MEASUREMENT OF MEAN LIFETIME OF COSMIC MUONS

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Abstract
We determine the mean or average muon lifetime in this experiment using a PMT coupled plastic scintillator, where, the incoming muons are stopped and electrons are produced by their decay. The difference in time between the pulse due to the entry of the muon and that due to the electron formed by the decay of the muon gives the lifetime of the muon. The decay times are counted in large numbers so that an exponential distribution is obtained. The inverse of the slope of the logarithmic plot gives the average lifetime of the muon.

1 Introduction

Muons were discovered by Carl D. Anderson and his student, Seth H. Neddermeyer, in cosmic rays in 1936. Muons (μ^-) are elementary or fundamental particles belonging to the second generation of the lepton family. Generation in particle physics is a classification of particles according to their masses. Electrons are the lightest leptons and hence belong to the first generation. Muons being heavier than them belong to the second. They are fermions of spin ½ and have one unit of electronic charge. They have a mass of about 105.7 MeV/c^2. The anti-particle of the muon is the antimuon (μ^+, also called positive muon.). Muons are unstable and decay into electrons and neutrinos. Their decay reaction is as shown below

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Muons take part in both strong and electromagnetic interactions. Muons being heavier than electrons do not get accelerated by electromagnetic fields as easily, in matter. Therefore they emit much less bremsstrahlung radiation. They are more penetrating than electrons. While passing through matter they can also be captured by nuclei in the following way

$$\mu^- + p \rightarrow n + \nu_\mu$$

Sources

Energy of about 105.7 MeV (rest mass energy) is required for a muon to be created in the COM frame. Normal radioactive decays do not possess such energies and neither do fission and fusion reactions occurring in nuclear reactors and weapons. Although single atom nuclear fission has the energy of this order, due to conservation laws, muons are not produced. The only known natural source of muons is the cosmic rays. Muons can be produced in high energy accelerators. In cosmic rays coming from space, about 89% of the nuclei are hydrogen (protons), 10% helium, and about 1% heavier elements. When the cosmic rays reach the upper atmosphere the protons interact with the atoms in the atmosphere and produce pions. Pions subsequently decay into muons. π^0 decays into two gamma photons and does not produce muons. The schematic diagram is as shown below.

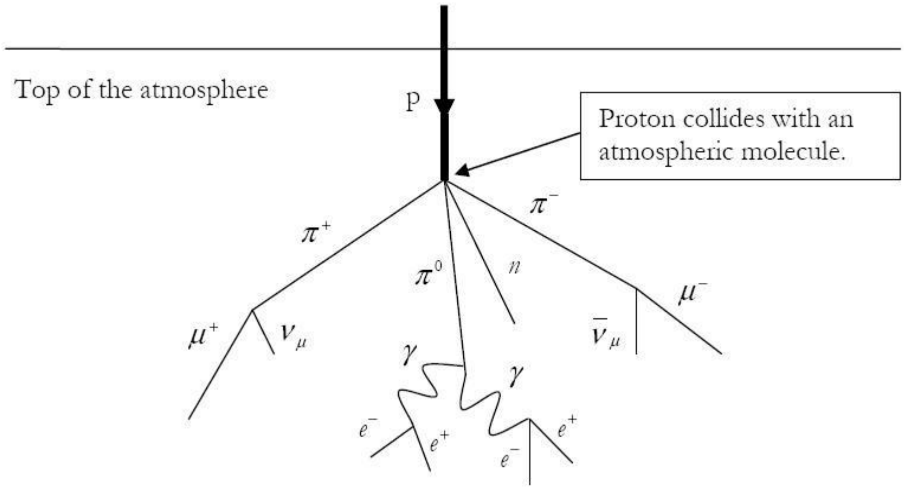

Figure 1: Proton colliding with atmospheric molecules and producing secondary particles.

Pions decay into muons as

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Possibility of detection and measurement

Pions have a lifetime of the order of 10^{-8} s. Hence they are not observed near sea level. The muons produced subsequently after their decay, decay as shown before. Muon lifetime (average) from many other experiments is found out to be about 2.2 □ s. If we use the formula *distance* = *velocity* x *time*, we see that it (muon) can only travel about 653.4 m. But we are able to observe muons at sea level even though they are formed at heights of several kilometers. This is because of relativistic time dilation. Muons from cosmic rays possess energies in the order of GeV. Assuming the energy of the muon to be about 1 GeV, we find that it will have a velocity of about 0.99c, where 'c' is the speed of light. Using the formula $t = t'/\sqrt{1-(v^2/c^2)}$ (t is the time in the rest frame and t' is the time as measured in the muon frame.) and taking t' = 2.2 μs, we see that the muon's life increases to 15.6 μs. By using the factor γ which is about 7.088 in this case, we see that, a distance of 4633.2 m would be seen as 653.4 m by the muon.

2 Experimental Setup

The components used in the setup are as follows:

1. Plastic Scintillator
2. Photo Multiplier tube
3. Time measuring circuit
4. Computer

1. Plastic Scintillator

This scintillator is very well suited for fast counting and has a very sharp lifetime. It produces scintillations in the blue and low UV region of the electromagnetic spectrum. The scintillator has been wrapped by two types of papers one above the other. First, it is wrapped by 'Tyvec' paper which has a reflective property. Scintillations produced are always spherically distributed. It helps in refocusing them. The second wrapping is of 'Tedlar', which prevents ambient light from entering into the scintillator.

The scintillator which we are using is a Bicron BC-404. It is an Organic Fluor – polyvinyltoluene plastic scintillator. The dimensions are 24 cm x 24 cm x 14.5 cm. Other details are given in the Appendix.

2. Photo Multiplier Tube

Photomultiplier tube is used to convert the light output of the scintillator to an electric signal. The PM tube we are using has a semitransparent bialkali photo-cathode of 2" diameter. It has 21 pins. The biasing voltage is about 1.7 kV, generated by means of a high voltage dc to dc converter (E20 – HVDCDC). The circuit is as shown in Fig. (3b). Its (PMT's) biasing circuit receives AC input from a common step-down transformer which is connected to the general power supply (230 V, 50 Hz AC). The transformer gives input to both time measuring circuit and PMT biasing circuit.

3. Time measuring Circuit

The main components (Fig. (3a)) and their function is listed in the table below.

IC	FUNCTION
LM360 (8 pins)	Comparator
74LS74 (14 pins)	D-Flip Flop
74LS161 (16 pins)	4 – bit counter
74LS541 (20 pins)	Buffer
74LS11 (14 pins)	AND gate
74LS04 (14 pins)	NOT gate
7805 (3 pins)	Positive voltage regulator
7905 (3 pins)	Negative voltage regulator
DB103 (4 pins)	Bridge rectifier

The circuit is fed by a 10 MHz oscillator. This means that the least count of the time in the circuit is 0.1 μs. There are two 4-bit counters in the circuit which together give a capacity of 256 bytes. Therefore the circuit can measure a time interval of 0.1 to 25.5 μs.

Working of the circuit

The pulse from the photomultiplier appears at Lemo (L1). The threshold voltage (-42 mV) is set using a suitable voltage divider. The signal is connected to the inverting terminal of the OP-AMP. The positive going pulse, which comes as output from the discriminator or OP-AMP is given as CLK to the D - F/F, U3A. Initially in both F/F U3A and U3B, Q is LOW and $\bar{Q}$ is HIGH. When the pulse due to the entry of the muon triggers U3A as CLK, $\bar{Q}$, D become LOW and Q becomes HIGH. This enables the first 4-bit counter U2 to start counting at 10 MHz. Now since $\bar{Q}$ is fed as CLK to U3B, $\bar{Q}$ of U3B does not change state and remains HIGH because the CLK is LOW. There are two cases after the circuit is in this stage. But before going to the cases we will see the working of the counters.

Both the counters are of 4 bit as described in the table. After the initiation of counting, U2 will count up to 1.5 μs. If the electron signal comes within this time interval, the counting is stopped. The way in which it is stopped is described in the different cases below. If the time exceeds 1.5 μs, the RCO of U2 is made HIGH and this enables the second counter U6 for a time equal to the oscillator pulse width (positive going edge). In the circuit, we can see that the CLK from the oscillator is common to both U2 and U6. U2 is already enabled (ENT = HIGH) by the arrival of the pulse. The counters will count only if ENT is HIGH. Therefore, when U6 is enabled by U2, it utilizes the common CLK pulse to record one count. This cycle will repeat for every 1.6 μs. The counter U6, in other words, records the number of 1.6 μs. In this way up to 25.5 μs can be counted. These data are recorded in the buffer.

We now discuss the two cases.

Case 1: The muon decays

The electron formed by the decay of the muon generates a signal. This signal or pulse after passing through the discriminator triggers U3A as another CLK. The state of D which is now LOW is transferred to Q. Q becomes LOW and it instructs the counter to stop counting. As D of U3A goes as CLK to U3B, $\bar{Q}$ of U3B becomes LOW. The busy line becomes LOW and instructs the computer connected via the parallel port to read the data. The PC takes 'nDatastrobe' LOW and reads the data from the buffer. After reading the data, it makes 'nDatastrobe' high and lowers 'nReset' for a few microseconds so that the counters and the F/F are reset and are now ready for collection of new data.

Case 2: The muon passes without decaying

If the muon passes through the scintillator without decaying, there will be no second pulse. The U6 counter will complete the counting up to 25.5 μs and after that it will take RCO high which connected through a NOT gate to the AND gate U5B. The AND gate gives a gives a LOW output and resets the counters and the F/Fs. Now the circuit is ready to collect new data.

The working of the whole circuit has been summarized in the flowchart.
The collected time intervals are saved as a text file with date and time.

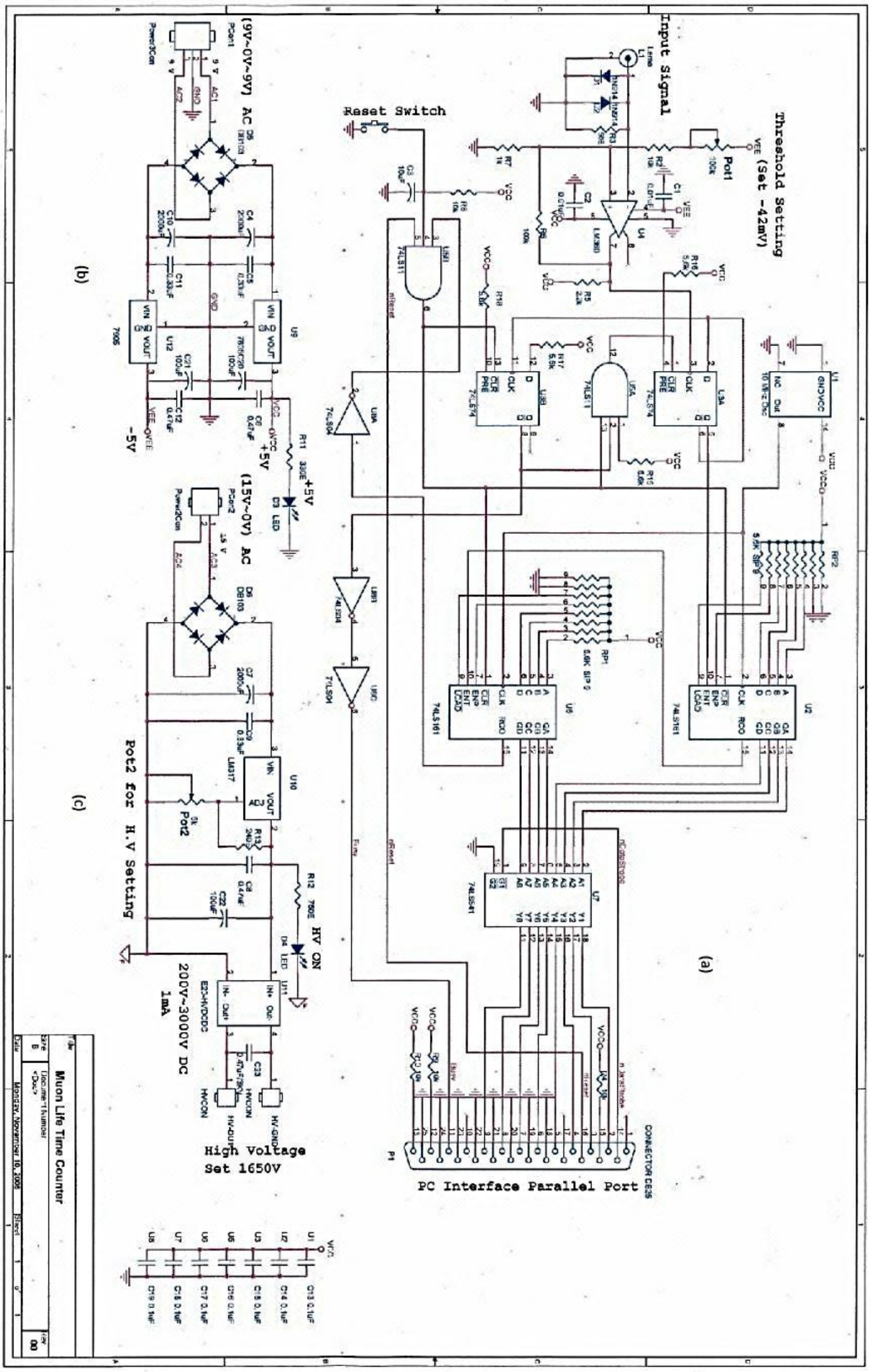
Input Signal
Threshold Setting (Set -42mV)
Reset Switch
PC Interface Parallel Port
(9V~0V~9V) AC
(15V~0V) AC
+5V
-5V
HV ON
Pot2 for H.V Setting
200V~3000V DC
1mA
High Voltage
Set 1650V
Muon Life Time Counter
(a)
(b)
(c)

Figure 2

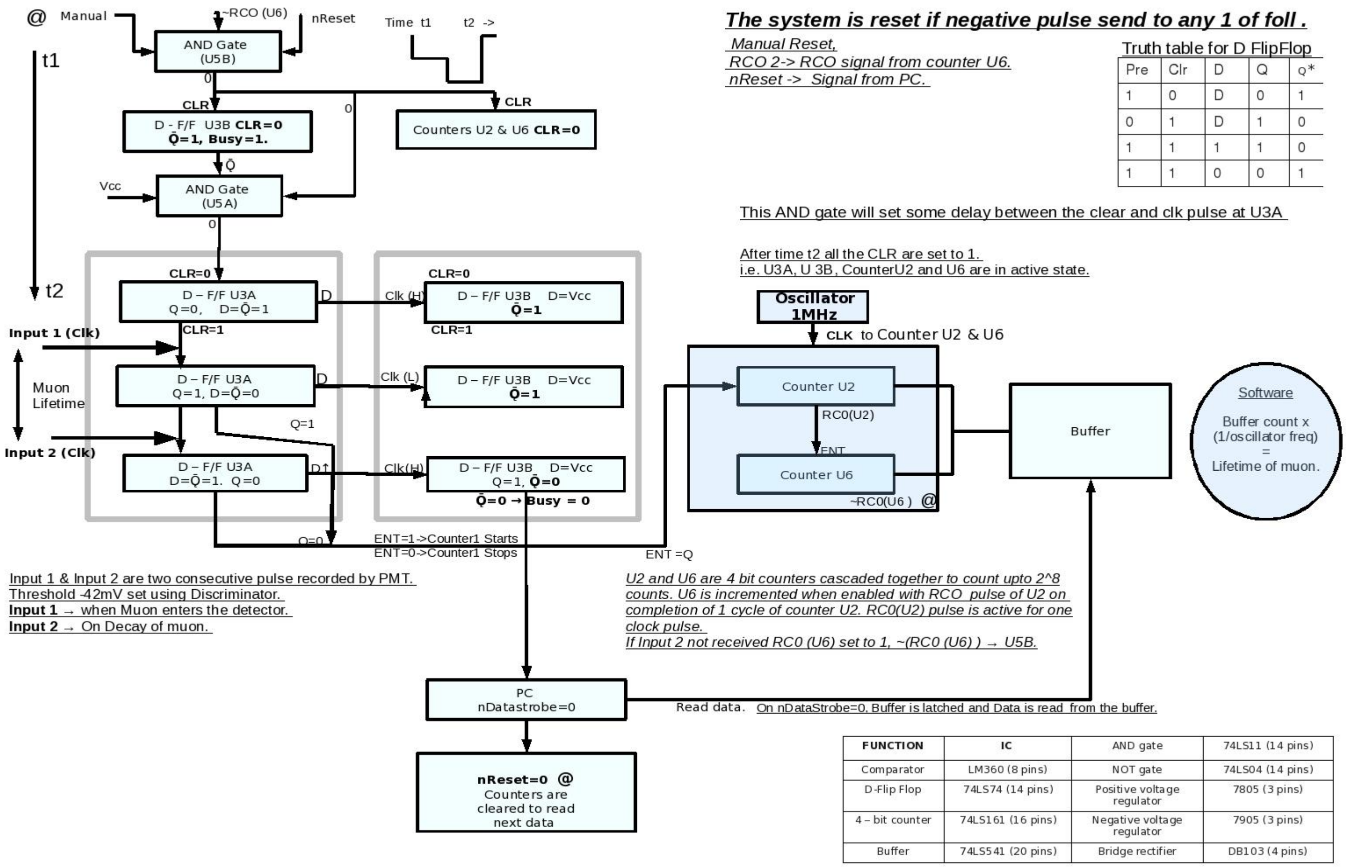

Figure 3 Flowchart describing the working of the circuit

3 Procedure

The lifetime of a muon as seen by us is not a constant quantity. The decay of the muon is a statistical process. Therefore the aim of this experiment is to determine the average lifetime of the muon. We do it by stopping muons in a plastic scintillator and detecting its decay. The time information is collected from the time measuring circuit on a PC, with the use of a parallel port. A computer program is written, which takes a note of the time interval between the muon's arrival and its decay on a text file. The experiment is run till sufficient number of counts is obtained. The recorded time intervals follow an exponential distribution. The distribution of the events is governed by the relation

$$N = N_0 e^{-t/\tau} \tag{1}$$

where, N_0 is the initial population of muons, N is the population muons at time t and τ is the lifetime of the muon. However background events are also present in the readings. They might be due to natural radioactivity, PMT after pulses, and other through going muons. The background pulses arising due to entry of one muon and due to the entry of another muon within the time interval of 25.5 μs is quite negligible as the avg. muon flux at the sea level is about 1 muon/sq. cm/min. Assuming that the background is constant over a period of time, the decay spectrum could be written as

$$N = N_0 e^{-t/\tau} + b, \tag{2}$$

where b is the number of background events. The values are binned and plotted on a logarithmic scale. The inverse of the slope of the curve gives the muon lifetime (Fig. (4)).

4 Observations

Figure. 4, shows the histogram without the logarithmic scale. Figure. 5, shows the plot with the logarithmic scale.

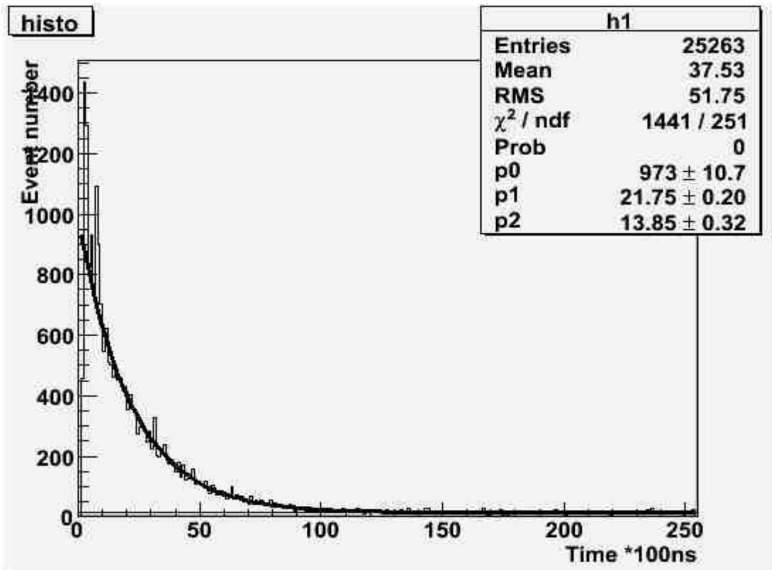

Figure 4

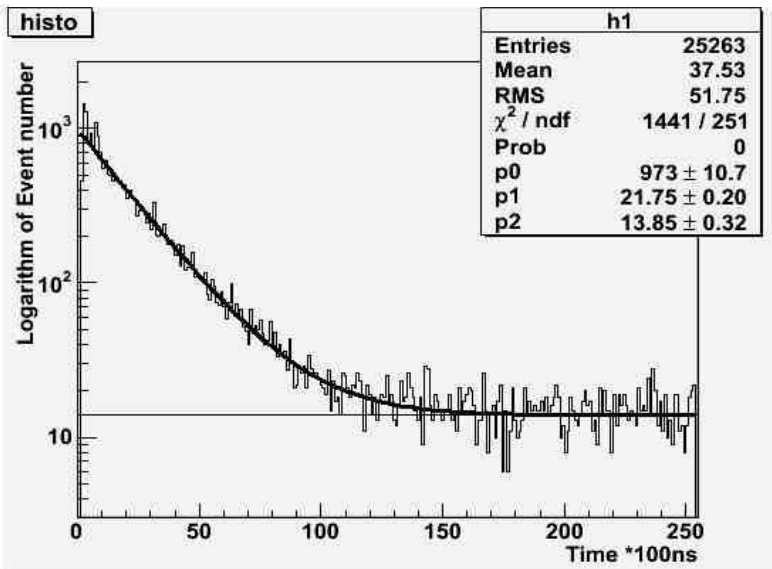

Figure 5

5 Result

The above function (Equation (1)) is fitted to the data using ROOT. The values of the fitting parameters are

$$p_0 = N_0 = 973 \pm 10.7$$
$$p_2 = b = 13.85 \pm 0.32$$
$$p_1 = \tau = 2.175 \pm 0.02\ \mu s$$

Hence the average or mean lifetime of the muon as obtained by our experiment is $2.175\ \pm\ 0.02\ \mu$s.

6 Conclusions

Using the above obtained value of the avg. lifetime of the muon, the Fermi Coupling constant G_F is calculated using the formula

$$G_F^2 = \frac{192\pi^3}{\tau m_\mu^5}.$$

The value obtained is 1.1696×10^{-5} GeV^{-2} (Standard model value $= 1.16637 \times 10^{-5}$ GeV^{-2}). The avg. lifetime of the muon as determined by our experiment has an error of 1% from the accurate standard model value 2.197 μs. The less accurate value may be attributed to line delays, formation of muonium atom and muon capture.

7 Acknowledgement

I am grateful to Prof. Naba K Mondal for giving me the oppurtunity to perform this experiment. I am also thankful to Dr. B Satyanarayana and Mr. L V Reddy for their guidance throughout. I thank my seniors for their help. Finally, I thank my collegues Rajesh Ganai, Raveendrababu Karnam, and Asmita Redij with whom I had discussions which increased my understanding.

References

[1] Radiation Detection and Measurement – G F Knoll
[2] Introduction to elementary particles – David J Griffiths
[3] ROOT user guide
[4] Muon lifetime measurement – Franz Muheim
[5] Measurement of the Muon lifetime - Carl W. Akerlof
[6] The Measurement, Simulation, and interpretation of the Lifetime of Cosmic Muons – Mathew E. Thrasher.
[7] Muon Physics - T.E. Coan and J. Ye
[8] Datasheets – Fairchild Semiconductor.
[9] D.F. Measday / Physics Reports (Elsevier) 354 (2001) 243–409

Appendix

Muon capture

Muons (μ^-) have a probability of being captured by Carbon and hydrogen atoms in their Bohr orbits in the scintillator. After its capture the muon cascades down the energy levels first by non radiative transitions (Auger electron emission) and later by radiative transitions emitting X rays. Since they are heavier than the electron they become so close to the nucleus that their orbital radius is comparable to the radius of the nucleus. This is the muonic 1s orbital. The time for this process is of the order of 10^{-13} s which is very small compared to the microsecond lifetime of the muon. It will undergo a nuclear capture with or without the emission of gamma rays. The nuclear capture happens in timescale of about 10^{-8} s. The emission of X-rays might give rise to premature pulses. Therefore there would be a reduction in the measurement of the lifetime of the muon.

Formation of muonic atom

Antimuons (μ^+) on the other hand, while travelling through the nucleus, can capture an electron to form a 'Muonic atom'. When electron falls into the potential well of the muon it emits photons. This also happens in the time scale of the order of 10^{-14} s. This can give rise to a signal which is not the prompt muon decay pulse and reduces the measured mean lifetime of the muon.

About plastic scintillator:

A particle like muon when traveling through fluorescent materials excites the atoms. The atoms after de-excitation release photons. These are called scintillations. The material is referred to as a scintillator if it can convert a large fraction of the incident radiant energy into prompt fluorescence. A plastic scintillator is essentially an organic scintillator dissolved in a polymerizable solvent. The polymerization of the solvent after the dissolution of the organic scintillator gives a solid plastic.

General characteristics

- Plastic scintillators can be shaped and fabricated into rods, cylinders and flat sheets.
- They are relatively inexpensive and can be made in large forms.
- They find very good application in fast counting.
- They can also sometimes recover from radiation damage over periods of time.

Manufacturer	Bicron
Type of scintillator	Plastic
Model No.	BC-404
*Light output, % Anthracene**	68
Wavelength of max emission	408 nm

Decay constant	1.8 ns
Pulse width	2.2 ns
Attenuation length	160 cm
Refractive Index	1.58
H/C Ratio	1.107
Density	1.032
Softening point	70 ^{0}C
Radiation detected	<100 keV X-rays , 100 keV -5 MeV gamma rays, >5 MeV gamma rays, fast neutrons, charged particles, cosmic rays, muons, protons etc.
Principal uses	Fast counting

*Anthracene = 100%

These data are from BC-404 data sheet.

About the Photo Multiplier Tube (PMT):

A photomultiplier tube utilizes the principle of the photoelectric effect. Its schematic diagram is as shown in Fig (6). The heart of the photomultiplier tube is the photo cathode. Photo cathodes are materials which eject or release electrons when light of sufficient energy are incident on them. Most photo cathodes today are bialkali materials. Bialkalies are compounds of alkali elements having high quantum efficiency (about 30%). Quantum efficiency is defined as the ratio of the number of photo-electrons emitted to the number of incident photons.

Photo cathodes may be semitransparent or opaque. Semitransparent photo-cathodes emit electrons in the same direction of the incident photons and are coated on a transparent backing (usually the glass end window of the PM tube). Opaque photo-cathodes are relatively thicker and are supported by a thicker backing material. Electrons are extracted from the same surface. Since semitransparent cathodes are more adaptable to tube designs they are most common.

The electrons liberated from the photo-cathode are accelerated and focused with the help of a focusing electrode on to another electrode known as *dynode*. The dynode upon impact of electrons from photo-cathode liberates even more electrons by secondary emission. Each dynode is at a higher potential from its predecessor. By using suitable voltage difference, and having more dynodes in cascade, a deluge of electrons can be obtained which are finally made to fall on the anode. The charge accumulated on the anode gives a sharp current pulse which denotes the incidence of the photon on the photo cathode. This is fed as signal to the time measuring circuit.

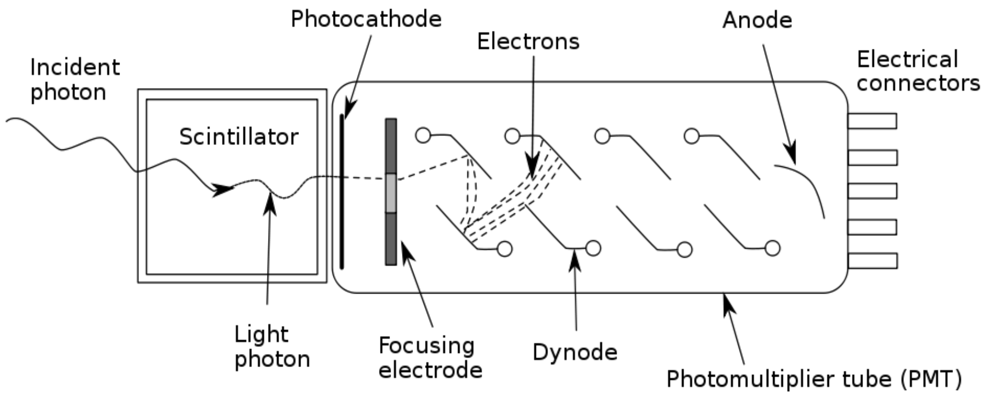

Figure 6: Schematic diagram of a photo multiplier tube.

Model No. : 9807B
Window characteristics:

Material	Borosilicate
Spectral range (nm)	290-630
Refractive index	1.49
K (ppm)	300
Th (ppb)	250
U (ppb)	100

Characteristics:

Photocathode	Bialkali
Quantum efficiency at peak	30%
Dynodes	12LFBeCu
Overall Luminous Sensitivity	2000 A/lm
Cathode Luminous Sensitivity	70 µA/lm
Dark current	Typ = 3 nA, Max =20 nA
Anode Pulse Rise Time	Single electron = 2 ns Multi electron = 3.2 ns
Anode Pulse Width	4.5 ns
Gain	30×10^6
Operating Voltage	Typical — 1650 V Max — 2000 V

D - Flip Flop truth table

Inputs				**Outputs**	
PR	CLR	CLK	D	Q	$\bar{Q}$
L	H	X	X	H	L
H	L	X	X	L	H
L	L	X	X	H (Note 1)	H (Note 1)
H	H	↑	H	H	L
H	H	↑	L	L	H
H	H	L	X	Q_0	$\bar{Q}_0$

H = HIGH logic level
X = Either LOW or HIGH logic level
L = LOW logic level
↑ = Positive going transition
Q_0= The output logic level of Q before the indicated input conditions were established.

Note 1: This configuration is unstable; that is, it will not persist when either the preset and/or clear inputs return to their inactive (HIGH) level.

About the circuits in Fig. 2(a) and Fig. 2(b)

The circuit in fig. 2(a) is a bridge rectifier circuit with capacitor filters which is center tapped to the ground. Two three terminal voltage regulators 7805 (positive voltage regulator) and 7905 (negative voltage regulator) are connected to the circuit. These enable us to extract regulated positive and negative DC voltages of 5V respectively (VCC =+5V and VEE = -5V). They are used to power the time measuring circuit.

The circuit in fig. 2(b) is similar to fig. 2(a) but without a center tap. This circuit powers the PMT. LM317 is an adjustable 3 terminal voltage regulator which can be adjusted to supply a voltage from 1.2V to 37 V. It provides current in excess of 1.5 A. This circuit is further connected to a high voltage DC to DC converter manufactured by EMCO. This converter can step up input voltage up to 3000V. We are using about 1650V which is the typical operating voltage of our PMT.