Experimental Project Report
On

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

(Under the guidance of Prof. Naba K. Mondal)

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

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Abstract

This experiment measures the average life time of a cosmic ray muon stopped in a plastic scintillator, by obtaining a time distribution consisting of consecutive pulses coming from the scintillator indicating time intervals between entry of muon stopped in the detector and their subsequent decay in to electrons. Muon decay follows the law of general radioactive decay, so to get the lifetime we measure the decay constant which on a logarithmic scale is 1/slope of the line. The lifetime hence obtained is 2.19 ± 0.02 µs.

INTRODUCTION:

The muon is an elementary particle belonging to the family of leptons(2^{nd} generation), and one of nature's fundamental "*building blocks of matter*". The other members of the lepton family are the Electron and the Tau. Muon was first discovered in cosmic ray experiments by Anderson and Neddermeyer in 1936, a cloud chamber was exposed to cosmic rays.

Muons are spin ½ particles with rest mass 105.658 Mev/c^2,i.e.,about 200 times the electronic mass. They participate in electromagnetic and weak interactions, but not in strong interactions. Due to their mass, muons are unstable and while passing through matter can decay in two ways ,either captured by the nucleus to emit a neutron ,or by spontaneous decay to produce an electron (or positron) and two neutrinos via weak force as:

$$\mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$$

$$\mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e$$

The distribution of muon decay time is given by,

$$N(t) = N(0) \exp(-t/\tau),$$

which is same as the general radioactive decays of nuclei and the decays of all unstable elementary particles.

Here, N (0) =initial population of muons,
N (t) =remaining muons at time t,
and, τ =the muon life time.

The muon life time is measured to be τ = 2.19703 μs.

THE EXPERIMENT:

This experiment is designed to measure the muon lifetime, or more precisely, the lifetime of cosmic muons that reach the earth's surface. Here we have used a plastic scintillation detector and a time measuring circuit.The source of muon is the cosmic radiation. The principle is to obtain a time distribution, consisting of consecutive pulses coming from the scintillator indicating time intervals between entry of muon stopped in the detector and their subsequent decay .Such a time distribution will contain an exponentially decaying component, corresponding to muon decays, from which the muon lifetime is extracted by fiting exp(-t/ τ) to it and correcting the background**.**

The source of cosmic muons:

The earth's upper atmosphere is bombarded by the primary cosmic radiation, which is mainly composed of protons and heavier nuclei (98%) and electrons (2%).They collide with the atmospheric nuclei and produce a shower of particles including neutral and charged pions, known as secondary cosmic rays. Many of the new particles are very short-lived and do not survive to reach sea level, but positive and negative pions created in the process decay into highly energetic muons which travel almost at the speed of light and are detectable at ground level. Muons are highly penetrating particles due to their heavy mass,as it limits the bremsstrahlung radiation when it passes through matter. The total secondary flux at sea level is approximately 1/min/sq. cm. Roughly 75% of the flux consists of positive and negative muons and 25% of it consists of electrons and positrons**.**

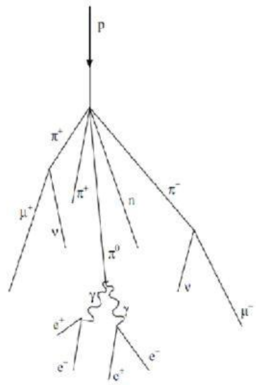

Figure 1: Cosmic ray cascade induced by a cosmic ray proton striking an air molecule nucleus.

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 radioactively into muons .The charged pions decay by weak interaction into a charged muon and muon neutrino, while the neutral pions decay into a pair of γ-rays by electromagnetic interaction .Then the muons decay into electron (or positron) and neutrinos. The decay modes are as follows:

$$p + p \rightarrow p + p + \pi^{+} + \pi^{-}$$

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

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

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

$$\mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu}$$

Muons have a lifetime of about 2.2 μs when measured in its rest frame. Assuming muon velocity close to the velocity of light, we readily find that they could travel to a distance of about 650 m before they decay, i.e., they should not reach the earth from the upper atmosphere where they are produced. But studies show that the muon production height is about 15kms from the sea level and it takes 50 μs for them to reach the sea level.

This may be explained by the relativistic time dilation.

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

Where,

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

t' = time measured in the rest frame of the system,

v= velocity of the system,

c = velocity of the light.

So, relative to an observer on earth, the lifetime of muon will be γτ.

If v =0.99c,then γ =7.089, and γτ = 15.59 μs

and the average distance traveled as measured by an observer on earth will be 4677 m.

The experimental set-up:

The experimental set up is shown in the following figure. It consists of a plastic scintillator , a photomultiplier tube (PMT), a time measuring circuit and a PC. Photo tubes are used to guide the scintillator signal from scintillator to PMT.

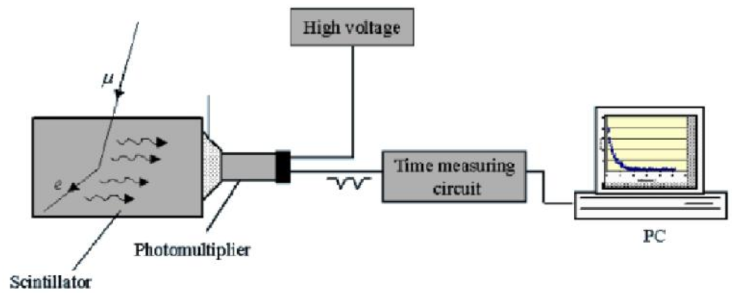

Figure2: Block Diagram of the Experimental Arrangement.

The principles of operation of scintillator and PMT are discussed below:

SCINTILLATOR

The detector used here is a plastic scintillator detector (refractive index =1.58) of dimension 24 cm X 24 cm X 14.5 cm,wrapped with 'Tybec',a light preventing material followed by a black paper called 'Tedler' to prevent interaction of visible light with scintillator material and hence to minimize stray scintillation. Plastic scintillator are characterized by a relatively large light output and a short decay time of the order of a nanosecond. This makes the material well suited for fast timing measurements.A charged particle passing through it loses some of its kinetic energy by ionization and atomic excitation of the scintillator molecules.The de-excitation of the molecules produces radiation near the blue and below UV region of the e.m. spectrum. The number of photons produced is proportional (with a statistical considerations) to the energy loss of the passing particle.

PHOTOMULTIPLIER TUBE

The PMT consists of a glass vacuum tube with a photocathode, several dynodes and an anode. During operation a high voltage is applied to the cathode – dynode – anode structure so that a potential ladder is built along the length of the tube.

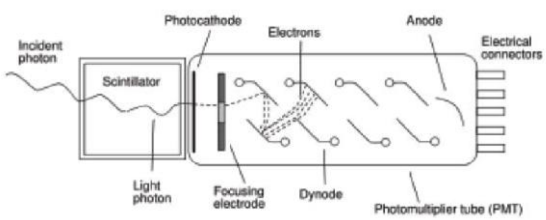

Figure 3 : Schematic diagram of a PMT coupled to a scintillator.

The PMT used here is a 2 inch diameter one with a 21 pin base (9807B manufactured by Electron Tubes Ltd). When an incident photon from the scintillator impinges upon the photo-cathode, electrons are emitted via photoelectric effect. The electrons are directed towards the dynodes and get multiplied by the process of secondary emission ,ultimately giving an electron cascade. This cascade is collected at the anode to give a sharp and strong electrical output **.** The PMT is operated at high voltage of about 1.7 kV by means of high voltage dc to dc converter (E20-

HVDCDC).The rise time of the pulse obtained is a few nanoseconds.

The overall spectral response, i.e., the sensitivity of the photocathode is expressed in terms of quantum efficiency, Q.E.,

Q.E. = (no of photoelectrons emitted) / (no of incident photons on the photocathode)

For ideal photocathode, Q.E. = 100%, but practically it is 20 – 30%.It is a strong function of wavelength or quantum energy of incident light and the photocathode material.

The efficiency of a dynode is determined by the overall multiplication factor (δ),

δ = (no of secondary electrons emitted) / (no of primary incident electron)

TIME MEASUREMENT CIRCUIT:

Occasionally a cosmic ray muon stops in the scintillator resulting in two signals, first coming from the incoming muon and the second from the decay electron. The time delay between the two signals is measured by a time measuring circuit and passed to a PC.

PMT Pulse:

When a muon passes through the scintillator,it produces signals in the form of light.This light is fed to the PMT to give negative analog pulses as output. A pair of PMT output pulses is shown below.

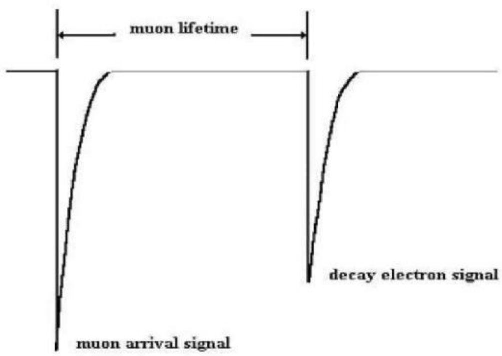

Figure 4: PMT pulses.

The electronic circuit:

The main counter circuit mainly consists of comparator,D- flip-flops, counters, oscillator, latches, a buffer IC and a Standard Parallel Port interfacing with the computer where the data is recorded .The diagram of the electronic time measuring circuit is shown below.

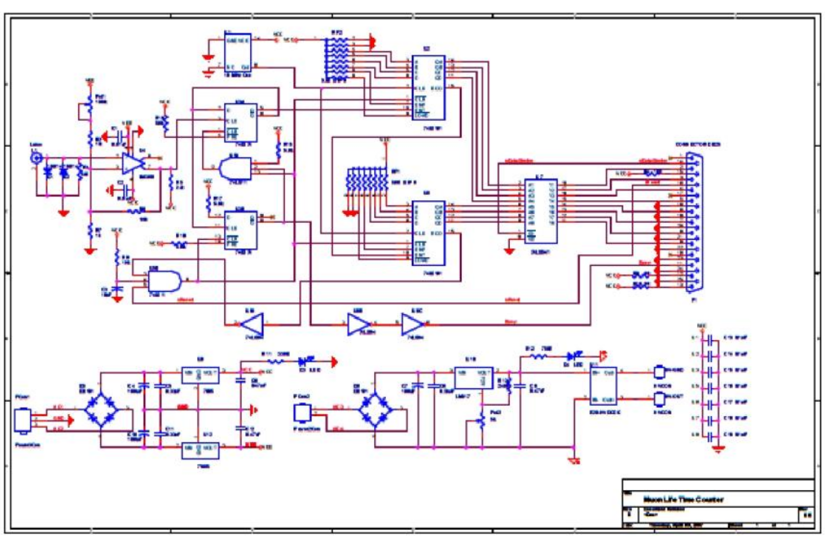

Figure 5: The Electronic Circuit of muon life time counter.

The voltage regulator circuits (for providing voltages to IC's and PMT base) are shown below the main circuit.

The component details of the counter circuit are as follows.

1.IC's:

IC Name	Description
LM360(8 PINS)	COMPARATOR
74LS74(14PINS)	D-FLIP FLOP
74LS161(16PINS)	COUNTER
74LS541(20PINS)	BUFFER
74LS11(14PINS)	AND GATE
74LS04(14PINS)	NOT GATE
7805(3PINS)	POSITIVE VOLTAGE REGULATOR
7905(3PINS)	NEGATIVE VOLTAGE REGULATOR
LM317	POSITIVE VOLTAGE REGULATOR
DB103(4 pins)	BRIDGE RECTIFIER

*2.*Crystal Oscillator(4 pins) *: frequency = 10 MHz (used to generate the clock for both LSB and USB counters, thus giving the resolution of 0.1μs.)*

- *Description of the different IC's used are given in the appendix*.

The electronic circuit operation:

The negative analog pulse output from the PMT passes through the high speed comparator (LM360) whose threshold voltage is set at -42mV at the non inverting terminal.This threshold signal is used to filter out noise signal and to allow larger genuine signals only.When the PMT pulse exceeds this threshold voltage, a positive digital pulse (TTL) output is obtained from the comparator, which acts as the clock of the first D-F/F.The $\overline{Q}$ output from this F/F is connected to its D-input. Initially, in the cleared state,Q=low and $\overline{Q}$ =high.

So when the digital pulse from the comparator comes to the clock,q goes high and goes to the ENT of the 1st 4- bit synchronous counter,so the counter starts counting at 10 MHz. also $\overline{Q}$ goes low and it is fed to the clock input of the 2nd F/F.Then for this F/F, Q=Low, $\overline{Q}$ =High.

Now we consider the two cases –

When muon decays to electron and when it does not decay.

When muon decays to an electron:

A second pulse comes from the PMT and passes through the comparator soon after the first.Then the Q output of the 1st F/F goes low and the counter is stopped.The $\overline{Q}$ output goes high and makes the clock input of the second F/F high.The $\overline{Q}$ output of this F/F goes low,it clears the 1st F/F as well as the counter. This $\overline{Q}$ output is buffered and the signal is sent to the BUSY pin of the PC parallel port. When the PC receives the BUSY signal,the DATA STROBE line (pin 1 of the octet buffer) is pulled low to enable the data buffer. The data buffer passes the count from the counter to the PC. After the PC has read the data, DATA STROBE is taken high and the RESET line is pulled low for a few μs. The low RESET signal clears all the F/F's (back to state waiting0 and counter ready for the next signal to come.

When muon doesnot decay:

If muons doesnot decay,the counter counts upto 255 bits ,i.e., after a time 25.5 μs. Then the RCO pin of the counter goes high and it clears all the counters and F/F's to make them ready for the next pulse to come.

DATA ANALYSIS:

The measured quantity saved in the file is the time lag between the start event and the stop event. To find the time distribution the data is sampled ,binned and then fitted. Background events may arise from some other radioactive source or light leakage through the scintillator, a muon coming before the decay of the previous one. So the distribution needs to be corrected from background events. The background events which are produced due to start from one muon and stop from another will be negligible as the flux reaching down sea-level is very small when compared to the 25.6μs window employed for counting. Assuming the background to be constant over a period of time the data are fitted with the function

$N(t)=N(0)\exp(-t/\tau)+b$, using ROOT.

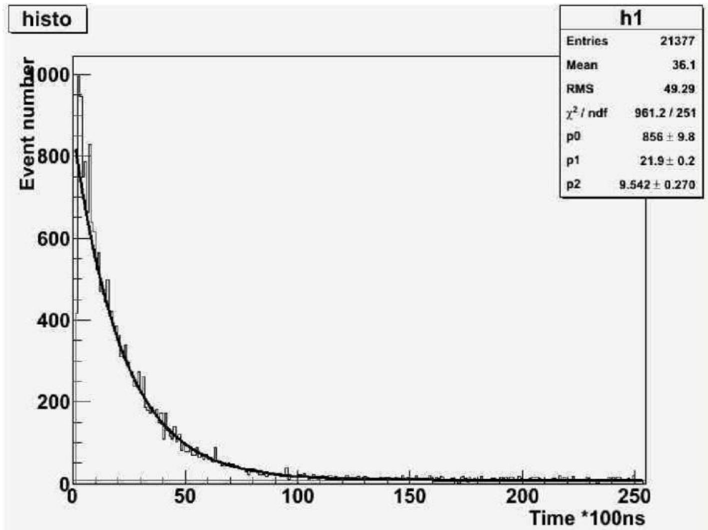

Figure 6: Plot of event number vs time with exponential fitting(with background).

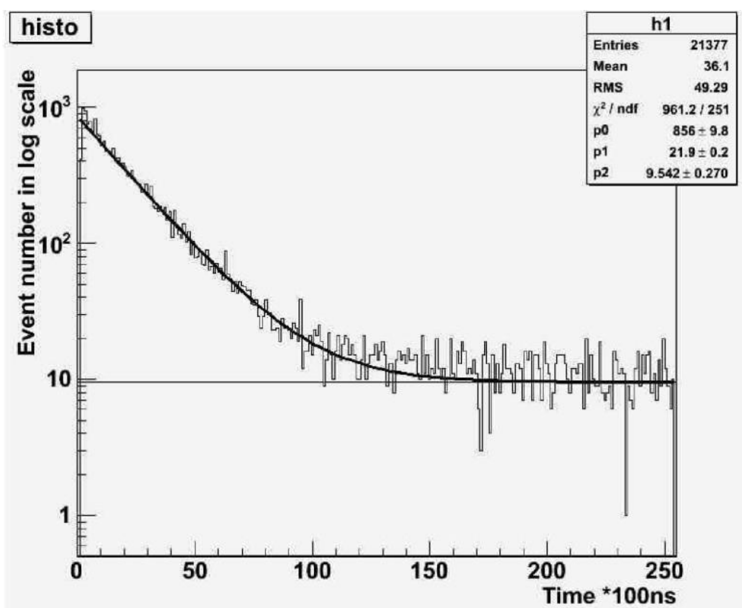

Figure 7 : Plot of event number in logarithmic scale vs time.

In each of the two plots above ,the straight line is giving the background.

We obtained the fitted parameters as :

$N(0) = 855.9 \pm 9.8$

$\tau = 21.9 \pm 0.2$

$b = 9.54 \pm 0.27$

The mean muon life time is determined to be 2.19 ± 0.02 μs

Calculation of Fermi Coupling Constant:

The universal constants for a process provide a tool to validate experimental results. In all precision tests of electroweak standard model the Fermi coupling constant plays a key role. From the muon lifetime (τ) , the fermi coupling constant can be calculated as(via a calculation in the Fermi model):

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

The value of G_F obtained for the value of we got from this experiments is

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

Conclusions:

The mean muon life is found out to be 2.19 ± 0.02 μs , and using that the Fermi coupling constant is calculated to be 1.16533×10^{-5} Gev^{-2} .

Acknowledgement:

I would like to extend my gratitude to Prof. N. K. Mondal for providing an excellent opportunity to work in the D423 lab, and motivating us throughout the work. I am very thankful to Mr. L.V. Reddy for his guidance in doing the project. I am very grateful to Md. Salim who helped us in learning ROOT to make the plots. Last but not the least; I thank my colleagues Neha, Mathimalar and Animesh for their supportive company and co-operation.

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- *"The CRESCRE Muon's Lifetime Experiment" J.Santos, et al.*
- *"Average Velocity and Lifetime of Muons",Philip J. Ilten.*
- *"Precision Lifetime Measurements On Positive and Negative Muons",S.L.meyer et al.*
- *"Digital electronics",Floyd and Jain.*
- *IC datasheets.*

APPENDIX:

1.PLASTIC SCINTILLATOR:

A scintillator is a material which emits light when charged particles pass through it .Actually it converts the K.E. of charged particles into detectable light with a high scintillation efficiency, which is defined as the fraction of incident particle energy that is converted into visible light. The number of photons produced is proportional (with a statistical considerations0 to the energy loss of the passing particle.

At present, six types of scintillator materials are in use - organic crystals, organic liquids, plastics, inorganic crystal, gases and glasses.

Plastic scintillator is prepared by dissolving organic scintillators in some solvents which then get polymerized. Some examples of the solvents are polyvinyl toluene, polyphenylbenzene, polystyrene, polymethylmethacrylate. They have become the most widely used organic detector due to their flexibility**.**

2. DESCRIPTION OF IC'S:

LM360 : The LM360 is a very high speed differential input, complementary TTL output voltage comparator which has been optimized for greater speed, input impedance and fan-out, and lower input offset voltage. Typically delay varies only 3 ns for overdrive variations of 5 mV to 400 mV.

It is an 8-pin configuration IC.The connection diagram is shown in metal can package and dual-in line package.

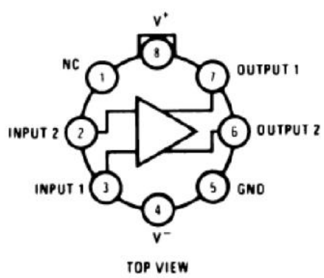

Figure 8 : Metal Can Package.

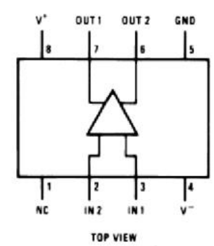

Figure 9 : Dual-In-Line Package.

Special Features of LM360 :

Guaranteed high speed: 20 ns max
Tight delay matching on both outputs
Complementary TTL outputs
High input impedance
Low speed variation with overdrive variation
Fan-out of 4
Low input offset voltage
Series 74 TTL compatible
Positive Supply Voltage +8V
Negative Supply Voltage −8V
Peak Output Current 20 mA
Differential Input Voltage ±5V
Input Voltage V+ ≥VIN ≥ V−
Operating Temperature Range 0°C to +70°C
Storage temperature range -65°C to +150°C.

74Ls74 : It is a dual edge triggered flip-flop that utilizes Schottky TTL circuitry to produce high speed D-type flip –flops.Each flip-flop has individual clear and set inputs,and also complementary Q and $\bar{Q}$ outputs.

Information at input D is transferred to the Q output on the +ve going edge of the clock pulse.Clock trigering occurs at a voltage level of the clock pulse and is not directly related to the transition time of the +ve going pulse.When the clock input is at either the HIGH or LOW level,the D input signal has no effect.

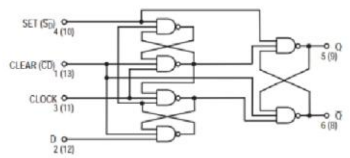

Figure 10 : LOGIC DIAGRAM (Each Flip-Flop).

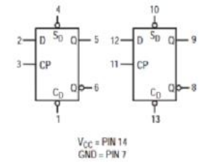

Figure 11 : Logic symbol.

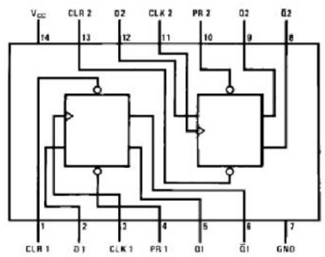

Figure 12 : Connection Diagram.

Inputs				Outputs	
PR	CLR	CLK	D	Q	$\overline{Q}$
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	$\overline{Q}_0$

The Truth Table

Here,

H = HIGH Logic Level
X = Either LOW or HIGH Logic Level
L = LOW Logic Level
↑ = Positive-going Transition
Q0 = The output logic level of Q before the indicated input conditions were established.

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

Important features: Supply Voltage 7V Input Voltage 7V
Operating Free Air Temperature Range 0°C to +70°C
Storage Temperature Range -65°C to +150°C.

74LS11: It is a 14 pin configuration IC consisting of triple three-input AND gates.

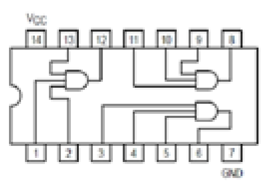

Figure 13: Pin Diagram.

Y = ABC

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

The truth table

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

Special Features:

Symbol	Parameter	Min	Nom	Max	Unit
Vcc	Supply Voltage	4.75	5	5.25	V
TA	Operating Ambient Temperature Range	0		70	C
IOH	Output current - High			-0.4	mA
IOL	Output current-Low			8.0	mA
VIH	Input Voltage-High	2.0			V
VIL	Input Voltage-Low			0.8	V
VOH	Output HIGH Voltage	2.7			V
VOL	Output LOW Voltage			0.5	V
IIH	Input High Current			0.1	mA
IIL	Input Low Current			-0.4	mA

74LS04: It is a triple 3-input AND gate with 14 pin.

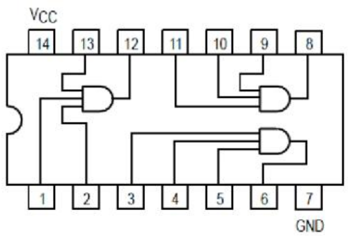

Figure 14 : The connection diagram.

74LS161: It is 4-bit synchronous counter with 16 pin configuration.

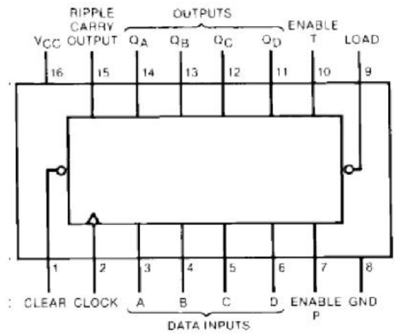

Figure 15 : The connection diagram.

The carry output is decoded by means of a NOR gate, thus preventing spikes during the normal counting mode of operation. Synchronous operation is provided by having all flip-flops clocked simultaneously so that the outputs change coincident with each other when so instructed by the count-enable inputs and internal gating.

A buffered clock input triggers the four flip-flops on the rising (positive-going) edge of the clock input waveform. These counters are fully programmable; that is, the outputs may be preset to either level. As presetting is synchronous,setting up a low level at the load input disables the counter and causes the outputs to agree with the setup data after the next clock pulse, regardless of the levels of the enable input. The clear function for the DM74LS161A is asynchronous;and a low level at the clear input sets all four of the flip-flop outputs LOW, regardless of the levels of clock,load, or enable inputs.

The carry look-ahead circuitry provides for cascading counters for n-bit synchronous applications without additional gating. Instrumental in accomplishing this function are two count-enable inputs and a ripple carry output. Both count-enable inputs (P and T) must be HIGH to count,and input T is fed forward to enable the ripple carry output.The ripple carry output thus enabled will produce a highlevel output pulse with a duration approximately equal to the high-level portion of the QA output. This high-level overflow ripple carry pulse can be used to enable successive cascaded stages. HIGH-to-LOW level transitions at the enable P or T inputs may occur, regardless of the logic level of the clock.

Guaranteed Operating Ranges

Symbol	*Parameter*	*Min*	*Type*	*Max*	*Unit*
Vcc	Supply Voltage	4.75	5	5.25	V
T_A	Operating Ambient Temperature range	0	2.5	70	ºC
I_{OH}	Output current - High			-0.4	mA
I_{OL}	Output current - Low			8	mA

74LS541: It is an octal buffer with 20 pin configuration.

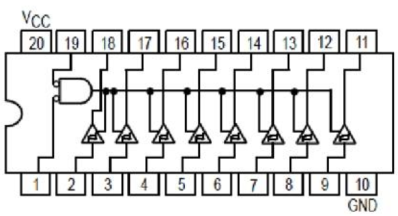

Figure 16 : The connection diagram.

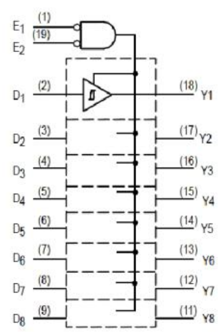

Figure 17 : The logic diagram.

INPUTS			OUTPUTS
E_1	E_2	D	
L	L	H	H
H	X	X	Z
X	H	X	Z
L	L	L	L

L = LOW Voltage Level
H = HIGH Voltage Level
X = Immaterial
Z = High Impedance

7805 : It is a three terminal 1A positive voltage regulator which employs internal current limiting, thermal shut down and safe operating area protection,making it essentially indestructible. If adequate heat sinking is provided, they can deliver over 1A output current.

7905 : It is a three terminal negative voltage regulator with thermal overload protection and shortcircuit protection.

LM317: It is an adjustible three terminal positive voltage regulator designed to supply more than 1.5A of load current with an output voltage adjustible over 1.2 to 37V. It employs internal current limiting, thermal shutdown and safe area compensation.