MUON LIFETIME MEASUREMENT EXPERIMENT

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Abstract:

In this experiment we are measuring the time taken by a muon to decay into an electron. At first when cosmic ray muon passes through the scintillator, it produces light signal & when this light signal passes through the PMT, PMT produces electrical signal. This signal is then passes through a time measuring circuit, which starts counting in the counter. When muon decays into electron , it produces another signal, which stops the counting of the counter. So by counting no. of the counts (bits), we can measures the mean life time of muon.

Introduction:

Muons are the fundamental particles and belong to the lepton family. These fundamental particles are heavier than electrons, with mass of about 105.7Mev/c^2, carry one unit of fundamental charge and they are unstable. Muons participate in electromagnetic and weak interactions and are not subjected to strong interactions. The muons while passing through the matter, can disappear in anyone of the two ways. Either by capturing the nucleus in which case a neutron and neutrino are emitted or by spontaneous decay in which electron along with neutrino, antineutrino pair are produced.

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

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

These are electroweak decays as, two of the decay products are neutrinos.

Production of cosmic ray muon:

The particles arriving from space are known as primary cosmic rays and the particles created in the collisions are known as secondary cosmic ray. Most of the primary cosmic rays consist in upper atmosphere and interacts with the atmospheric nuclei such as nitrogen or oxygen producing secondary particles. These collisions produce mostly neutral and charged pions. These pions with a mass 273 times that of the electron are not stable and have a lifetime of about 10^{-8}secs. They decay into muons exponentially similar to radioactive nuclei. Each neutral pion decay into a pair of gamma rays and the charged pions decay into a charged muon and a muon neutrino .The sequence of events is illustrated in fig.1.

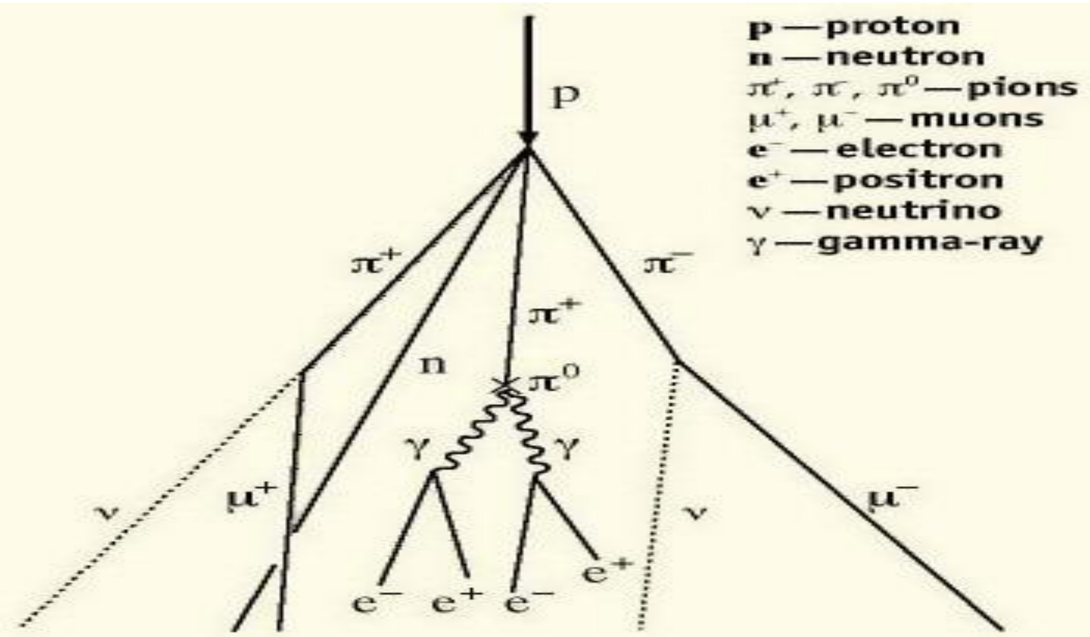

Fig 1. A typical interaction between a cosmic ray proton and an atmospheric nucleus.

The particles created in this interaction are mostly short lived. They cannot reach sea-level, but we can find muon at sea level. The total secondary flux at sea level is $1cm^{-2}min^{-1}$. Roughly 75% consists of positive and negative muons and only 25% electrons and positrons.

Principle of muon decay:

Muons have a lifetime of 2.2 μs when measured in its rest frame. Given this muon lifetime and assuming a velocity close to that of light, we would find that muons could only travel a distance of about 650 m before they decay. Hence classically, they could not reach the Earth from the upper atmosphere where they are produced. However, experiments show that a large number of muons do reach the Earth. This is due to the relativistic time dilation. As we are measuring the time from the lab frame, so the time actually measured from lab frame is

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

Where t' is the time measured in the rest frame of the muon and t is the time in the lab frame, v is the velocity of the muon. Relative to an observer on Earth, the muons have a lifetime equal to $\gamma t'$, where $t' = 2.2\mu s$ is the lifetime in a frame of reference travelling with the muons. For example, for v = 0.99c, $\gamma t' = 15.6\mu s$. Hence, the average distance travelled as measured by an observer on Earth is 4678.62m.

In this experiment muons are stopped by the scintillator and then it decays to electron. If N_0 be the initial muon coming to the scintillator (say at time t=0) then at any time t, decay is followed by this law

$$N = N_O e^{\frac{-t}{\tau}}$$

Where τ is the mean life time of the muon. The average muon life time is then determined by fitting *exp (-t/τ)* to the distribution of the time intervals between entry of muon stopped in plastic scintillator and their subsequent decay and determining the value of τ after correcting for the background.

Experimental arrangement:

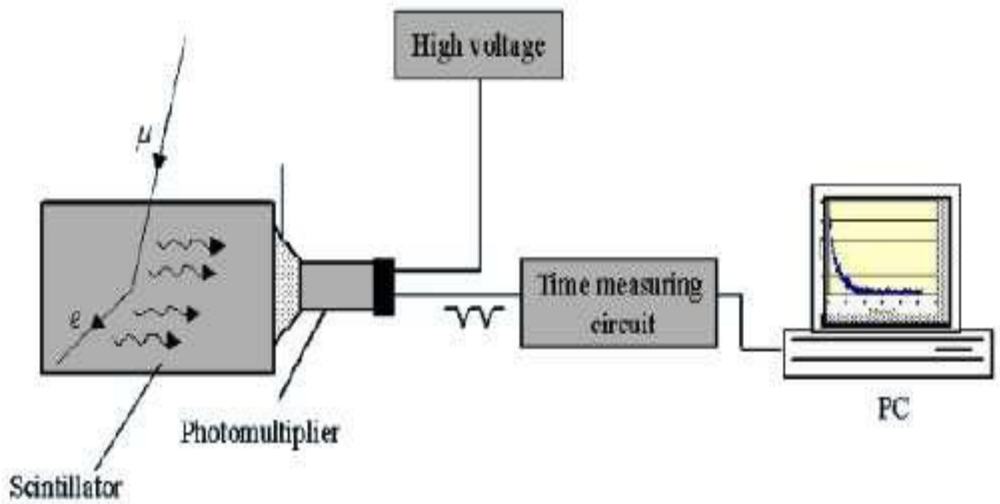

Fig 2. Block Diagram of Experimental Arrangement

The requirement for this circuit are

1. Plastic Scintillator
2. Photomultiplier tube(PMT)
3. Time measuring circuit

1) Plastic Scintillator:

The dimension of the scintillator box used here is 24cm*24cm*14.5cm. A scintillator is a transparent material containing molecules which are excited by the passage of charged particles. When a charged particle passes through the scintillator, it lose some of its kinetic energy by ionization and excites the atomic electrons of the molecules. When this electrons deexcites, it produces photon. Here when muon passes through the scintillator then de excitation of the molecules produces radiation near the blue and below UV region of electromagnetic spectrum. The efficiency of the Scintillator depends on the number of charged particle entering to the scintillator to the number of photons created. The scintillator wrapped with black paper to avoid the light coming from outside. Here we have used plastic scintillator.

2) Photomultiplier Tube:

It consists of a glass vacuum tube with a photocathode, several dynodes and an anode .The plastic scintillator is directly coupled to the PMT, when light signal coming from the scintillator falls on the photocathode, it emits electrons by the principle of photoelectric effect. These electrons are now being multiplied by the method of secondary emission by dynodes. Finally the electrons reach the anode where the accumulation of charge results in a sharp current pulse thus producing a strong electrical signal at the output. The Quantum efficiency of the PMT is ratio of photons incident and the no. of electrons collected by the anode.

Time measuring circuit:

- **Shape of the PMT Pulse**:

  When muon passes through the scintillator, it produces light signals which are fed to the PMT to produce negative pulses at the output. A pair of such pulses are shown in fig below

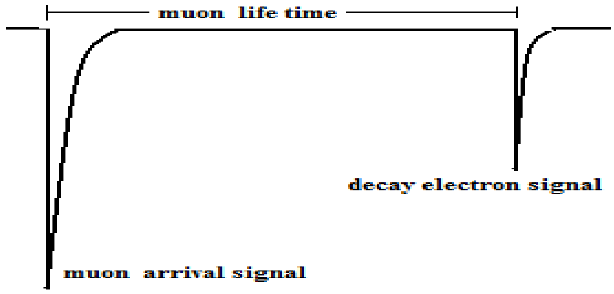

Fig 3. PMT pulse

IC Details:

IC Name	Description
LM 360(8 pins)	Comparator
74 LS74(14pins)	Dual edge-triggered FlipFlop
74LS161(16pins)	4 bit synchronous operation
74LS541(20pins)	Octal Buffer
74LS11(14pins)	AND Gate
74LS04(14pins)	NOT Gate
7805(3pins)	Positive voltage Regulator
7905(3pins)	Negative voltage Regulator
DB103(4pins)	Bridge Rectifier

Circuit Operation:

At first reset switch is pressed before starting the experiment to ensure that all F/F's are in clear states through the AND gate (IC 74LS11) and also the counters. Hence initially both flip flops are in a cleared state, waiting for a start pulse from the PMT signifying the entry of a muon. In clear states the Q o/p of the F/F's are set to low while $\overline{Q}$ is set to high. The D of the first F/F is set to high and the clock of the second F/F is high. However the o/p of the second F/F does not change state because of the clear signal.

The negative analog pulse coming from the PMT enters to the Comparator LM360.Now noise signal coming from the PMT can also give output voltage of the comparator, to avoid these noise signal a threshold voltage(-42mv here) is applied to the non-inverting terminal of the opamp. when the PMT signal at the inverting terminal is greater than the threshold voltage, then we get a positive digital pulse(TTL) output from the comparator, because we are applying negative voltage at the inverting terminal.

This digital pulse is the clock of the 1st FF. Initially in the cleared state of the FF Q=LOW & $\overline{Q}$ =HIGH,so D input of the FF is is high.Thus when digital pulse comes from the comparator to the clock ,then Q=HIGH & $\overline{Q}$ =LOW.This Q goes to the ENT of the 1st counter and starts the counting with the frequency of the clock pulse ,which is 10MHz here. Now we consider two cases 1st when muon decays to electron and second when muon doesnot decay.

1ST Muon Decays to electron:

when muon decays to electron ,a second pulse immediately comes from the PMT and passes to the comparator, so we get a digital pulse

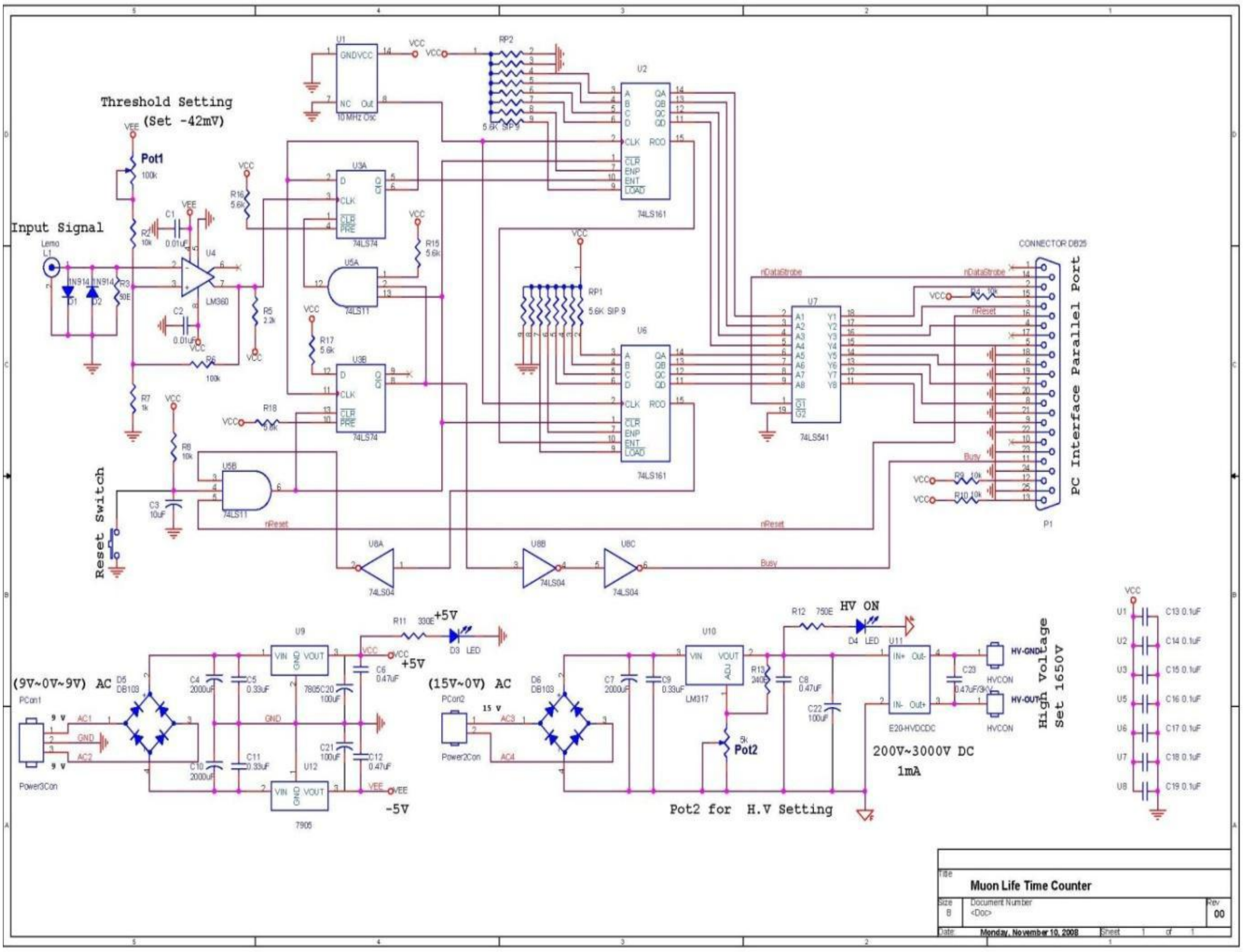

Fig4-Time measuring circuit

which comes to the 1st FF. This time D input of its is LOW so this time Q=LOW & $\overline{Q}$ =HIGH.So the output of the 1st FF Stops the counter. The $\overline{Q}$ output of 1st FF Is the clock of the 2nd FF. Thus $\overline{Q}$ of the 2nd FF is LOW. It clears the 1st FF and counters. The $\overline{Q}$ output of the 2nd FF is buffered and the signal is sent to the BUSY pin of the PC parallel port. When PC receives the BUSY signal as low, then DATA-STROBE line of the BUFFER changes to LOW immediately. The Data BUFFER passes the count to the PC. After the PC has read the data, DATA_STROBE is taken high and the RESET line is pulled low for a µs. This RESET signal clears the F/F's and counter ready for the next signal from the PMT. The interfacing program writes the total number of counts, the time and date of written file.

When muon doesn't decay:

If the muon passes through the scintillator without decaying, the USB counter reaches 255, i.e., a second pulse is not received within 25.5µs, and its RCO pin goes high. This is inverted through a NOT gate(IC 74LS04) to clear the counters and F/F's, to wait for the next pulse from the PMT.

Data analysis:-

The data is saved in a file, where different time intervals for each muon decay i.e. the time lag between the start event and stop event are in a column. The sampled data is not free from the background events. The detector doesn't know if the events produced are from the stopping of muon and its decay or from starting from some other radioactive source or light leakage and stopping from another of the same. The background events which are produced due to start from one muon and stop from another one will be very small as the flux reaching down at sea level is very small when compared to the 25.5µs window we have put in for counting. If the background for the data is assumed to be constant over a period of time then

$$N = N_0 e^{\frac{-t}{\tau}} + b$$

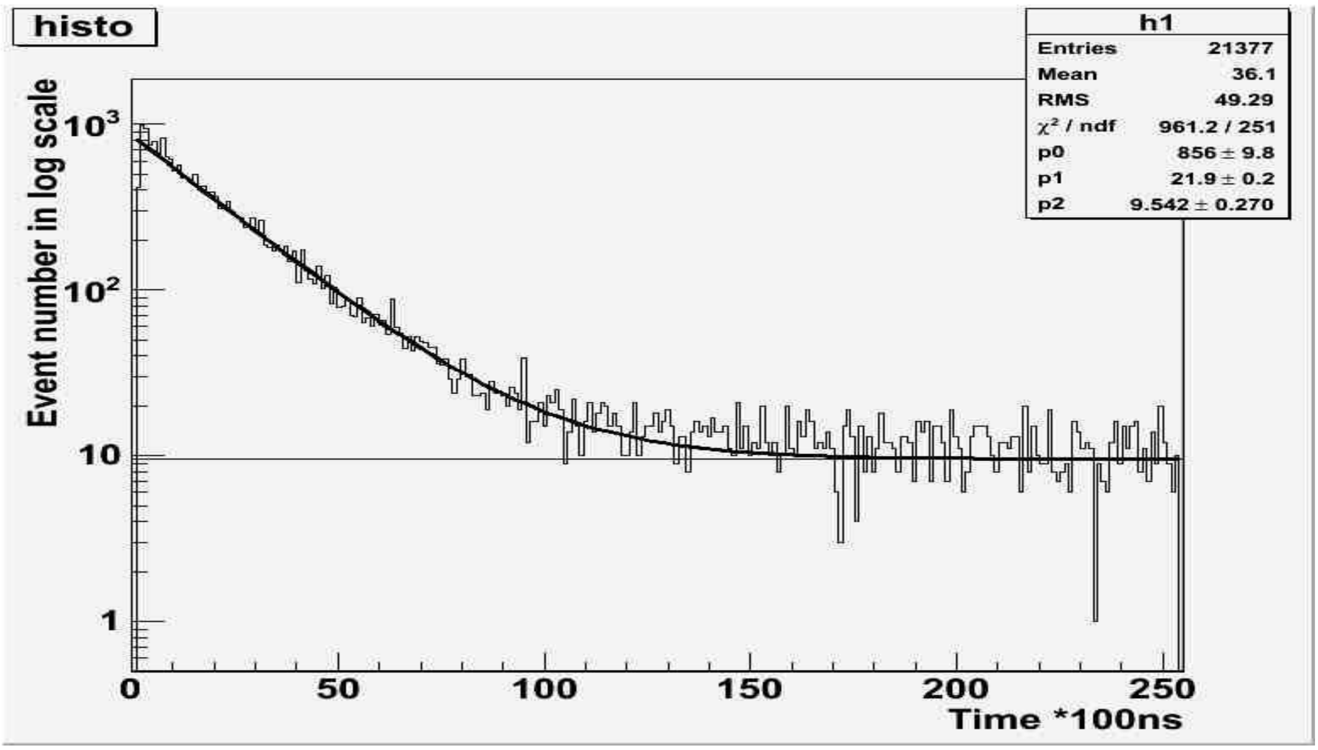

Fig5:- Plot of number of events in log scale with background

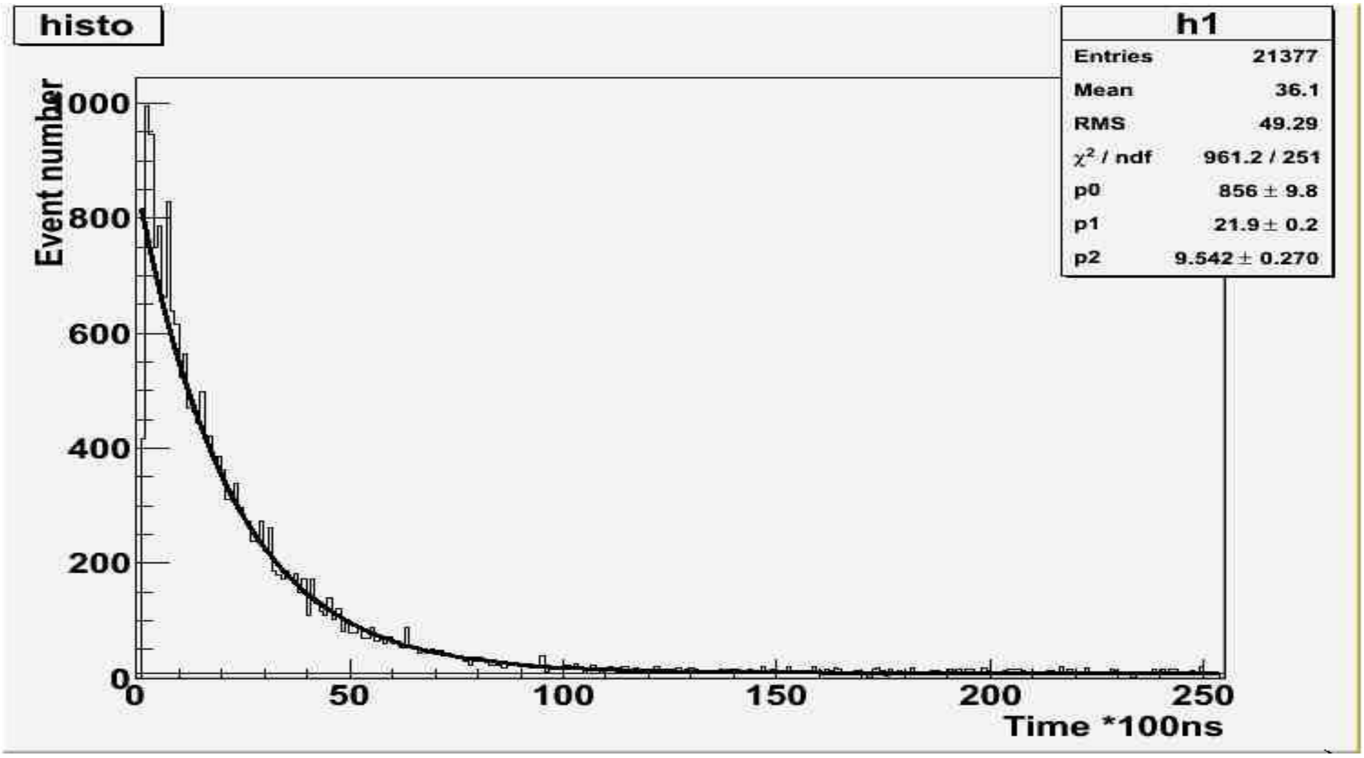

Fig6:-Plot of number. of events vs time

The value of the decay time of muon is

$$\boldsymbol{\tau} = (2.19 \pm .2)\mu s$$

The value of $N_0 = (855.9 \pm 9.8)$

$$b = (9.54 \pm 0.27)$$

Fermi Coupling Constant:

The Fermi coupling constant plays a key role in all precision tests of electroweak standard model. It is obtained from the muon lifetime (τ) via a calculation in the Fermi model as:

$$\boldsymbol{\tau} = 192\,\pi^3 / G_F^2 m_\mu^5$$

The value of G_F obtained for the above value of $\boldsymbol{\tau}$ is, where m_μ is taken as 105MeV.

$$G_F = (192\pi^3 / \boldsymbol{\tau}\, m_\mu^5\,)^{1/2}$$

$$G_F = 1.16533 \times 10^{-5}\ Gev^{-2}$$

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4) David Griffiths,”INTRODUCTION TO ELEMENTARY PARTICLES”.
5) Dr. F.Muheim, “Muon Lifetime Measurement
6) J.Santos, J.Augusto, A.Gomes, L.Gurriana, N.Laurenco, A.Maio,C.Marques, J.Silva, “The CRESCRE Muon's Lifetime Experiment” .

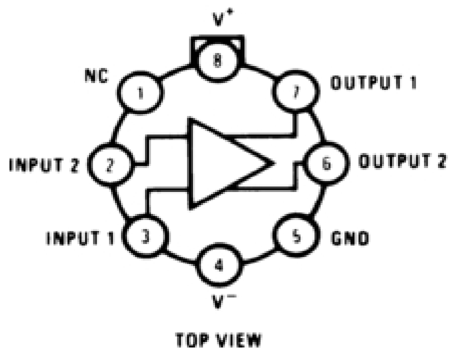
APPENDIX

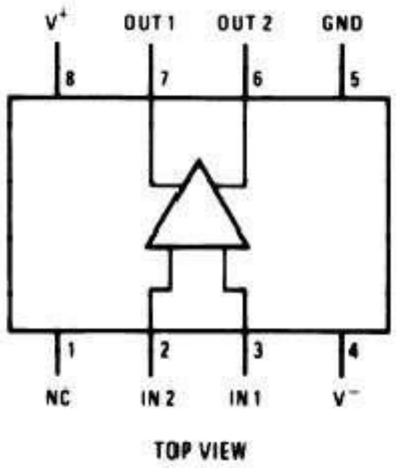
Circuit Component:-

I. **Discrimenator**(LM360):-

Discrimenator is basically A/D Converter or it is also called voltage comparator.An OP-AMP can be used as a Discrimenator by operating it in the open loop condition and applying the two voltages to be compared to the inverting and noninverting inputs.The voltage at the inverting terminal is negative so the output will be positive voltage.

Here if the voltage at the inverting terminal(2) is slightly greater than the threshold voltage at the noninverting terminal,which is -30mv,then output switch to the saturation voltage which is 5 volt here

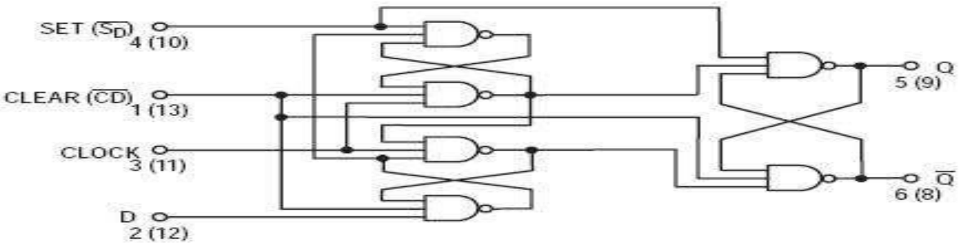




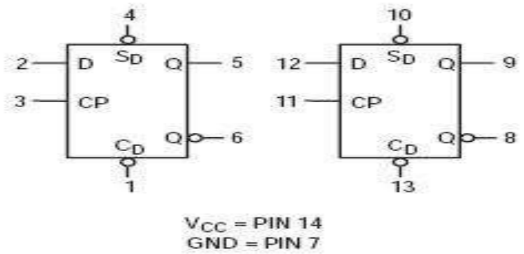
II. D type Flip Flop(74LS74):-

The 74LS74 dual edge-triggered flip flop utilizes Schottky TTL circuitry to produce high speed D type flip flop.Each lsflip-flops has individual clear and set inputs and also complementary Q and Q outputs. Information on the data input is transferred to the Q output on stheLOW-to-HIGH transition of the clock pulse. When the clock input is at either the HIGH or LOW level,the D input signal has no effect.(Detail circuit is in Appendix).

LOGIC DIAGRAM (Each Flip-Flop)

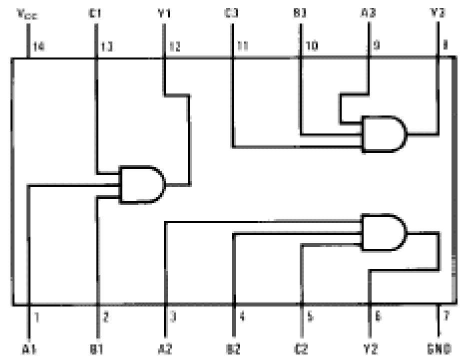


LOGIC SYMBOL



III. TRIPLE 3-INPUT AND GATE(74LS11):-

Connection Diagram



Function Table

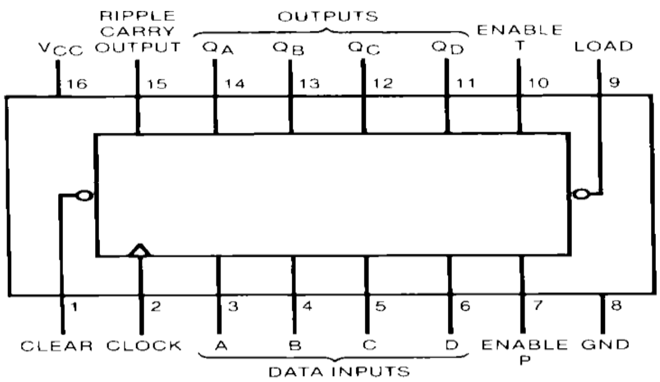
Y = ABC

Inputs			Output
A	B	C	Y
X	X	L	L
X	L	X	L
L	X	X	L
H	H	H	H

H = HIGH Logic Level
L = LOW Logic Level
X = Either LOW or HIGH Logic Level

IV. Synchronous 4-Bit Binary Counter(74LS161):

The 74LS161 are 4-bit synchronous counter. Synchronous operation is provided by having all flip flops clocked simultaneously so that the outputs change coincident with each other.



Operating Ranges

Symbol	parameter	Min	Type	Max	Unit
Vcc	Supply Voltage	4.75	5	5.25	V
TA	Operating Ambient Temperature range	0	2.5	70	^{o}C
IOH	Output current High			0.4	mA
IOL	Output current Low			8	mA