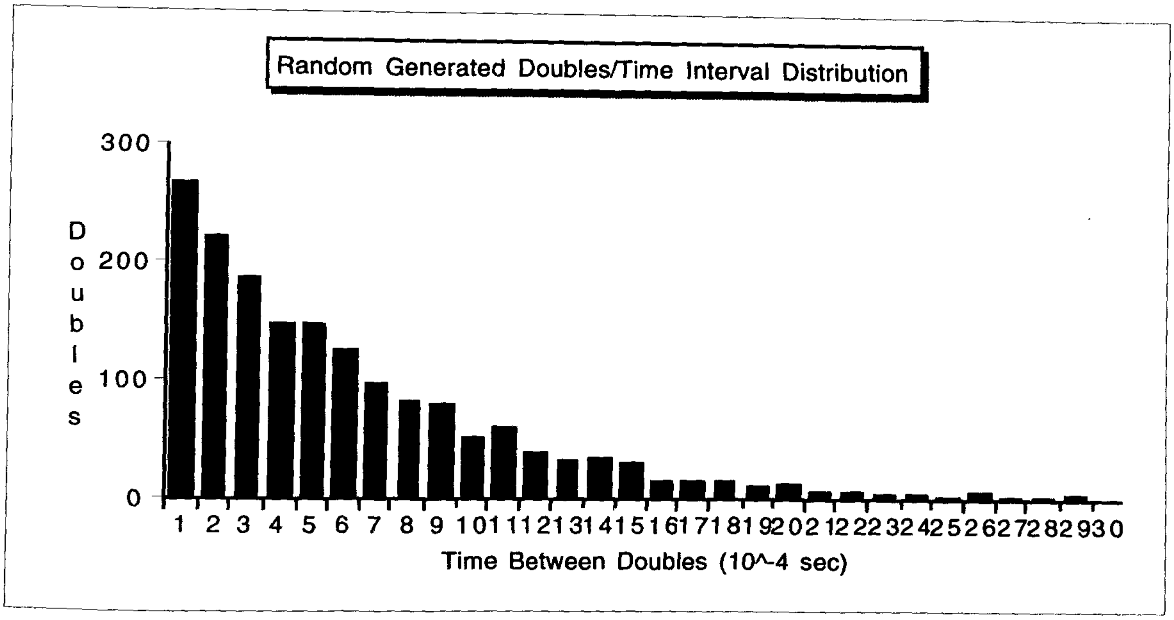


Figure 18 - Random Generated Doubles For Various Time Intervals
A spreadsheet generated 1725 'pulses' at random times in a one minute period. The time intervals between two adjacent pulses was binned in 100 μs wide bins and the above histogram was produced.

time allowed between pulses for this experiment) the second term in the expression above can be approximated as the constant C. For this example, and thus for this experiment, the value of this second term only varies by 0.07% when considered over the entire 25 μs range. Thus, one IS justified in considering the background to be constant.Note 1 The number of counts in each bin may therefore be expressed as

$$N(t_i) = [\, K\, e^{-(t_i/\tau)} \,] + C$$

where C represent the number of fake events in each bin. How does one determine 'C'? There are many techniques that may be utilized. Two methods were used in this experiment and their results are compared below.

[1] The big problem with using the tiles in the first experimental design was that in order to see anything we had to operate the phototube base near 1400 V. At this voltage, noise was so prevalent that τ_b was very near the muon lifetime. I believe I was fooled for a long time thinking that I was looking at muon decay when in fact it was primarily coincident background/noise pulses showing the same decay curve!

1. **Reading from of Graph.** The simplest method by far, and one that was easily understood by my high school students, is merely reading the background from the decay graph of the number of double pulses as a function of the time between pulses. The advantage to gathering data out to 25 μs, over 10 times the mean lifetime of the muon, is that one can be assured that nearly every count in this region of the graph is due to background. To illustrate this point, consider that if one were to count 100,000 "true" muon decays, only 5 counts would be expected to be muons at 15 μs while less that 1 would be expected at 20 μs! Figures 19a and 19b are theoretical plots of such a graph without background and with a constant background. The second graph shows the ease with which this can be read off the graph. For the sample size of this experiment--approximately 40,000 counts (even less than the 100,000 in the example)--our background was estimated to be 43 fakes/bin using this method.

2. **Minimization of Chi Squared.** A second technique used to determine C is the minimization of χ^2. It was described above how one can, by linearizing and exponential function, vary two parameters in order to minimize χ^2. I extended this to minimizing χ^2 for three parameters. This was done by repeatedly running a spreadsheet program that minimized χ^2 for the two parameters discussed above with various background values subtracted off. When this was done, a background of 42.5 subtracted from each bin yielded the lowest χ^2 value.

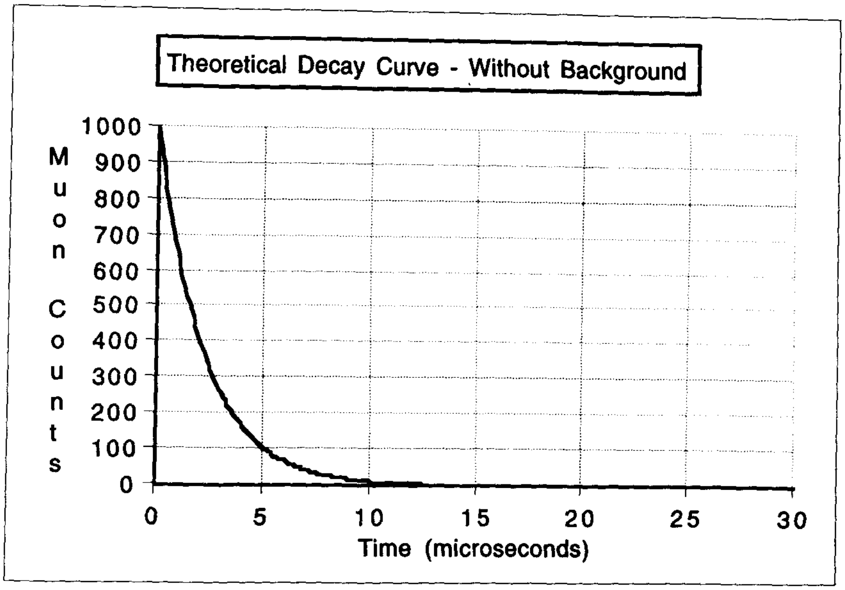


Figure 19a - Theoretical Muon Decay Curve Without Background
It is easy to see how this curve quickly drops to zero counts for the larger time intervals.

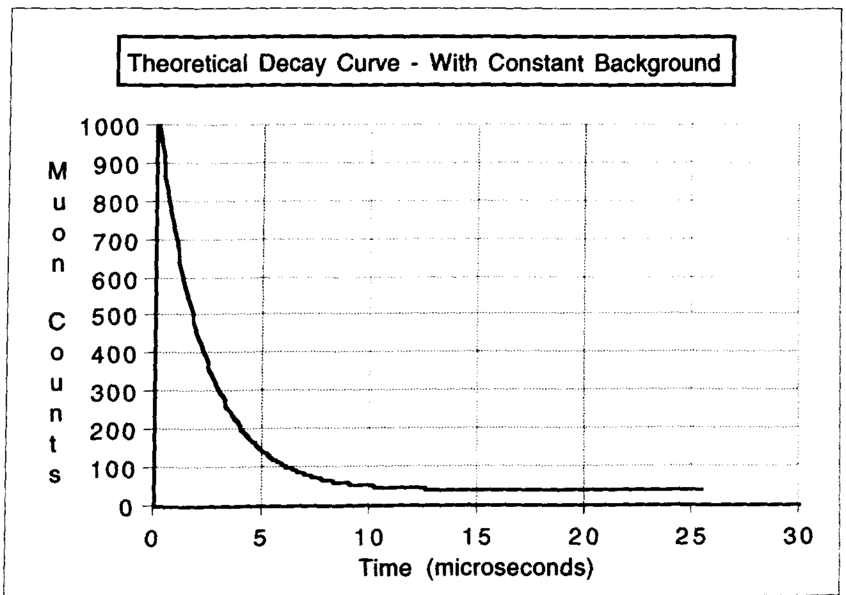


Figure 19b - Theoretical Muon Decay Curve With Constant Background
Here one sees how this curve drops to a constant background value for the larger time intervals.

5. Mean Lifetime Value

Once this background subtraction was performed, and after applying the above minimization of χ^2 technique, a value of 2.10 ± 0.02 μs was obtained. Plots 20 and 21 on the next pages show the background subtracted data over a range of 0.5-11.0 μs with best fit lines.

B. Flux Comparison

It was reported earlier that 1725 singles/minute were detected with this detector. Since the area of the detector was 1120 cm^2, this translates to 2.5×10^{-2} particles/sec/cm^2, assuming that all singles are due to cosmic ray particles. Such a rate is larger than the flux rate of 1.8×10^{-2} muons/sec/cm^2 that a previous experiment has confirmed.[4] If one considers the fact that energetic electrons traversing the detector may also signal a pulse, the flux for this experiment seems reasonable.

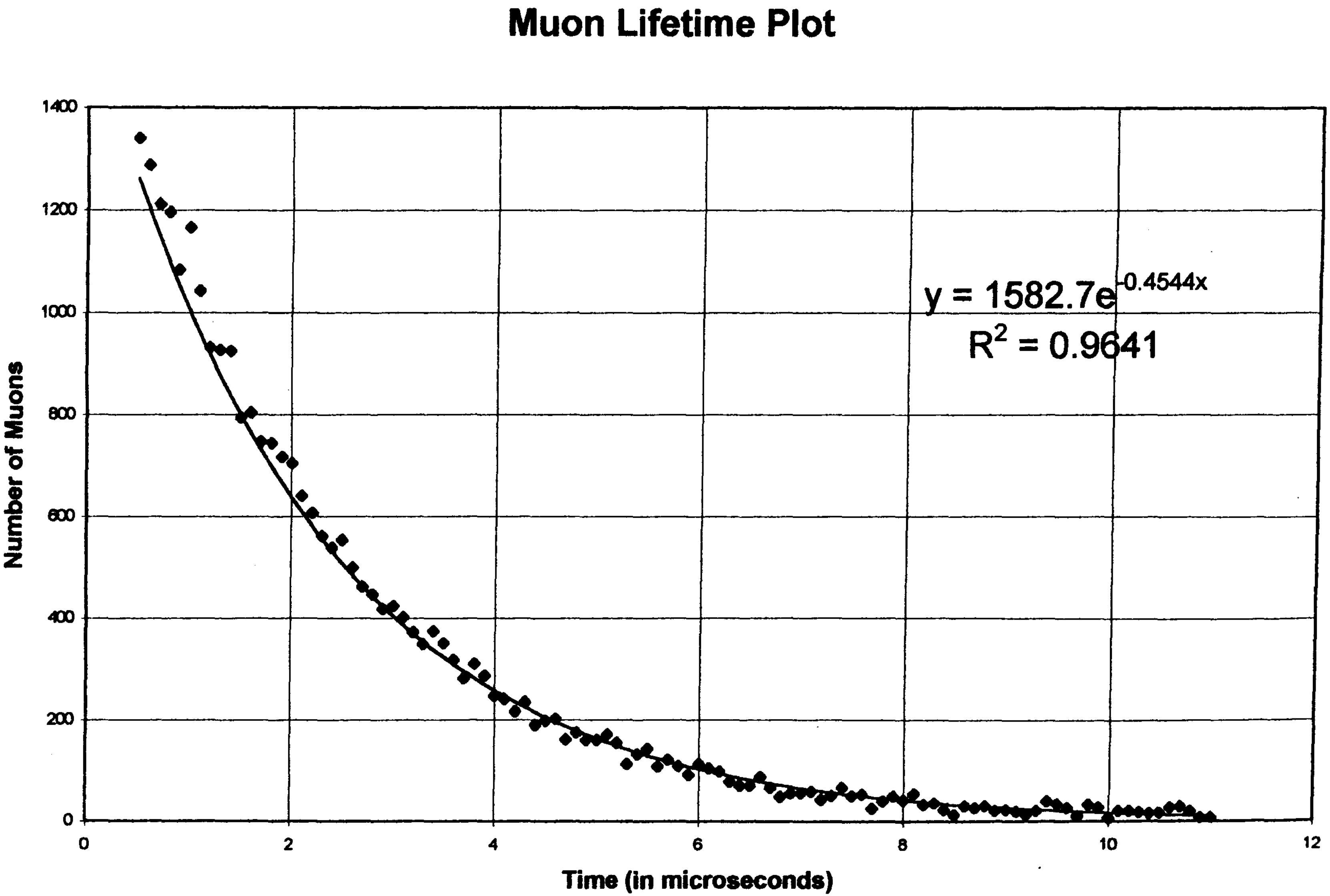


Figure 20 - Background Subtracted Muon Lifetime Data with Best Fit to Exponential Decay Function

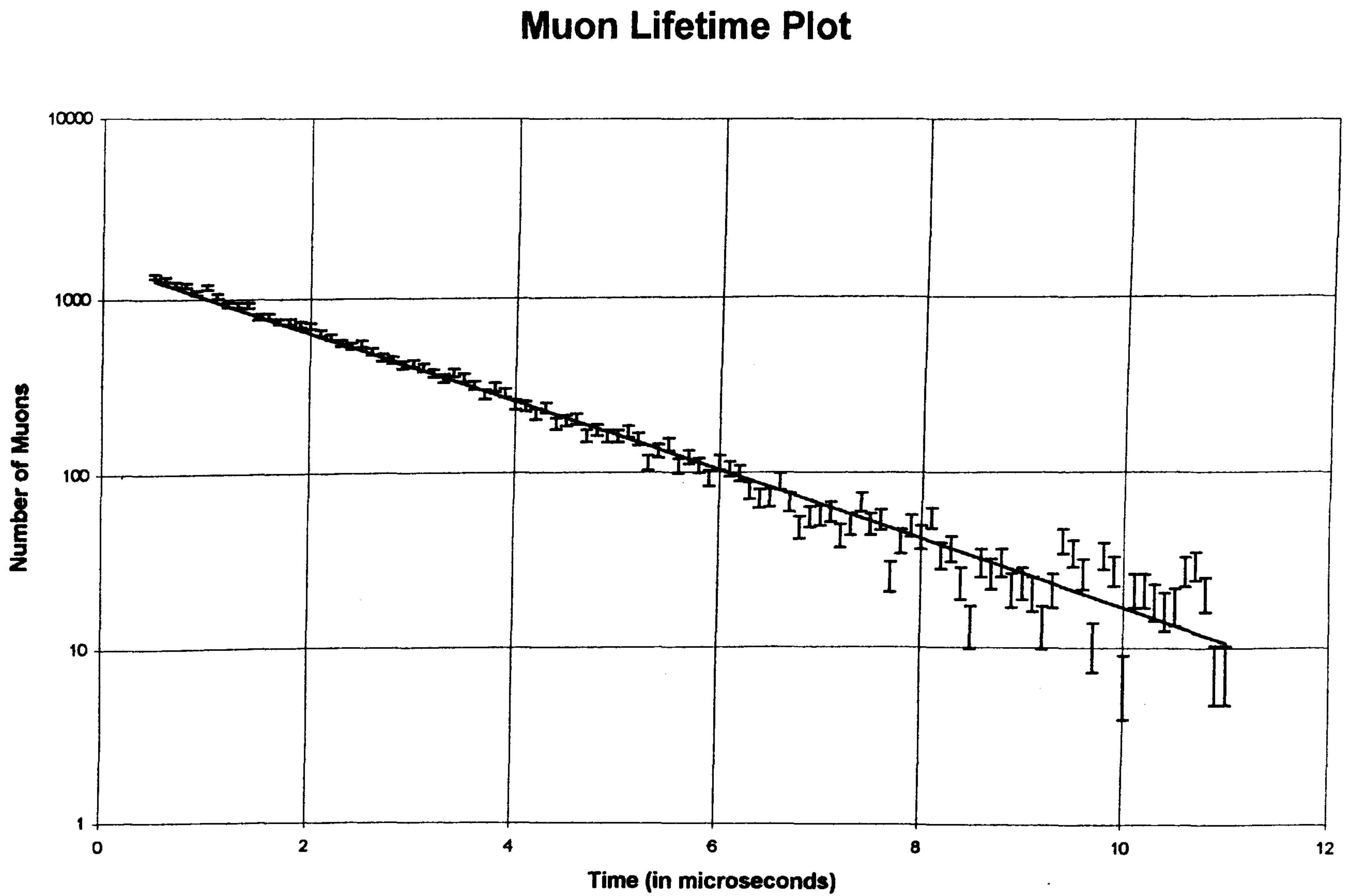


Figure 21 - Semi-Log Plot of Background Subtracted Muon Lifetime Data with Best Fit Line

V. Results

A. Comparison of this Experiment's Value to Accepted Value

The measured mean lifetime of the muon from this experiment is 2.10 ± 0.02 μs. The accepted free-space value is 2.19714 ± .00007 μs[18]. This seems reasonable, however, since the μ^-, which make up about 46% of the incident muons, may undergo nucleon capture hence shorting its lifetime.[8,19] This was first verified experimentally by Conversi *et al.* [20] in 1947. The negative muon will undergo one of two processes if it is stopped in the scintillator: (1) it will "wait around" until it decays, or (2) it will be captured by the nucleus. In both processes a double pulse will result, but in the latter, mass turns into energy as the disappearing meson produces a kind of tiny nuclear explosion with the nucleus. In this case, the muon did not live long enough for it to decay on its own. The nucleon capture process occurs so rapidly, in comparison to the mean free-space lifetime of the muon, that it can be assumed to have happened instantaneously.[8] Unfortunately, the percentage that undergo nucleon capture in this experiment is unknown. It is known, however, that the number of μ^- captures is greater for larger atomic numbers of the absorber. Figures 22a and 22b show data from Ticho[8] compared with theory from Wheeler.[21] It is clear that the probability of decay is very large for elements with atomic numbers under that of carbon. Since the plastic scintillator is made up of organic molecules composed primarily of hydrogen and carbon, the percentage of negative muons that undergo such a capture should be relatively small. For the NE 102 scintillator used in this experiment, 48% of the atoms are carbon atoms while 52% are hydrogen atoms.[12] If one assumes that no negative muons will undergo nucleon capture with hydrogen atoms, and that 10.1% of the negative muons will undergo nucleon capture with carbon atoms,[21] the theoretical lifetime in this scintillator can be predicted. If one considers for this experiment that 10.1% of the 46% stopped negative muons undergo nucleon capture in the 48% carbon atoms, this shortens the expected lifetime to roughly 2.16 μs. This value is closer to the lifetime obtained in this experiment.

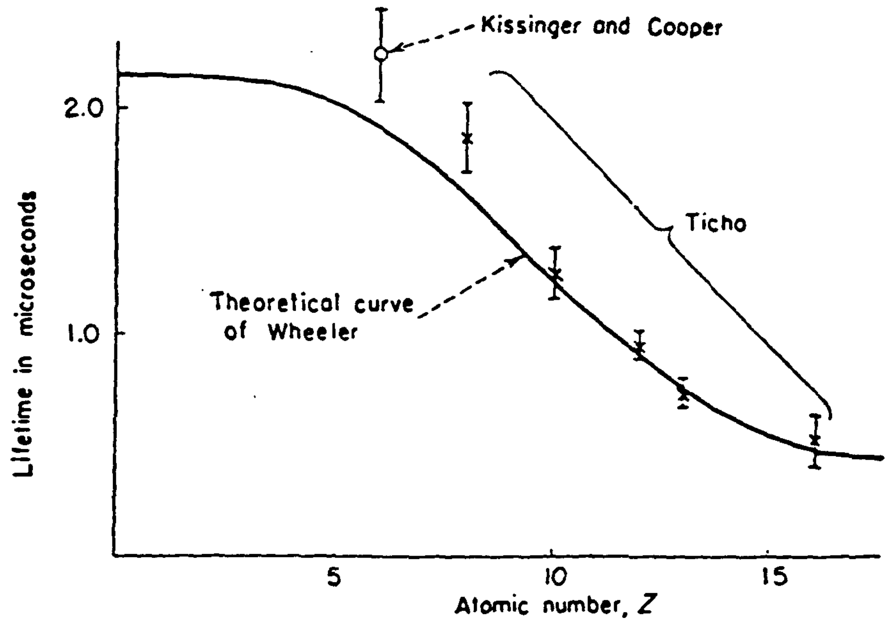


Figure 22a - Muon Lifetime as a Function of Absorber's Atomic Number[8]

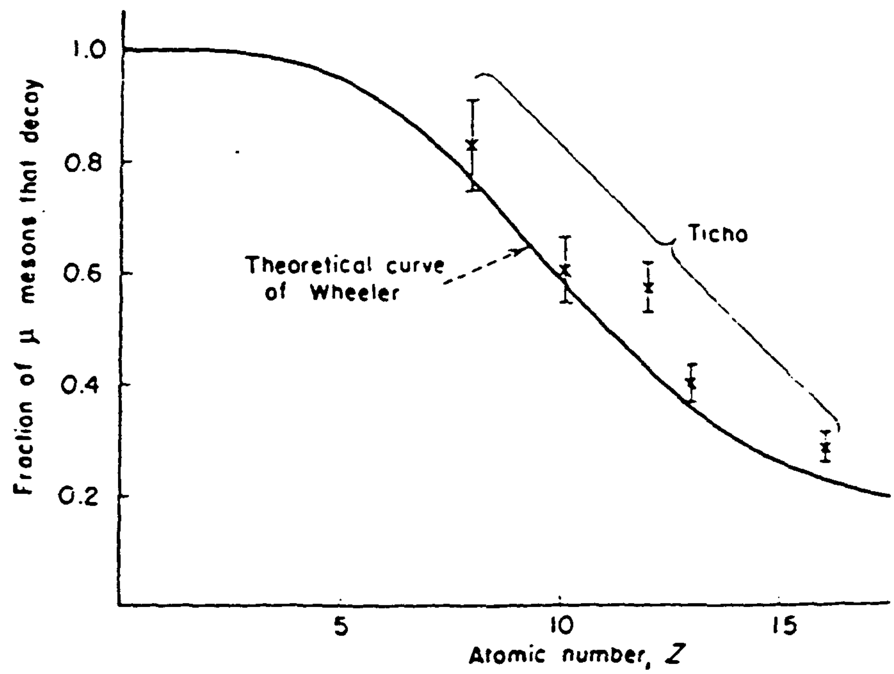


Figure 22b - Fraction of Muons that Decay as a Function of Absorber's Atomic Number[8]

B. Improvements for the Future

One improvement that could be made to shorten the time that the experiment would have to be in operation and yet achieve the same statistics is the addition of Pb above the detector. Since the peak muon flux is right around 1 GeV, we would like to slow down these 1 GeV muons to the 25 MeV range. Since 1 mm of Pb absorbs about 16 MeV per muon,[22] it works out that just over 6 cm of Pb would shift this higher flux "energy window" to the range that will be captured by this scintillator. One may consider the substitution of steel instead of lead for the high school classroom due to health concerns. Increasing surface area and the thickness of the detector would decrease the time needed to achieve the same statistics as well.

VI. Use in a High School Classroom

A. A Real High Energy Physics Experiment

The beauty of this experiment is that it can be transported and assembled in a high school classroom. Though the cost and size of such an experiment pales in comparison to high energy physics experiments currently being performed at some of the large accelerators, this experiment, on a smaller scale, still has nearly all the characteristics of a 'real' high energy physics experiment. Such an experiment as this allows a high school class to do high energy physics and uses some of the techniques employed by experimentalists today.

Along with the measure of a fundamental particle's lifetime, this experiment can be used to illustrate time dilation, a topic that I could never tangibly illustrate until now. Since the muons that traverse the atmosphere have velocities very near the speed of light relative to the observer, the apparent lifetime of the muon, τ', is longer than the lifetime of a muon that is at rest in our reference frame according to the expression

$$\tau' = \tau\,[1/(1-v^2/c^2)]$$

If one assumes that muons are created about 30 km above sea level and that they are traveling at the speed of light, one can simply use $v = d/t$ to find that they must live for at least 100 μs according to our watches just to get here! A more formal method of time dilation measurement for the muon is suggested by Easwar.[23]

B. Summary of Investigations

Below is a brief synopsis of how this experiment was used in a high school physics class. A handout, similar to the one used for my classes, is included in appendix D.

The experiment was conducted over a period of two weeks. Student lab groups performed the data collection process in a manner described earlier. Once all the data runs were sorted, each student worked through the mean lifetime calculation by generating a plot showing the exponential decay that was then used for their own estimated background subtraction value. By making a semi-log plot of the background subtracted data, each student determined the lifetime of the muon. Students then used this lifetime measurement, along with the assumption that muons are created in the upper part of our atmosphere, to verify time dilation. Although the technique used here to illustrate time dilation is somewhat hand waving, the point was clearly understood by the students.

VII. Appendices

Appendix A: Progeny of Cosmic Ray Particles

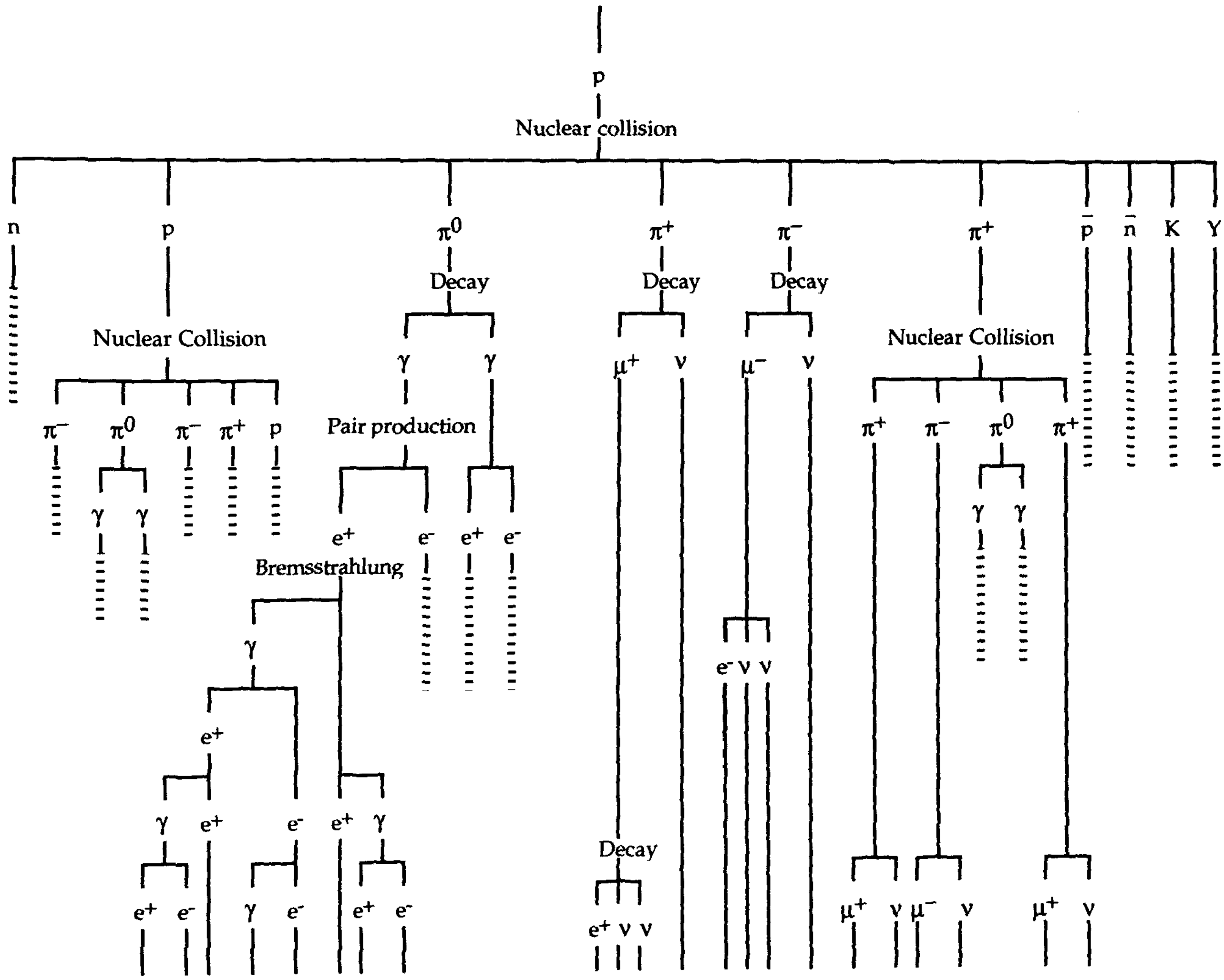


Table taken from Rossi[1], p. 172.

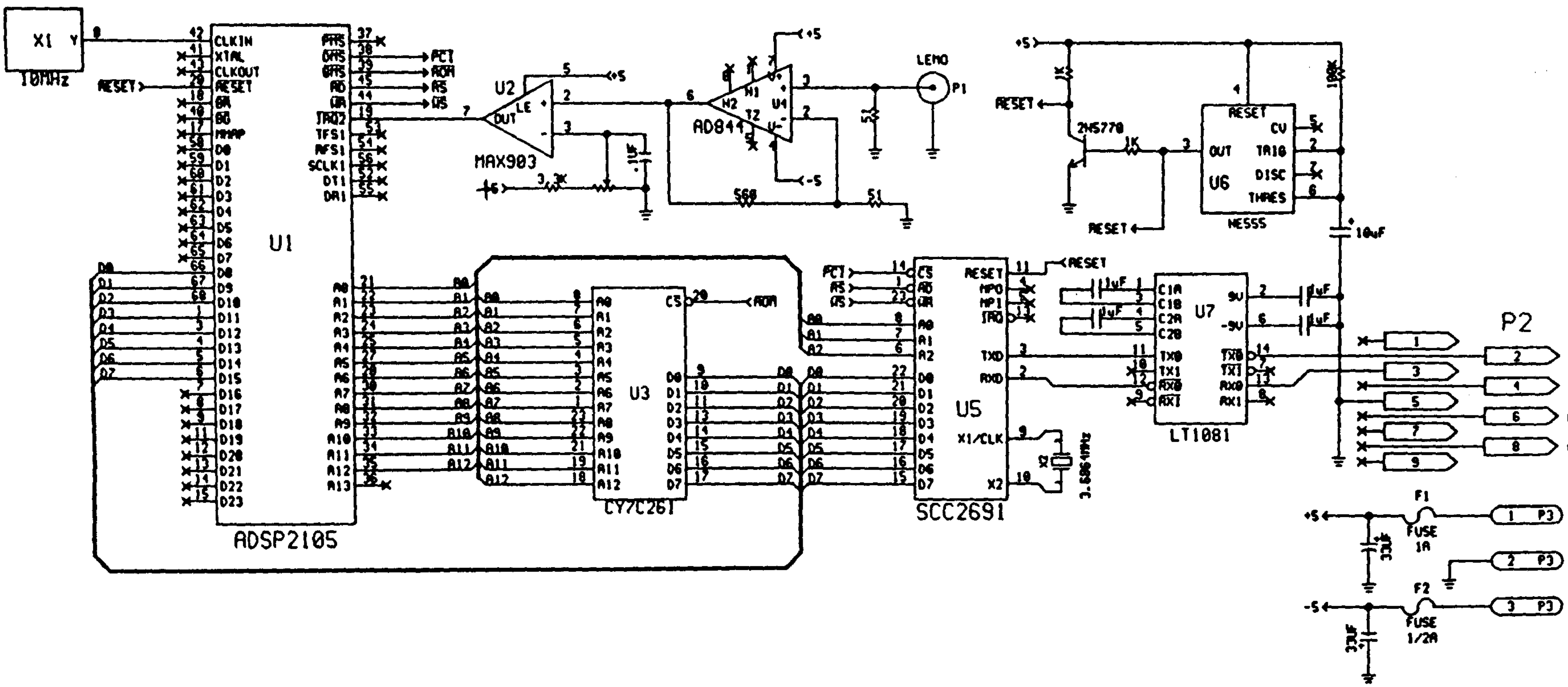
Appendix B: Decay Modes of the π and K Mesons

Group	Particle	Mean lifetime (sec)	Decay Modes	
Pi	π°	2×10^{-16}	$\gamma + \gamma$	
	π^{+}	2.55×10^{-8}	$\mu^{+} + \nu_{\mu}$	✔
	π^{-}	2.55×10^{-8}	$\mu^{-} + \nu_{\mu}$	✔
K Mesons	K°_{1}	1×10^{-10}	$\pi^{+} + \pi^{-}$	
			$\pi^{\circ} + \pi^{\circ}$	
	K°_{2}	6×10^{-8}	$\mu^{+} + \nu_{\mu} + \pi^{-}$	✔
			$\mu^{-} + \nu_{\mu} + \pi^{+}$	✔
			$e^{+} + \nu_{e} + \pi^{-}$	
			$e^{-} + \nu_{e} + \pi^{+}$	
			$\pi^{+} + \pi^{-} + \pi^{\circ}$	
			$\pi^{\circ} + \pi^{\circ} + \pi^{\circ}$	
	K^{+}	1.22×10^{-8}	$\mu^{+} + \nu_{\mu}$	✔
			$\mu^{+} + \nu_{\mu} + \pi^{\circ}$	✔
			$e^{+} + \nu_{e} + \pi^{\circ}$	
			$\pi^{+} + \pi^{\circ}$	
			$\pi^{+} + \pi^{+} + \pi^{\circ}$	
			$\pi^{+} + \pi^{\circ} + \pi^{\circ}$	
	K^{-}	1.22×10^{-8}	$\mu^{-} + \nu_{\mu}$	✔
			$\mu^{-} + \nu_{\mu} + \pi^{\circ}$	✔
			$e^{-} + \nu_{e} + \pi^{\circ}$	
			$\pi^{-} + \pi^{\circ}$	
			$\pi^{-} + \pi^{-} + \pi+$	
			$\pi^{-} + \pi^{\circ} + \pi^{\circ}$	

The ✔ denotes a decay mode that produces a muon.
Table taken from Rossi[1], p.259.

PRGRAMMABLE INTERVAL TIMER

STEN HANSEN FERMILAB PHYSICS SECTION 8-9-94



Appendix C: Circuit Board Diagram

Appendix D: Handout to High School Students

Measurement of the Muon Lifetime

A Verification of Time Dilation!

I. Introduction

It has been known for many years that a charged electroscope, if left standing, will eventually discharge no matter how well it is insulated. Attributing this discharge to radioactive materials, in 1903 Rutherford and Cooke surrounded a charged electroscope with bricks in hopes to shield out unwanted radiation. To their dismay, the discharge rate did not decrease significantly as they had anticipated. In 1912 , Hess took an electroscope over five miles into the atmosphere in a balloon in order to get away from the ground radiation that seemed to plague earlier experimenters. To the surprise of many, as his electroscope rose higher into the atmosphere the discharge rate increased rather than decreased! Hess suggested, "The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above." He believed that there must be some radiation coming from space. Because of this explanation, Hess is generally credited for the discovery of cosmic rays--these particles "from above." He was awarded a Nobel Prize in physics for this discovery. And so began the study of cosmic rays.

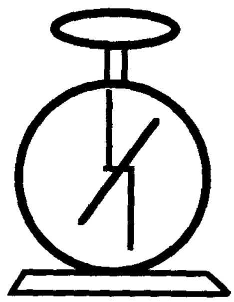


Figure 1 - Charged Electroscope

II. Where do these particles come from?

Although the existence of cosmic rays is unquestionably confirmed through countless experiments, the source of these cosmic rays is still a mystery. Many cosmologists believe that cosmic rays originate from or are in some way linked to supernovas. Many also believe they are extragalatic in origin.

These cosmic rays that approach the earth from outside our atmosphere are called "primary particles." These primary particles that enter the upper part of our atmosphere are made up of about 90% protons and 10% heavier positive nuclei. When these energetic particles collide with other nuclear particles in our atmosphere, other "secondary particles" are created. These secondary particles may in turn collide with other nuclei or decay before doing so. (By decay we are speaking of a process by which a particle breaks down into other particles.) Such is the case for the creation of a cosmic ray muon.

When a high energy proton (p), for example, enters the atmosphere, the chances of it interacting with another proton in our upper atmosphere are very great. In the interaction of primary particle in our atmosphere, secondary particles called pions (π) are created. Here are two possible resulting collisions:

$$p + p \rightarrow p + p + \pi^+ + \pi^\circ + \pi^-$$

and

$$p + p \rightarrow p + n + \pi^+ + \pi^+ + \pi^-$$

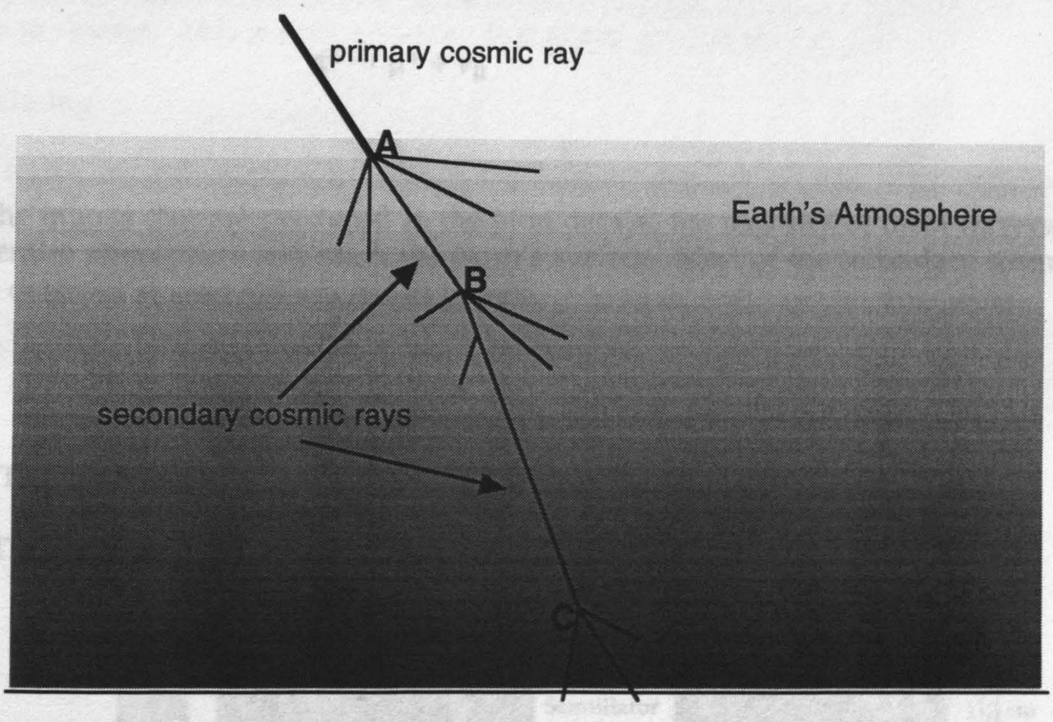


Figure 2 - Cosmic Ray Production Schematic

A primary cosmic ray proton enters the atmosphere and collides with another proton (A). A charged pion is a product of this interaction. It quickly decays (B) into a charged muon and neutrinos. The charged muon, which this experiment seeks to detect, will eventually decay (C) into an electron and two neutrinos.

The charged pions (π^+ and π^-) that are created in the above collisions are very short lived (~2 x 10^{-8} seconds) and will themselves most likely decay before reaching the earth's surface. The negative and positively charged pions decay into a muon (μ) and neutrinos (ν) via these decays,

$$\pi^- \rightarrow \mu^- + \nu_\mu$$

and

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Of the muons that are produced in the pion decays, the majority of them traverse the entire atmosphere and reach the earth's surface. Most of the secondary cosmic rays detected at sea level are in fact muons.

III. The experiment

A. The Detector

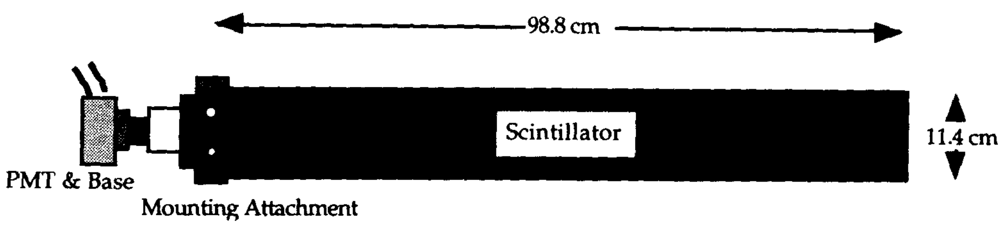


Figure 3 - The Detector

The figure above shows the detector. It is composed of two main parts: (1) a special piece of plastic called a scintillator, and (2) photomultiplier tube (PMT for short).

Here's how it works! As the muon enters the plastic scintillator it loses energy as it bumps into atoms and excites the electrons of the scintillator to a higher energy level. Very quickly, however, the electrons give up this energy in the form of light. This process is called fluorescence...this is what is happening inside fluorescent light bulbs! In most cases the muon has so much energy that it just continues through the plastic. It may happen, though, that it doesn't have enough energy to continue through the scintillator and instead 'stops' in the plastic and waits around until it decays. When a stopped muon does decay, it produces more excited electrons which quickly decay giving a second pulse of light. We're interested in measuring the time between these two pulses (one when it enters and one when it decays) because that will lead us to how long the muon lived!

The pulses of light are very, very faint...on the order of just a few photons so that you could never see them. When a photon hits the PMT it kicks off some electrons from a piece of metal inside. These electrons in turn kick off more...which in turn kick off more... This process is repeated until maybe a million electrons strike the last piece of metal. This number of electrons is enough to cause a measurable voltage change. This is how we know that we've got something.

B. Timing

The whole experiment hinges on us being able to measure the time it takes from when the first pulse of light comes in until the second one occurs. Unfortunately a stopwatch won't do the trick! The time between these pulses is on the order of millionths of seconds. We'll use a little circuit board with a 10.0 MHz clock to do the timing for us. These times will then be fed into the Macintosh computer and we can analyze our data from here.

IV. Data Collection and Analysis

Each lab group will collect one run of data. Later, all the runs can be compiled and the entire set of data analyzed.

V. Your Lab Write-Up

Along with the usual stuff you include in lab write-ups (ie. purpose, procedure, data, etc.), you should include these things in the results section:

1. There are two plots that you need to make:
    a. An exponential decay plot of data

        This plot will be useful to see the exponential decay of these particles, but it will also be important for your background subtraction estimate.

    b. A semi-log plot of background subtracted data

        We've said all along that in order to fit an equation to a graph, we'd like to change our axes such that we get a straight line. The way this is done with an exponential function is to make a semi-log plot of such data. The 'slope' of such a graph will lead you to the mean lifetime of the muon.

2. Along with this, show the necessary calculations that you performed leading to the lifetime of the muon.

3. We will assume that, on average, muons are created in the upper atmosphere at about 30 km above the surface of the earth. Let's assume that they are moving at the speed of light (they really are moving just about this fast!). Use s = d/t to calculate the amount of time that it takes a muon to get from the upper atmosphere to the earth. (If you've done this right, the answer you should get is about 50 times longer than the muons' lifetime!!) The only way to explain this is that **TIME IS RUNNING SLOWER FOR THESE MUONS SINCE THEY ARE TRAVELING SO FAST!** This is probably the first way that Einstein's theory of special relativity was verified!!

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