Measurement of mean lifetime of cosmic muons by stopping them in plastic scintillator

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Abstract

In this experiment we measure the mean life time of a muon by stopping it in a plastic scintillator, where subsequently it decays into electron. From the stopping of muon we get two pulses, one is due to muon entry and another is due to electron which arises from the decay of muon. The time delay between the two pulses is the life time of muon and this time delay between the two signals is measured for a large number of decays and produces an exponential distribution. To get the life time we measure the decay constant which on a logarithmic scale is 1/slope of line.

Introduction :

Muons were discovered by Carl D. Anderson and Seth Neddermeyer while studying cosmic radiations in 1936 and their existence was confirmed in 1937 by J.C. Street and E.C. Stevenson in a Cloud chamber.

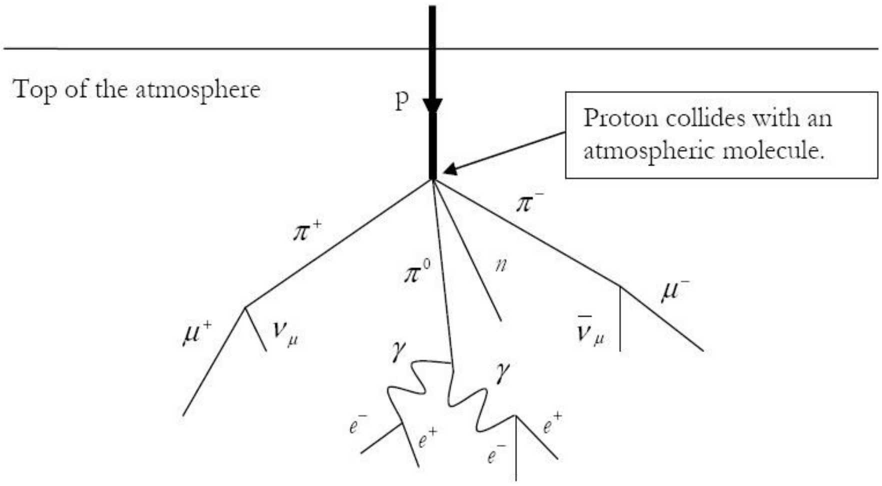
Muons are fermions of spin ½ and are fundamental particles belonging to second generation of leptons. They have a mass of 105.7 MeV/c^2, which is about 200 times the mass of the electron and their interactions are very similar to those of the electron.

Sources of Muons:

For the production of muons, we require an available center of momentum frame energy of 105.7 MeV. Thats why neither ordinary radioactive decay events nor nuclear fission and fusion events are energetic enough to produce muons. Nuclear fission produces energies in this range, but due to non conservation of lepton number they are not produced.

On earth, most naturally occurring muons are created by cosmic rays,originating from outer space. About 89% cosmic rays consist of protons, 10% being helium nuclei, 1% are heavier elements, and about 1% of electrons. When cosmic ray protons, of energy in the order of GeV, impact atomic nuclei of air atoms in the upper atmosphere produce a shower of particles including neutral and charged pions known as secondary cosmic rays. The neutral pions decay quickly into photons which multiply into showers, while the charged pions decay into a muon and a neutrino (or) anti-neutrino.

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



Many of the new particles are very short-lived and do not survive to reach sea level, but the muons travel almost at the speed of light and are detectable at the ground level. The reason is that due to their heavier mass, muons do not emit as much bremsstrahlung radiation and they can penetrate through the matter easily and their average flux at the sea level is 1 muon per minute per centimeter square. At sea level we have roughly 75% of positive and negative muons and 25% of electrons and positrons.

Muon interactions with matter:

Muons participate in electromagnetic and weak interactions, but not in strong interactions. A negative muon can disappear either captured by a nucleus by emitting neutron or by spontaneous decay to an electron:

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

(or)

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

and positive muon decays spontaneously into positron:

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

Time Dilation and Length Contraction:

Muons have a mean life time of about 2.2 μs in its rest frame. By assuming muon velocity is close to the velocity of light, we find that they could travel a distance of about 650m before they decay, i.e., they should not reach the earth from the upper atmosphere where most of them are produced at about 4km above from the earth surface.

We can explain this by relativistic time dilation:

$$t = \frac{t'}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma t'$$

where,

t = time measured in the lab frame of the system,

t' = time measured in the rest frame of the system = 2.2 μs .

v = velocity of the system,

c = velocity of light.

For v = 0.99c, $\gamma = 7.089$ => $t = \gamma t' = 15.59$ μs , and the average distance traveled by the muon for the observer on the ground is 4632m.

The distribution of muon decay time is given by

$$N_t = N_0 e^{-t/\tau},$$

which is same as the general radioactive decays.

Here, N_0 = initial population of muons,

N_t = muons at time 't',

and τ = muon mean life time.

The Experimental setup:

The basic components which are used in the experiment are

- Plastic Scintillator
- Photomultiplier Tube
- Time Measuring Circuit
- Computer.

Plastic Scintillator:

When a particle interacts with some material, the atoms in that material may get excite and by the de-excitation process they can emit photons, the process is called scintillation and the material is called scintillator. Plastic scintillators are solutions of organic scintillators in a solvent which is subsequently polymerized to form a solid.

The detector here we used is Bicron-404 plastic scintillator and it is Anthracene scintillator in polyvinyltoluene as a solvent . The dimensions of this scintillator are 24cmx24cmx14.5cm. It is wrapped with "Tybec" paper, a light preventing material followed by a black paper called "Tedler" to prevent interaction of light with scintillator material and hence to minimize stray scintillation.

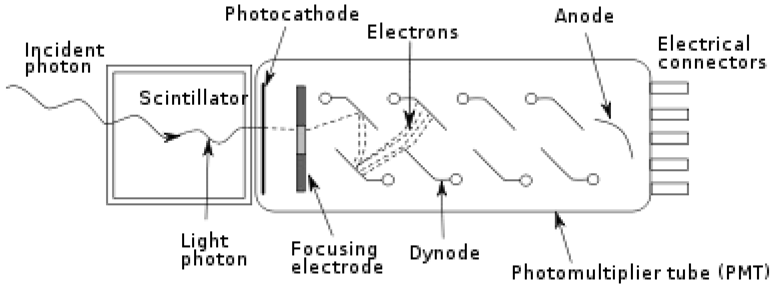
General Features:

- Gives fast signal and a high light output.
- They can very easily shaped and machined to the forms of desired detectors.
- Relatively inexpensive.

Other details are in Appendix.

Photomultiplier Tube:

Photo multipliers are constructed from a glass envelope with a high vacuum inside, which houses a photocathode, several dynodes, and an anode. Photons from the scintillator strike the photo cathode material, which is present as a thin deposit on the entry window of the device, with electrons produced as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where the electrons are multiplied by the process of secondary emission.



The electron multiplier consists of cascade of electrodes called dynodes where each of them is held at a more positive voltage than the previous one. The electrons leave the photocathode, having the energy of the incoming photon minus the work function of the photocathode. As the electrons move toward the first dynode, they are accelerated by the electric field and arrive with much greater energy and upon striking the first dynode more low energy electrons are emitted, and these electrons in turn are accelerated toward the second dynode. In this way each dynode accelerate electrons to the next one in the cascade by increasing electron number at each stage and finally the electrons reach the anode, where the accumulation of charge results in a sharp current pulse indicating the arrival of a photon at the photocathode.

The PMT used in this experiment is bialkali photocathode type and is a 2 inch diameter one, with a 21 pin base and manufactured by 9807B Electron Tubes Ltd.. The PMT is operated at high voltage of about 1.8kV by means of high voltage dc to dc converter(E20-HVDCDC).

The sensitivity of photocathode is expressed by the quantum efficiency η,

$$\eta = \frac{\text{number of photoelectrons released}}{\text{number of incident photons on cathode}}.$$

For an ideal Photocathode the quantum efficiency should be 100% but in practical case it is about 20-30% .

And the efficiency of a dynode is determined by the multiplication factor δ ,

$$\delta = \frac{\textit{number of secondary electrons emitted}}{\textit{primary incident electron}}.$$

Time Measuring Circuit:

Shape of the PMT Pulses:

The shape of the pulses formed by muon and electron which are fed to the PMT to produce negative pulses at the output are shown below:

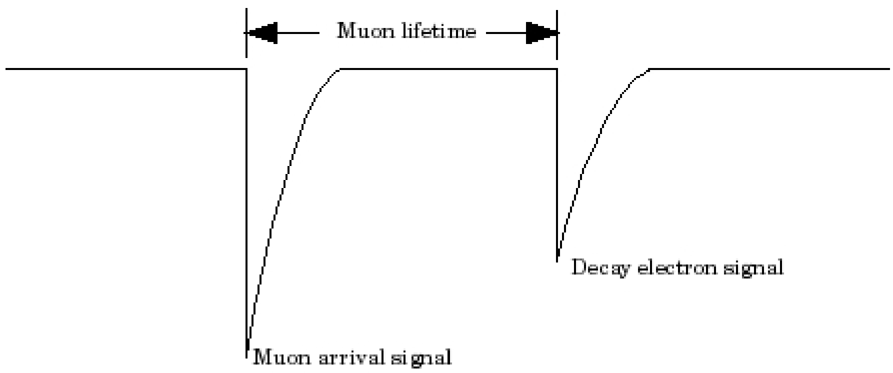


Fig: Output of signal of PMT

Details of IC:

The main components and their functions which are used in the circuit are as tabulated below:

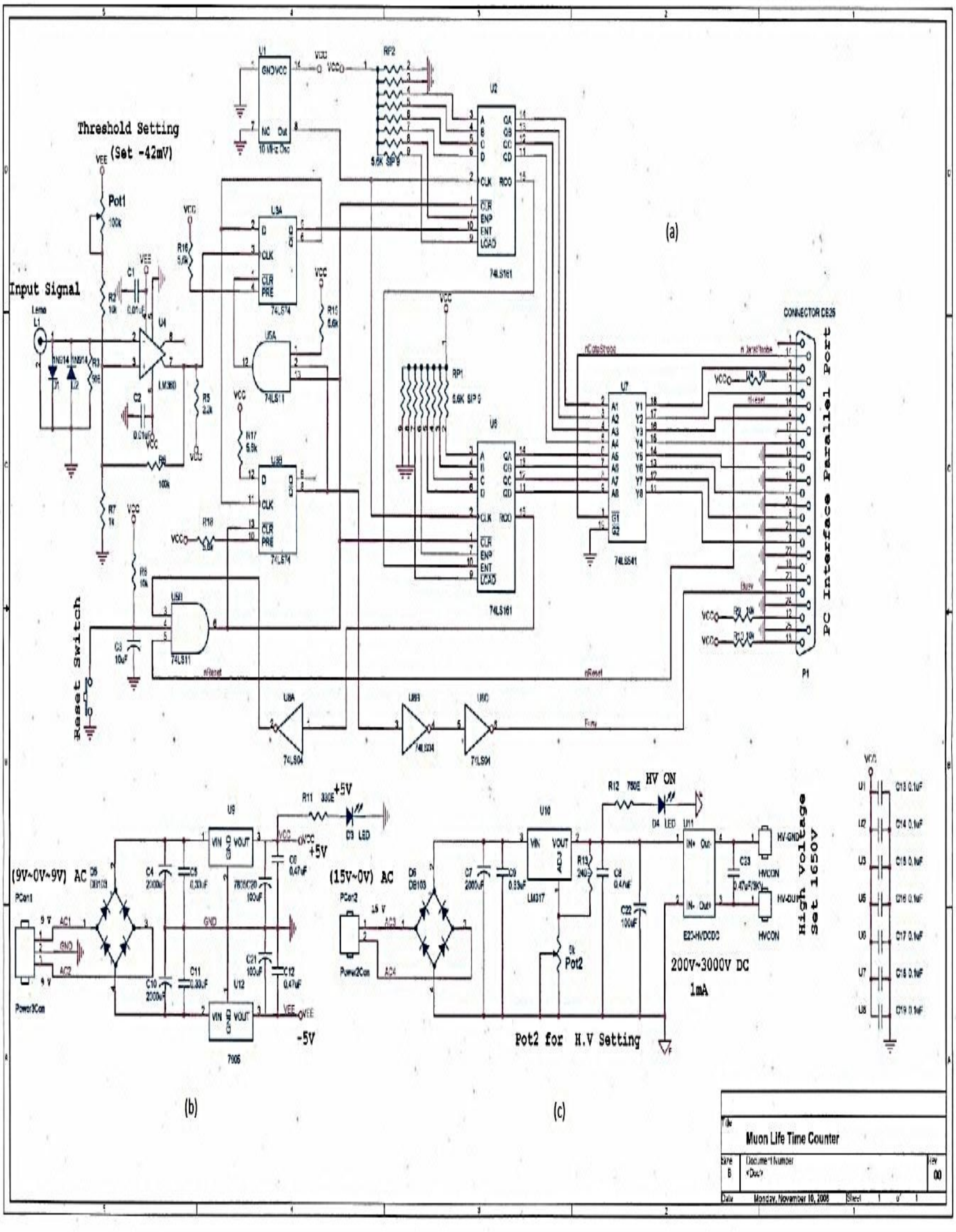
IC	FUNCTION
LM360 (8 pins)	Comparator
74LS74 (14 pins)	D-Flip Flop
74LS161 (16 pins)	4 – bit counter
74LS541 (20 pins)	Buffer
74LS11 (14 pins)	AND gate
74LS04 (14 pins)	NOT gate
7805 (3 pins)	Positive voltage regulator
7905 (3 pins)	Negative voltage regulator
DB103 (4 pins)	Bridge rectifier

The circuit is fed by 10MHz Oscillator with 0.1 μs resolution. The two 4-bit counters in the circuit helps to measure the time interval of 0.1 to 25.5 μs .

Circuit Operation:

The signal from the PMT appears at Lemo, L1, and it may contains noise and the actual signal rides over this noise. If present, the noise can trigger the counters and gives the false results. Hence the negative analog pulse from the PMT is fed to the comparator U4, whose threshold voltage set at -42mV at the non inverting terminal, and it filters out the noise by allowing only those signals to generate high logic pulse whose levels are above the threshold voltage. The output of the comparator is positive high logic pulse of 5V, since the negative input signal is fed into the inverting terminal.

The positive signal from the output of comparator is fed as CLK to the D-Flip Flop,U3A. At initial stage the Q and $\bar{Q}$ of both Flip Flops are LOW and HIGH respectively and D also HIGH. When muon enters into the scintillator the signal due to it triggers U3A as CLK, D flips its state to LOW and due to this $\bar{Q}$ becomes LOW and Q becomes HIGH. Then 4-bit counter U2 is enable to count at 10MHz. At the same time $\bar{Q}$ of first Flip Flop goes as LOW CLK to the second Flip Flop U3B and due to this LOW CLK Q and $\bar{Q}$ of the second Flip Flop remains as initial. This HIGH $\bar{Q}$ goes as Busy to Parallel Port to tell that the counters are busy in counting.


Threshold Setting
(Set -42mV)
Input Signal
Reset Switch
(a)
CONNECTOR DB25
PC Interface Parallel Port
74LS161
74LS74
74LS11
74LS04
74LS541
10 MHz Osc
LM360
(9V~0V~9V) AC
+5V
-5V
(b)
(15V~0V) AC
HV ON
LM317
High Voltage Set 1650V
200V~3000V DC
1mA
Pot2 for H.V Setting
(c)
Muon Life Time Counter
Monday, November 10, 2008

Now we consider two cases that when muon decays to electron and when it doesn't decay.

When muon decays to electron:

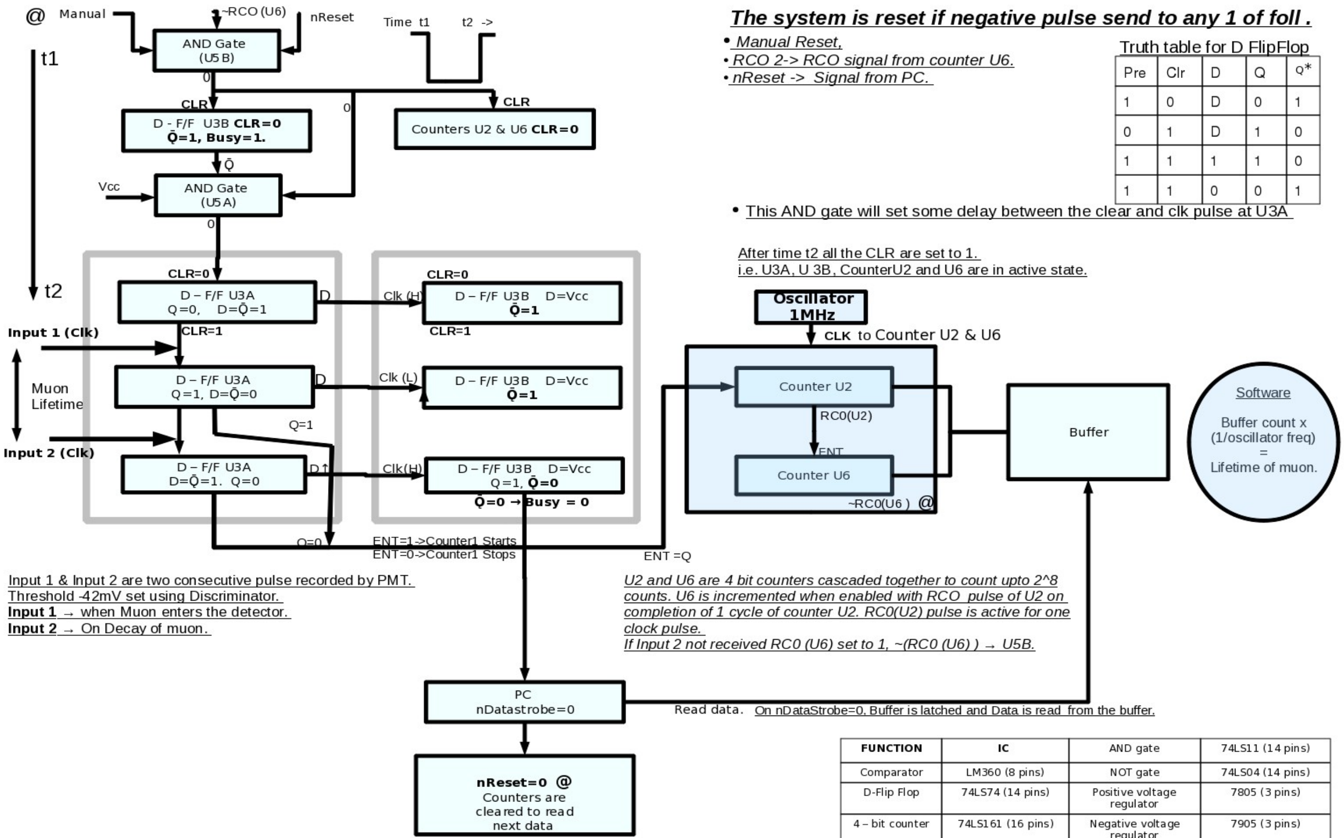
When muon decays to electron, the signal due to it passes through the comparator and it triggers U3A as another CLK. Then D flips to HIGH and $\bar{Q}$ of U3A becomes HIGH and Q becomes LOW. Now HIGH $\bar{Q}$ of U3A goes as HIGH CLK and it triggers U3B and its $\bar{Q}$ becomes LOW and this LOW goes as Busy to parallel Port to instruct the PC to read the data. The PC makes “nDataStrobe” LOW and reads the data from the Buffer. After reading the data, PC makes “nDataStrobe” HIGH and it lowers the “nReset”, which is connected to the AND gate U5B, for a few microseconds. The output of this AND gate clears the Counters and Flip Flops to become reset and ready for the new data.

Now we discuss the counting system. Both counters which are used in our circuit are 4-bit. The CLK from the 10MHz Oscillator U1, is common to both of these counters and the counter starts counting only when its Enable(ENT) is HIGH. After initiation of the counting, U2 can count up to 1.5 μs and if the electron signal comes with in this interval after decaying of muon, the counting will stop and PC reads the data as above. If the time exceeds 1.5 μs , the RCO of U2 becomes HIGH and this enables the second oscillator U6. At the same time U6 utilizes the common CLK from the Oscillator to record one count and this cycle repeats at every 1.6 μs . Here the second counter U6 record the number of 1.6 μs and in this way up to 25.5 μs can be counted by using the two counters. The buffer records this data.

When muon doesn't decay:

When muon passes the scintillator with out decaying, there will be no second pulse. Then U6 counts up to 25.5 μs and its RCO becomes HIGH, which is inverted by the NOT gate U8A, connected to AND gate U5B. The output of this AND gate clears the Flip Flops and Counters to make ready for the new data.

The below flow chart gives the working of the whole circuit.



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

Data Analysis:

The data file is saved in a column as different time intervals for each muon decay, i.e., the time lag between the start event and stop event. The data obtained may also contain background, which arise due to some other radio active sources or a muon coming before the decay of the previous one or light leakage through the scintillator. The background events which are produced due to start from one muon and stop from another will be very small as the muon flux reaching the sea level is 1 muon /sq.cm/min. , which is very small as compared to 25.5 μs window we put for counting.

Assuming the background to be constant over period of time we can write the statistical distribution of muon decay as:

$$N_t = N_0 e^{-t/\tau} + b\,,$$

where 'b' is a constant.

The data is binned using a C++ program and the following plots are obtained using ROOT.

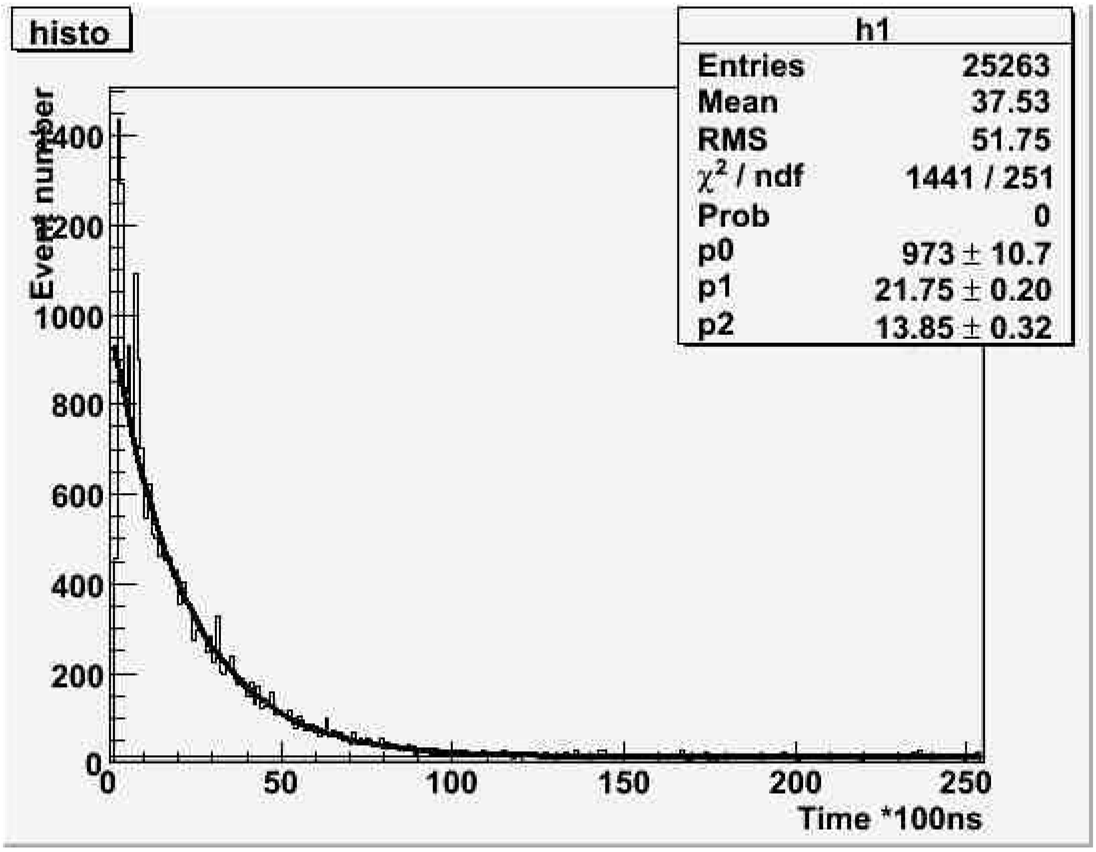


Fig: Plot of number of events with time

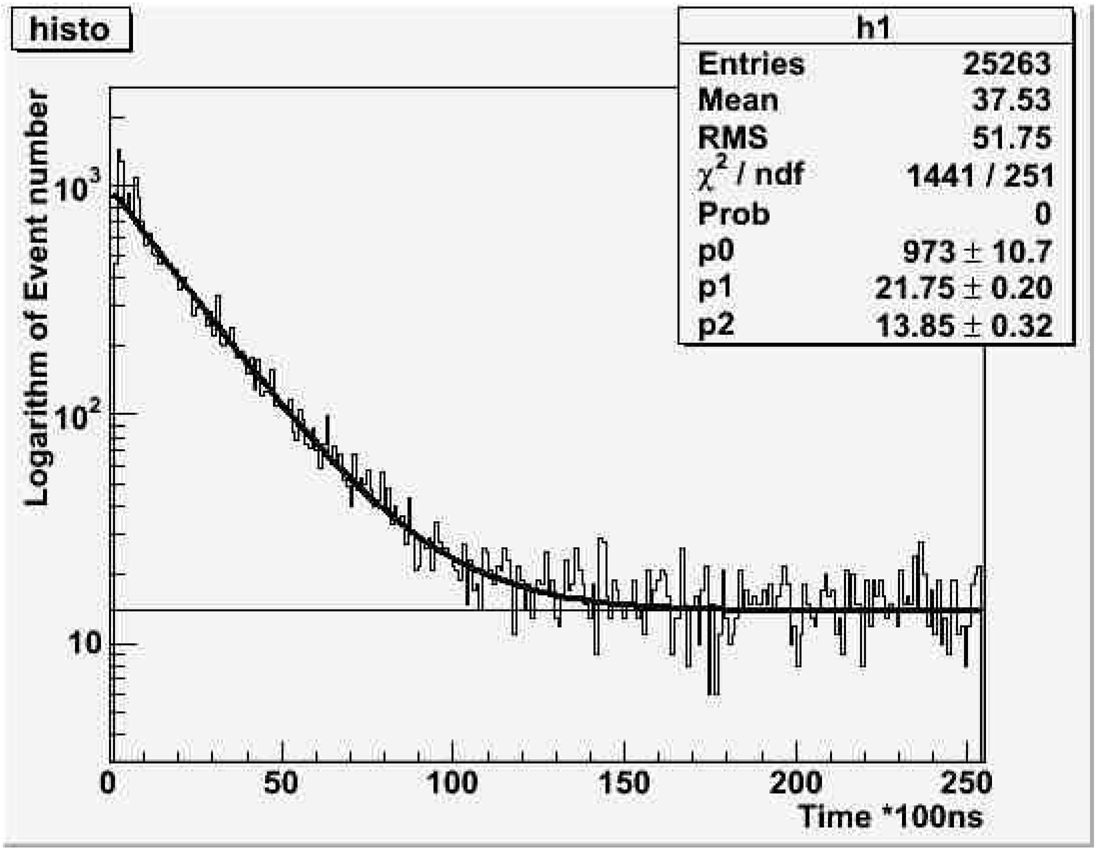


Fig: Plot of number of events in logarithmic scale with time

The fitted parameters are obtained as:

$$N_0 = 973 \pm 10.7$$

$$\tau = 2.175 \pm 0.02 \mu s$$

$$b = 13.85 \pm 0.32$$

Therefore the muon mean life time of muon obtained from our experiment is

$$\tau = 2.175 \pm 0.02 \mu s$$

.

Results and Conclusions:

Our experimentally determined muon life time is 2.175 μs and from standard model it is 2.197 μs . This difference in muon life time was resolved by analyzing the cable delays, muon capture by nucleus, and the formation of muonium atom.

The Fermi Coupling Constant can be calculated from our experimentally determined muon mean life time (τ) by using the expression:

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

This gives as

$$G_F = \left(\frac{192\pi^3}{\tau m_\mu{}^5}\right)^{1/2}.$$

Now by taking our measured muon life time τ =2.175 μs and mass of the muon m_μ =105.7MeV , we get the value of Fermi Coupling Constant as:

$$G_F = 1.1684 \times 10^{-5} (\mathrm{GeV})^{-2}$$

Acknowledgments:

I would like to thank to our Prof. Naba K Mondal for providing this great opportunity. I would also like to thank to Dr. Satyanarayana and Mr. L V Reddy for guiding us to do this experiment. I would like to thank to my seniors and colleagues who answered all my questions.

References:

1) "Techniques for Nuclear and Particle Physics Experiments", by W. R. Leo.
2) "Radiation Detection and Measurement", by Glenn F. Knoll.
3) "Introduction to Elementary Particles", by David J. Griffiths.
4) "The Measurement, Simulation, and Interpretation of the Life Time of Cosmic Muons" , by Matthew E. Thrasher.
5) About Plastic Scintillator and PMT from "Saint- Gobain Crystals ".
6) Truth Table of D- Flip Flop from "Fairchild Semiconductor Corporation".

Appendix:

Plastic Scintillator:

The following table gives the details about the scintillator used in this experiment:

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

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	$30x10^6$

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.