MUON LIFETIME MEASUREMENT USING STOPPED COSMIC MUONS IN A PLASTIC SCINTILLATOR DETECTOR

EXPERIMENTAL REPORT SUBMITTED TO INO FOR THE PARTIAL FULFILMENT OF COURSE WORK FOR THE "INO GRADUATE SCHOOL"

BY

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ABSTRACT

Muon, a fundamental particle in the standard model and belongs to the family of lepton. It was first discovered in 1937 by J. C. Street and E. C. Stevenson in a cloud chamber. Measurement of lifetime of muons provided an early test for relativistic time dilations. It is now known that lifetime of muon is 2.19micro seconds. In this experiment we intent to measure the lifetime of muons. Muon are produced in the upper atmosphere by the decay of cosmic ray pions. Muon thus produce reach the earth's surface. Muons being charged particle losses its energy on passing through the scintillation detector and if completely stopped it decays into electrons and neutrinos. The difference in time between the signal produced when it enters the detector and when on it decay gives value of lifetime of that muons. In this experiment we intent to measure the lifetime of the muon.

CHAPTER- 1

1.1 Introduction:-

The muon is one of nature's fundamental "building blocks of matter". It is an elementary particle belonging to second generation of the family of Leptons and acts in many ways as if it was an unstable heavy electron, for reasons no one fully understands. The muon was discovered by J. C. Street and E. C. Stevenson at Harvard University and almost simultaneously at Caltech by C.D. Anderson and S. H. Neddermeyer in 1937. The subsequent work of Millikan, Anderson, Neddermeyer, Neher, Stever and Leighton during the decade preceding, and the years immediately following World War II helped establish the foundations of cosmic ray physics. Natural muons continue to be of interest in many areas of physics, while the production of intense beams of the artificial variety at various "meson factories", permits exploiting the muon's large magnetic moment, violation of parity, and unique ability to closely approach nuclei, and to develop the muon spin relaxation techniques that provide for an exceptional sensitivity in investigating the structure of materials. Its finite lifetime was first demonstrated in 1941 by F. Rasetti.

1.2 Muons:-

Muons (+ or -) carry the same charge as an electron, with a mass 206.8 times larger. Their kinetic energy is from zero to many GeV, they have a spin of 1/2, and a magnetic dipole moment 3.18 times that of the proton. The μ- disappears in either of two ways; capture by a nucleus, with the emission of a neutrino and a neutron, or by spontaneous decay to an electron and neutrino-anti-neutrino pair after coming to rest: $\mu^- \rightarrow e^- + \nu_e + \nu_\mu$. The probability of capture by a nucleus is small for low Z materials but increases rapidly with increasing Z. The μ+, strongly repulsed by nuclei, have only the decay path: $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$. Energy losses are by ionization until they come to rest. The subsequent decay-electron spectrum is a continuum with a shape similar to a β-spectrum, with an energy range from near zero to an end point of about 53 MeV. While the lifetimes for a μ+ and a μ- are the same (2.1970 μs), the measured mean lifetime in matter becomes shorter for the μ- with increasing Z because of the competing capture by nuclei. Lifetime measurement must be examined carefully since it will most probably be a composite value for the lifetimes of both μ+ and μ-.

1.3 Our muon source:-

The top of earth's atmosphere is bombarded by a flux of high energy charged particles produced in other parts of the universe by mechanisms that are not yet fully understood. The composition of these "primary cosmic rays" is somewhat energy dependent but a useful approximation is that 98% of these particles are protons or heavier nuclei and 2% are electrons. Of the protons and nuclei, about 87% are protons, 12% helium nuclei and the balance are still heavier nuclei that are the end products of stellar nucleosynthesis.

The primary cosmic rays, consisting of the extremely high energy (>10^9 eV) protons, α-particles, and a few light nuclei collide with the nuclei of air molecules and produce a shower of particles that include protons, neutrons, pions (both charged and neutral), kaons, photons, electrons and positrons. These secondary particles then undergo electromagnetic and nuclear interactions to produce yet additional particles in a cascade process. Figure 1 indicates the general idea. Of particular interest is the fate of the charged pions produced in the cascade. Some of these will interact via the strong force with air molecule nuclei but others will spontaneously decay (indicated by the arrow) via the weak force into a muon plus a neutrino or antineutrino:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\pi^- \rightarrow \mu^- + \nu_\mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The schematic diagram is shown below:-

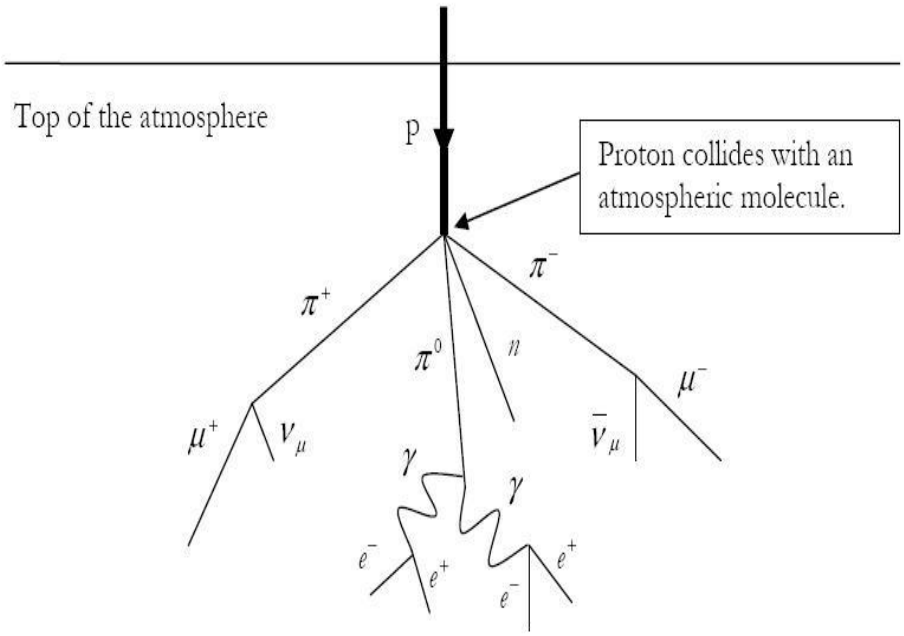


Fig. 1:- The cosmic ray shower enjoyed by us.

The muon does not interact with matter via the strong force but only through the weak and electromagnetic forces. It travels a relatively long instance while losing its kinetic energy and decays by the weak force into an electron plus a neutrino and antineutrino. We will detect the decays of some of the muons produced in the cascade. (Our detection efficiency for the neutrinos and antineutrinos is utterly negligible.) Not all of the particles produced in the cascade in the upper atmosphere survive down to sea-level due to their interaction with atmospheric nuclei and their own spontaneous decay. The flux of sea-level muons is approximately 1 per minute per cm^2 with a mean kinetic energy of about 4 GeV.

Careful study shows that the mean production height in the atmosphere of the muons detected at sea-level is approximately 15 km. Travelling at the speed of light, the transit time from production point to sea-level is then 50 μsec. Since the lifetime of at rest muons is more than a factor of 20 smaller, the appearance of an appreciable sea level muon flux is qualitative evidence for the time dilation effect of special relativity. This can be explained by relativistic time dilation:

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

Where, t' is the time measured in the lab frame of the system.
t is the time measured in the rest frame of the syatem.
v is the velocity of the system.
c is the velocity of the light.

If $v = 0.99\,c$, t'=2.1970 μs (average lifetime of muon), then the calculated value of "t" comes out to be 15.575 μs. Hence the average distance travelled by muon as measured by an observer on earth is 4672.5m.

1.4 <u>Muon decay</u>:-

A μ^- can disappear either by capture by a nucleus with the emission of a neutrino and a neutron

$$\mu^- + p \rightarrow n + \nu_\mu \qquad \text{.......................... (3)}$$

Or by spontaneous decay to an electron, a neutrino and anti-neutrino pair.

$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu \qquad \text{............................ (4)}$$

The probability of μ^+ capture by a nucleus for low Z material is small, but increases rapidly with increasing Z. The is strongly repulsed by the nucleus and has only the decay path

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \qquad \text{........................... (5)}$$

The lifetime of both μ– and μ^+ are the same (about 2.1970 μs), however, the lifetime of μ^- in matter becomes shorter with increasing Z because of the nuclei capture.

The decay times for muons are easily described mathematically. Suppose at some time "t" we have N(t) muons. If the probability that a muon decays in some small time interval "dt" is "λdt", where, λ is a constant called "decay rate" that characterizes how rapidly a muon decays, then the change "dN" in our population of muons is just

$$dN = -N(t)\lambda dt$$

$$\frac{dN}{dt} = -\lambda dt$$

Integrating, we have,

$$N(t) = N_0 \exp(-\lambda t) \qquad \text{...................... (6)}$$

Where,

N(t) is the number of surviving muons at some time t.
N_0 is the number of muons at t = 0.

The lifetime "t" of a muon is the reciprocal of λ, $\tau = 1/\lambda$. This simple exponential relation is typical of radioactive decay.
Now, we do not have a single clump of muons whose surviving number we can easily measure. Instead, we detect muon decays from muons that enter our detector at essentially random times, typically one at a time. It is still the case that their decay time distribution has a simple exponential form of the type described above. By decay time distribution D(t), we mean that the time-dependent probability that a muon decays in the time interval between t and t + dt is given by D(t)dt. If we had started with N_0 muons, then the fraction ($-dN/N_0$) that would on average decay in the time interval between t and (t + dt) is just given by differentiating equation (6)

$$-dN = N_0 \lambda e^{-\lambda t} dt$$

$$-\frac{dN}{N_0} = \lambda e^{-\lambda t} dt$$

The left-hand side of the last equation is nothing more than the decay probability we seek, so

$$D(t) = \lambda \exp(-\lambda t).$$

This is true regardless of the starting value of N_0. That is, the distribution of decay times, for new muons entering our detector, is also exponential with the very same exponent used to describe the surviving population of muons. Again, what we call the muon lifetime is,

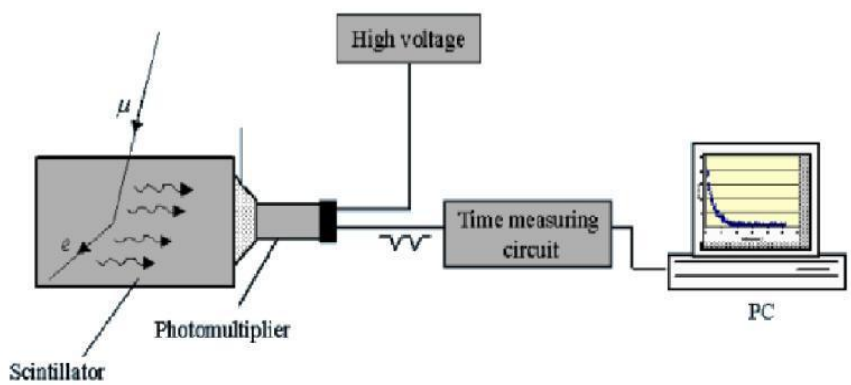
$$\tau = \frac{1}{\lambda}$$

Because the muon decay time is exponentially distributed, it does not matter that the muons whose decays we detect are not born in the detector but somewhere above us in the atmosphere. An exponential function always "looks the same" in the sense that whether you examine it at early times or late times, its e-folding time is the same.

1.5 **Detection techniques**:-

The active volume of the detector is a plastic scintillator. Plastic scintillator is transparent organic material made by mixing together one or more fluors with a solid plastic solvent that has an aromatic ring structure. A charged particle passing through the scintillator will lose some of its kinetic energy by ionization and atomic excitation of the solvent molecules. Some of this deposited energy is then transferred to the fluor molecules whose electrons are then promoted to excited states. Upon radiative de-excitation, light in the blue and near-UV portion of the electromagnetic spectrum is emitted with a typical decay time of a few nanoseconds. A typical photon yield for a plastic scintillator is 1 optical photon emitted per 100 eV of deposited energy.

To measure the muon's lifetime, we are interested in only those muons that enter, slow, stop and then decay inside the plastic scintillator. Figure 2 summarizes this process. Such muons have a total energy of only about 160 MeV as they enter the tube. As a muon slows to a stop, the excited scintillator emits light that is detected by a photomultiplier tube (PMT), eventually producing a logic signal that triggers a timing clock. (See the electronics section below for more detail.) A stopped muon, after a bit, decays into an electron, a neutrino and an anti-neutrino. Since the electron mass is so much smaller that the muon mass, $m_\mu/m_e \sim 210$, the electron tends to be very energetic and to produce scintillator light essentially all along its pathlength. The neutrino and anti-neutrino also share some of the muon's total energy but they entirely escape detection. This second burst of scintillator light is also seen by the PMT and used to trigger the timing clock. The distribution of time intervals between successive clock triggers for a set of muon decays is the physically interesting quantity used to measure the muon lifetime.



CHAPTER- 2

2.1 <u>Experimental set up</u>:-

The experimental set up to measure the lifetime of muon consists of the following:

i. Plastic scintillator.
ii. Photo-multiplier tube.
iii. Time measuring circuit.
iv. Computer.

The experimental set up is shown in the diagram below.

Fig. 2:- Schematic experimental set up to measure average muon life time.

1) <u>Plastic scintillator</u>:-

There are some materials which shows scintillation property (the property of luminescence), when excited by ionization radiation. These materials, when struck by an incoming particle, absorb its energy and re-emit the absorbed energy in the form of light. A scintillator detector is made by coupling a scintillator with an electronic light sensor e.g. PMT (photo multiplier tube).

Plastic scintillators are solutions of organic scintillators in a solvent which is subsequently polymerized to form a solid. Some of the common solutes are p-Terphenyl, PBD, b-PBD, PBO,POPOP. The most widely used plastic solvents are polyvinyltoluene and polystyrene. They give a fast signal (a few ns) and a high light output.

The scintillator which we are using for this experiment is also a plastic scintillator. It is an Organic Fluor – polyvinyltoluene plastic scintillator. The dimensions are 24 cm x 24 cm x 14.5 cm. 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 details of the plastic scintillator we are using are tabulated below:-

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.

2) **Photo-multiplier tubes**:-

A PMT (Photo-multiplier tube) is a device which is very sensitive to light and hence used to detect light signals in the ultra-violet, visible and near infra red regions of electromagnetic spectrum. These are the members of a class of vacuum tubes. A typical PMT is made of a glass envelope with a high vacuum inside. In one end of the tube, we have a cathode and in the other end we have an anode. In between these two electrodes we have several other electrodes called “dynodes”. A very high voltage typically in the order of few kV is applied between the cathode and the anode. The cathode is coated with photo sensitive material, rich in free electrons and hence undergoes photo-electric effect when struck by light created due scintillation. Each dynode is maintained at a higher potential than the previous dynode. When an electron emitted from cathode hits the first dynode, it causes secondary emission in the dynode and these secondary electrons hit the next dynode resulting into further secondary emission. This produces millions of electrons at the anode. The geometry of the dynode chain is such that a cascade occurs with an ever-increasing number of electrons being produced at each stage. A schematic diagram of a PMT connected to a scintillator is shown below :-

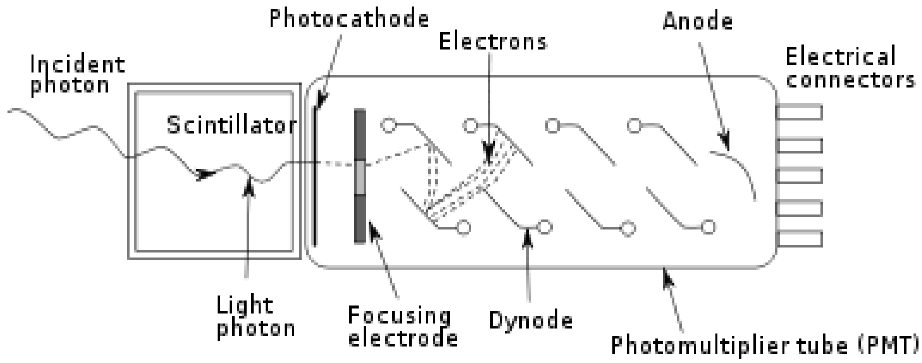


Fig. 3:- Working of a PMT

The details of the PMT being used is tabulated below:-

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	$30x10^6$

3) Time measuring circuit:-

The main components of the time measuring circuit (fig. 4) are 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 a 10 MHz oscillator resulting the least count of the time in the circuit to be 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.

2.2) <u>Working of the circuit</u>

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 of the CLR signal. 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 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.

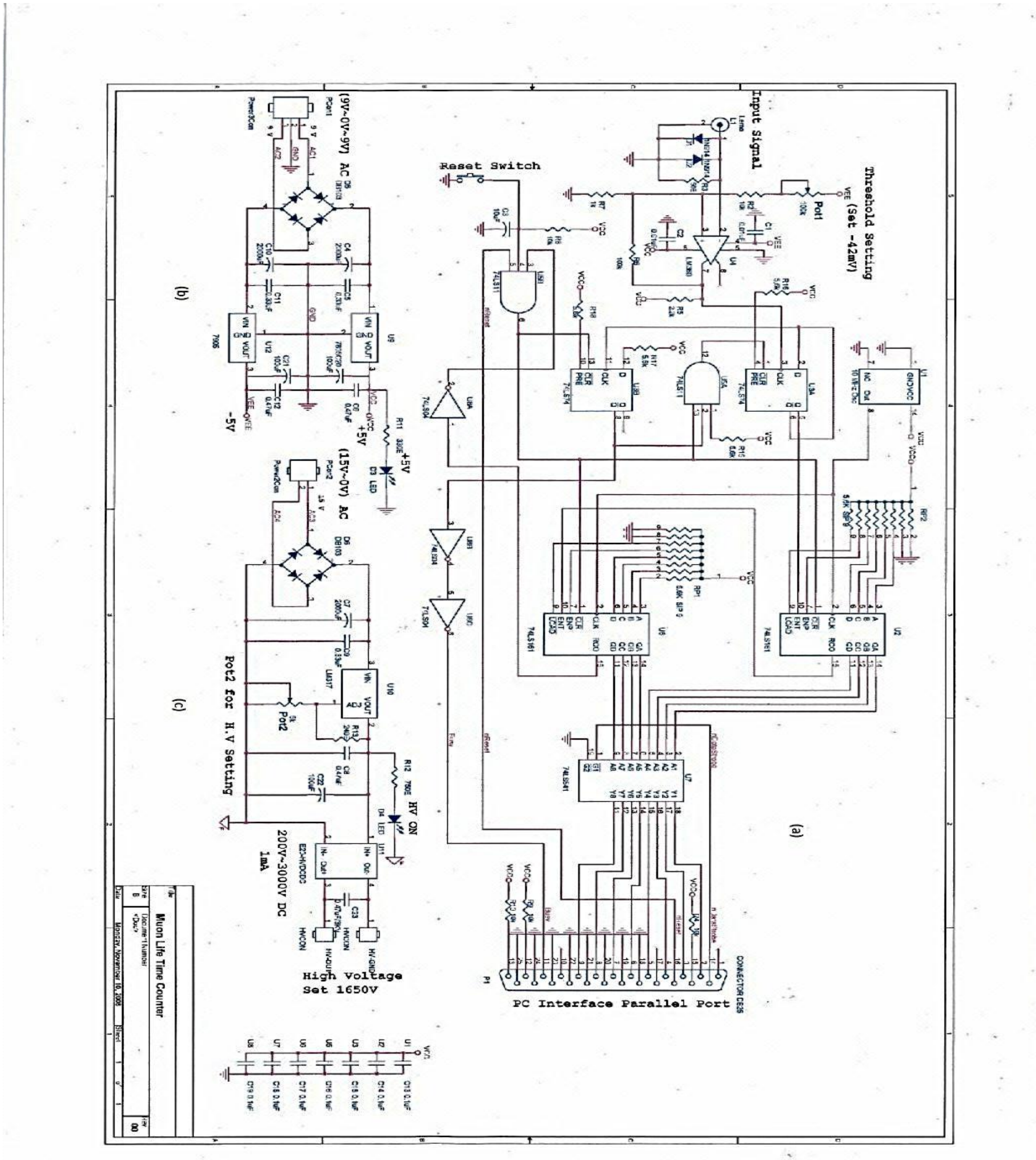
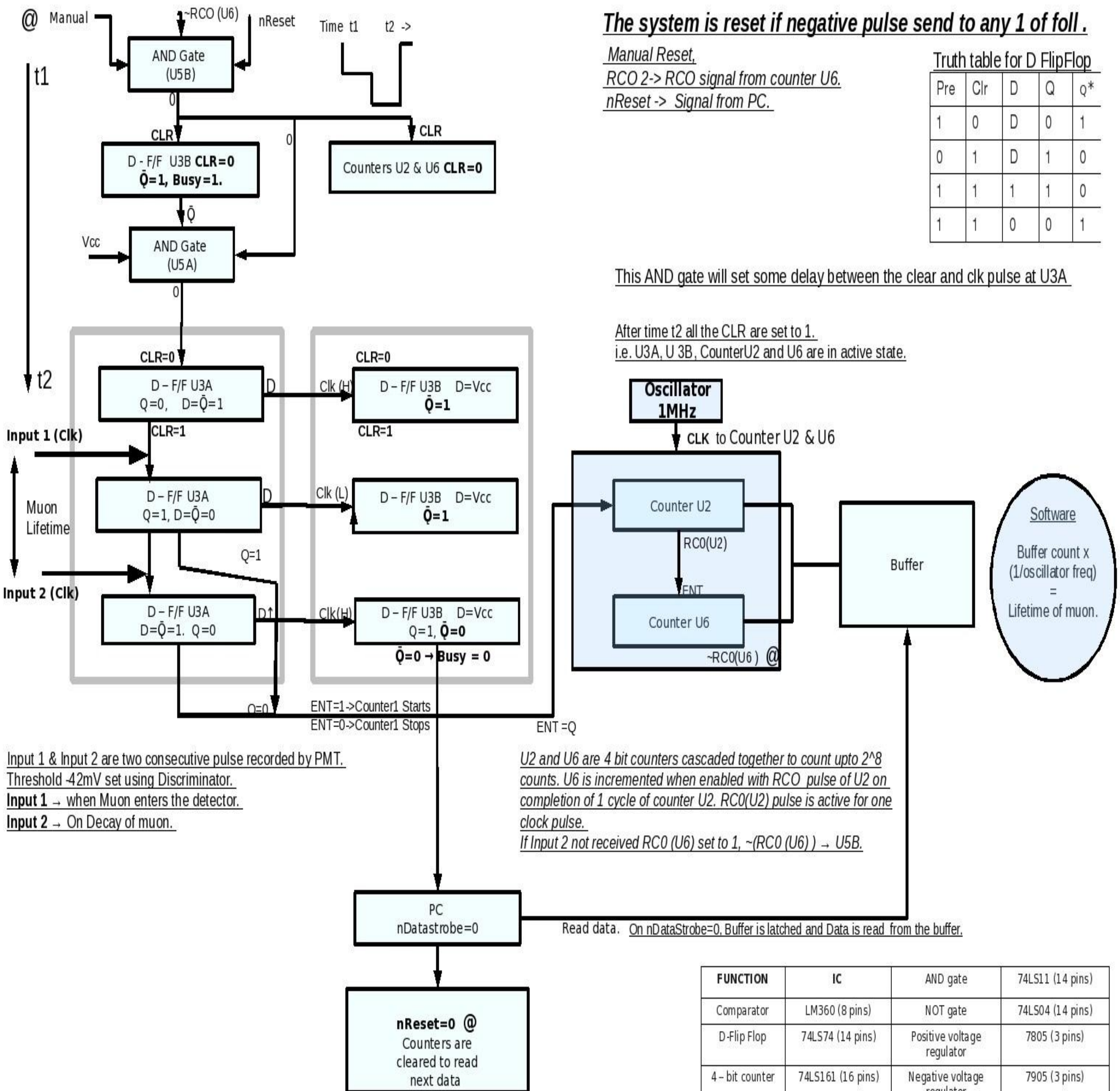


Fig. 4:- Circuit diagram of the detector used.



Pre	Clr	D	Q	Q*
1	0	D	0	1
0	1	D	1	0
1	1	1	1	0
1	1	0	0	1

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)

Fig. 5:- Flow-chart explaining the working of the time circuit.

CHAPTER- 3

3.1) OBSERVATIONS:-

The following figure shows the histogram without the logarithmic scale.

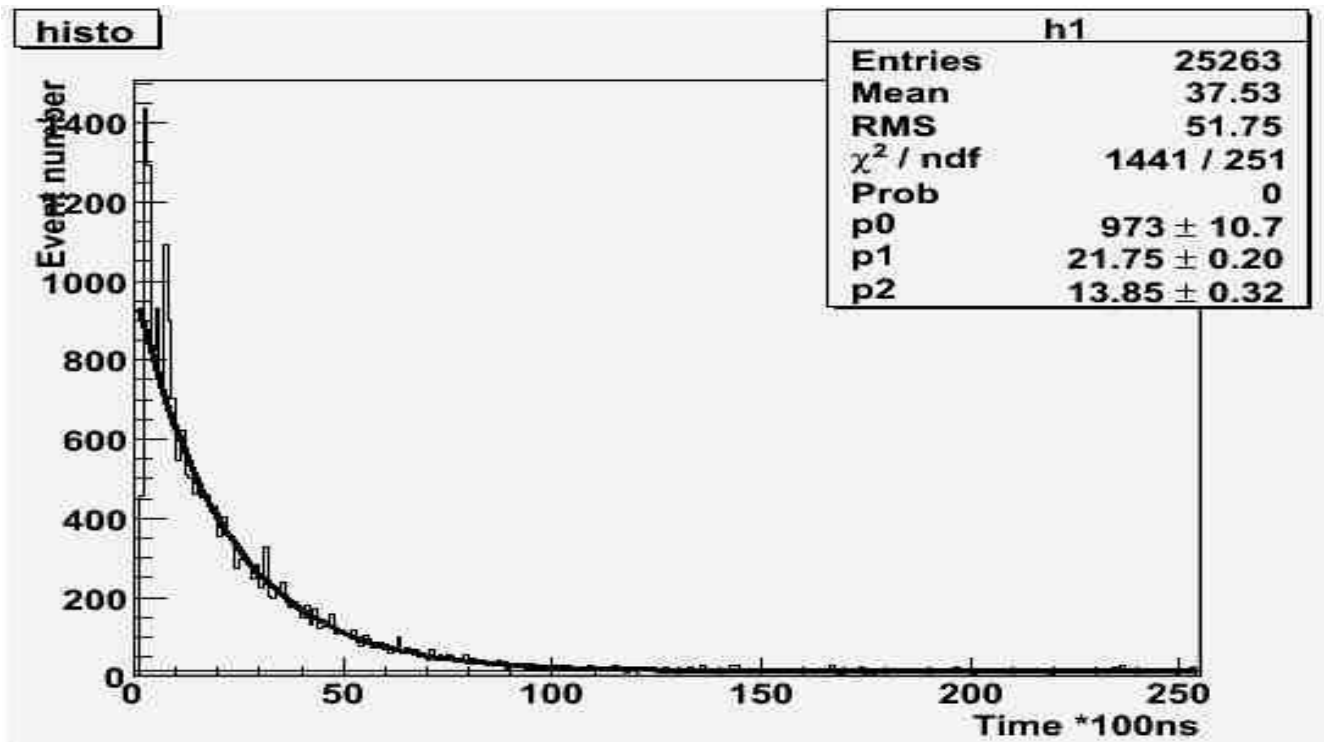


Fig. 6:- Histogram without log scale.

The following figure shows the plot with the logarithmic scale.

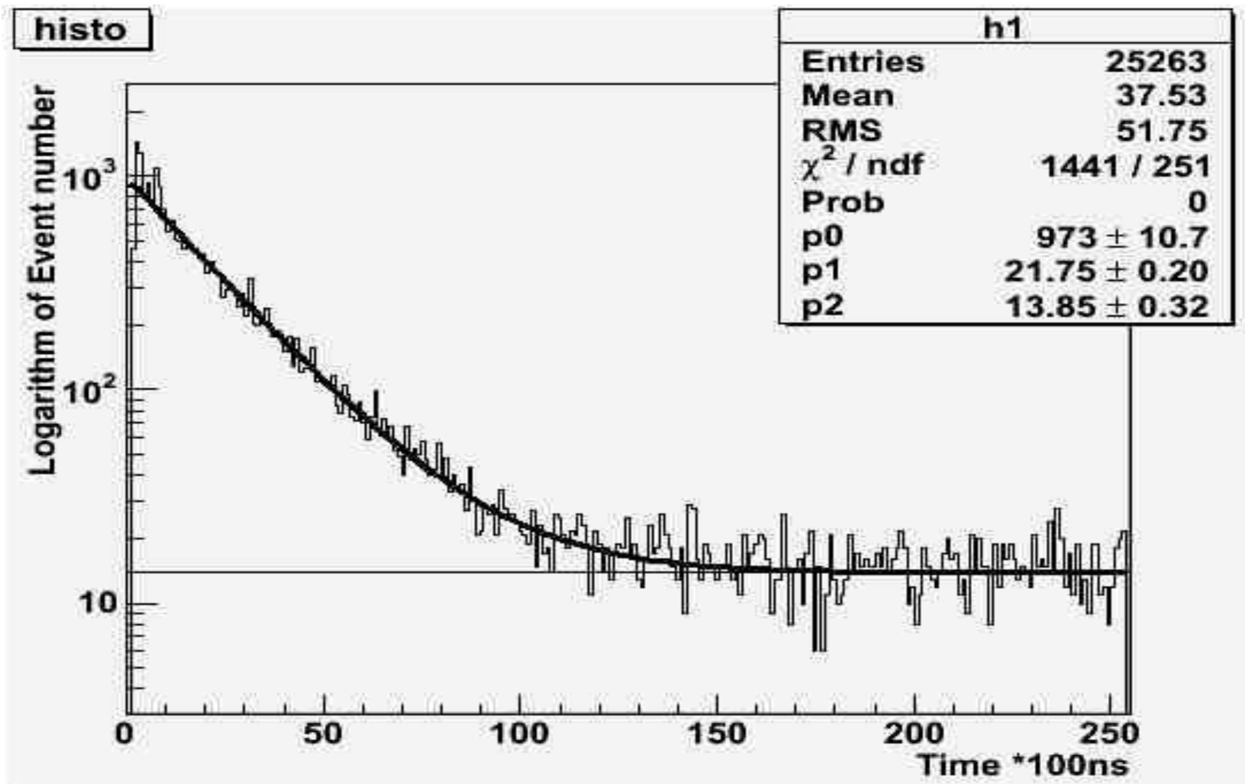


Fig. 7:- Histogram with log scale.

3.2) <u>RESULTS</u>:-

The above function (Equation (6)) is fitted to the data using ROOT. The values of the fitting parameters are

$$N_0 = 973 \pm 10.7$$

$$b = 13.85 \pm 0.32$$

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

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

Using the above calculated 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}.

3.3) <u>CONCLUSION</u>:-

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

The Fermi Coupling constant "G_F" was determined to be 1.1696×10^{-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 and muon capture.

3.4) <u>REFERENCES</u>:-

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4) ROOT user guide
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