Measuring the muon lifetime using stopped cosmic muons in a plastic scintillator detector

Meghna.K.K

INTRODUCTION:

Muons are discovered by Anderson and Nedermeir in 1936 in cosmic rays. It is an elementary particle belongs to a group called lepton. It is similar to electron with negative charge and spin ½. Muons have a mass of 105.7 MeV/c^2, which is about 200 times the mass of the electrons and its interactions are very similar to those of the electron. 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:

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

The probability of capture by a nucleus is small for low Z materials but increases rapidly with increasing Z. The μ+s are strongly repulsed by nuclei.
The distribution of the muon spontaneous decay is governed by the general radioactive decay distribution.

$$N = N_0 e^{(-t/\tau)}$$

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. The mean life time of both positive and negative free muons is about 2.2μsec. Captured muons have a shorter life time.

SOURCES OF MUON:

The cosmic radiation, which consists of high energy particles mostly protons, enters the Earth's upper atmosphere and interacts with the atmospheric nuclei produces secondary particles. Collisions of cosmic rays with atoms in the upper atmosphere produce mostly neutral and charged pions. Each neutral pion decays into a pair of gamma rays. The charged pions each decay into a charged muon and a muon neutrino. This muons travel at the speed of light.

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

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

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

EXPERIMENTAL SETUP:

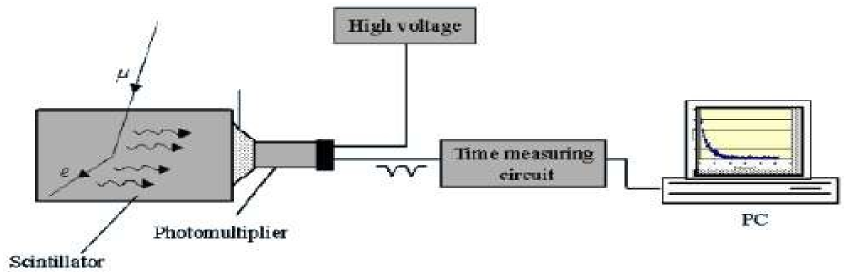


Fig1. Block diagram representing the experimental setup

Detector used is a (24 cm X 24 cm X 14.5 cm) plastic scintillator. Plastic scintillators are the solutions of organic scintillators in a solvent. The Scintillator materials exhibit the property of luminescence when excited by ionizing radiation. They absorb energy of incoming particles and reemit radiation near blue and below UV region of electromagnetic spectrum. This relaxing period of the detector is very short with typical decay time of nano seconds. The photon energy is approximately the same as that lost by the particle in the scintillator. Plastics scintillators give a fast signal (a few ns) and a high light output.

Photomultiplier tube (PMT) is used to convert these light signals into electrical signals. A typical photomultiplier tube consists of a photoemissive cathode (photocathode) followed by focusing electrodes, an electron multiplier and an electron collector (anode) in a vacuum tube. When light enters the photocathode, the photocathode emits photoelectrons into the vacuum. The number of electrons produced is determined by the quantum efficiency of the photocathode of the PMT and the number of electrons thus produced is very small. The signal produced by the photo cathode is then focused on dynodes where secondary emission of electrons proportional to the incident electron energy takes place. The final charges are accumulated and collected at the anode which gives rise to a sharp and strong electrical output. Because of secondary-emission multiplication, photomultiplier tubes provide extremely high sensitivity and exceptionally low noise. The process in scintillator and photomultiplier tube is shown in Fig.2.

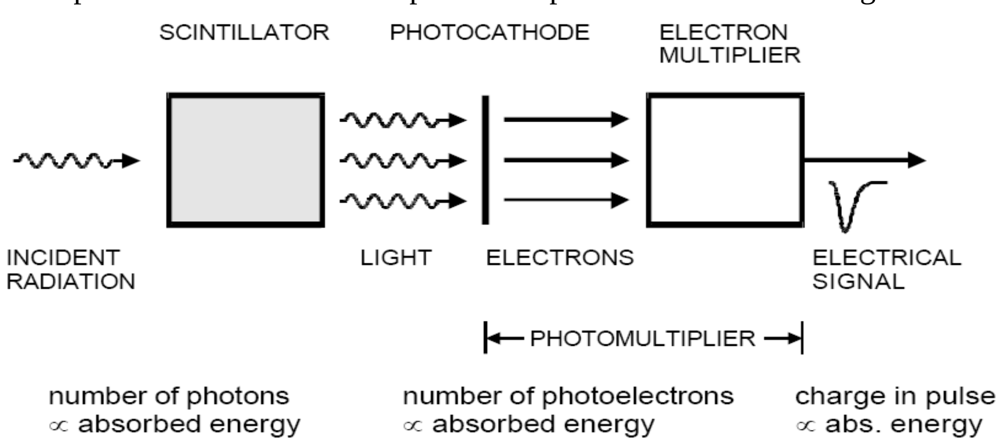


Fig2. Process in scintillator and photomultiplier

For the experiment Plastic scintillator is wrapped using a light reflecting material called "Tyrek", followed by a black paper called "Tedler". Tedler prevents light to enter the detector. The PMT is biased at (1.7kV).

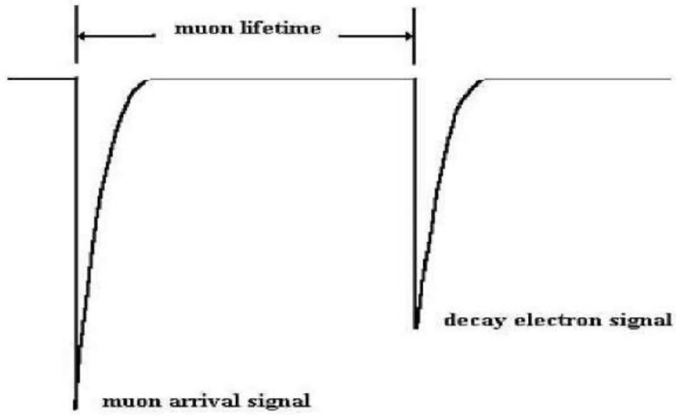


Fig3. PMT pulses.

LIFE TIME MEASUREMENT:

The main components of the electronic circuit are comparator, two flip flop latches, crystal oscillator clock(10MHz) and two buffered 4 bit counters.

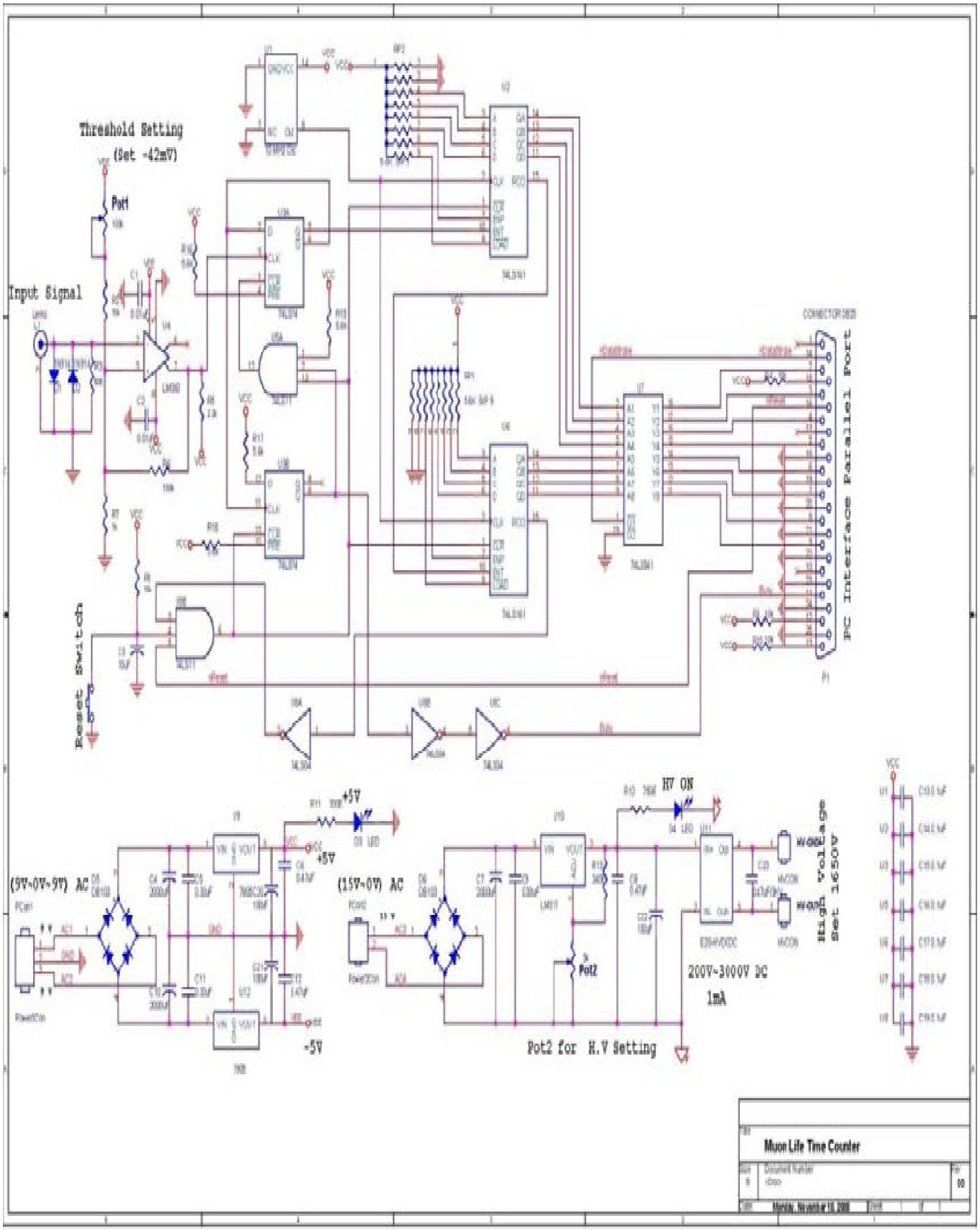


Fig4: Muon Lifetime counter circuit

When the muon passes through the scintillator it produces light signals which are fed to PMT. The PMT amplied signals are not noise free. This signal is fed to the inverting terminal of the comparator. The output of the comparator is a positive high (the negative input signal is fed to the inverting terminal) digital pulse (TTL) of 5 Volts. Here the reference voltage of the comparator is set to 45mV. The comparator allows only the signals with amplitude greater than the reference voltage. The output of the comparator is fed to clock pin of the first flip flop. The Q output of the flip flop goes high and fed to the ENT of the 4 bit LSB counter. Both the LSB and USB counter are clocked by a 10MHz crystal oscillator, giving the resolution of 0.1μs.. The $\overline{Q}$ goes to low making D low. If the second pulse comes from the PMT and passes through the comparator soon after the first, the Q output of the first flip flop goes low and the counter is stoped. The $\overline{Q}$ goes high and make the clock input of the second flip flop high. The $\overline{Q}$ of the second flip flop, which is buffered, goes low 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 is pulled low and enables the data buffer. The data buffer passes the count from counter to PC. The interfacing program writes the number of counts date and time to the file. After the PC as read the data, DATA_STROBE becomes low and the RESET line also becomes low for a microsecond. The reset signal clears the flip flops and the counter is ready for the next pulse.

The counter can count only up to 255 ie.25.5 microseconds. If the second pulse is not received within 25.5 microseconds the RCO pin will go high and this signal is inverted to clear flip flops and the counter to wait for next pulse from PMT.

The components used are listed in the Table .

IC Name	**Description**
LM360(8 Pins)	Comparator
74LS74(14 Pins)	D-Flip Flop
74LS161(16 Pins)	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
DB101(4 Pins)	Bridge Rectifier

Oscillator (4 Pins) : Frequency = 10 MHz

ANALISYS:

Measured quantity is the time lag between the start event and stop event. For time distribution, the data is sampled, events binned and then fitted. Now background events may arise due to light leakage through the scintillator, a muon passing through the scintillator without decaying or a muon comes before decay of the previous one etc. The distribution then needs to be corrected taking into the background events. If the background for the data is assumed to be constant over a period of time then

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

The data is fitted with the above function using ROOT and the fitting parameters obtained are

$$N_0 = 1175 \pm 11.8$$
$$\tau = (2.15 \pm 0.02)\mu s$$
$$b = 18.81 \pm 0.37$$

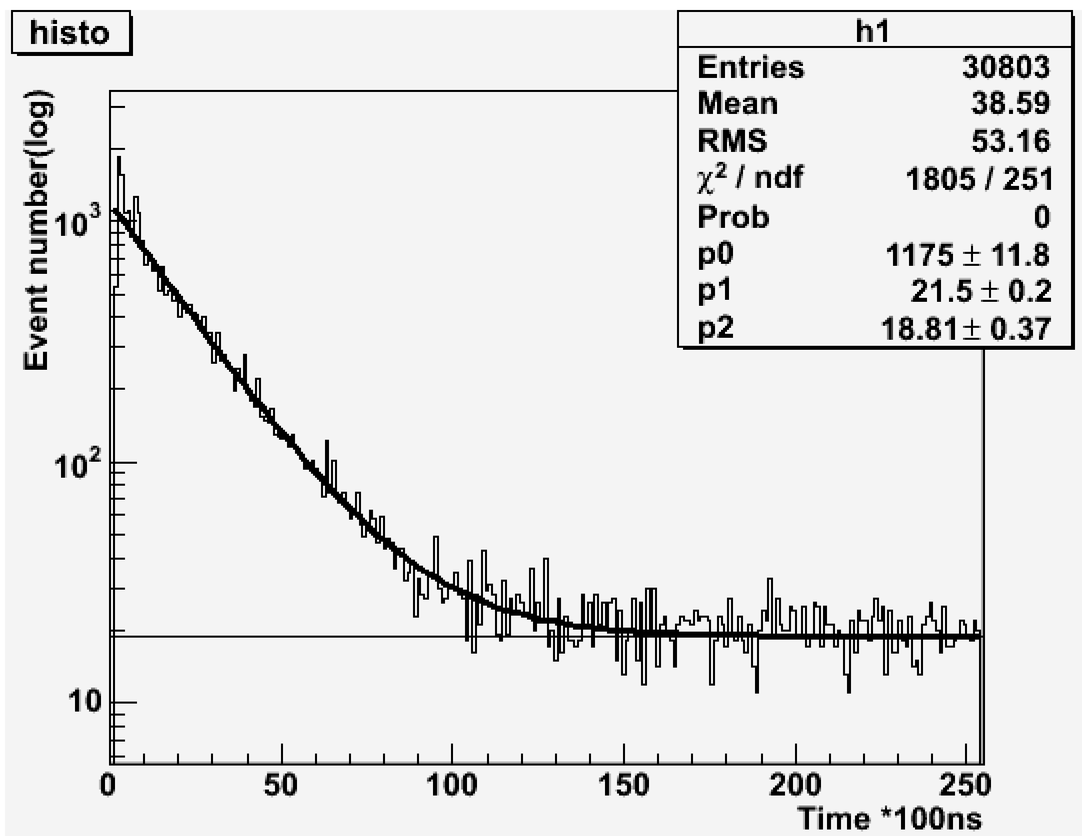


Fig5. Muon Lifetime Distribution with background.

The average muon life is hence determined to be (2.15 ± 0.02)µs.

FERMY COUPLING CONSTANT:

The muon decay is an electroweak process and the coupling constant is the Fermi Coupling constant (G). In the theory of muon decay the expression for average life time of muon is expressed as

$$\tau = \frac{192\pi^3 \square^{7}}{G^2 m_\mu^5 c^4}$$

$$\tau = \frac{192\pi^3}{G^2 m_\mu^5} \text{ in Natural units}$$

Substituting the value of τ obtained from this experiment, in this equation , the value of Fermi coupling constant is obtained as:

$$G = 1.176X10^{-05}GeV^{-1}$$

REFERENCE:

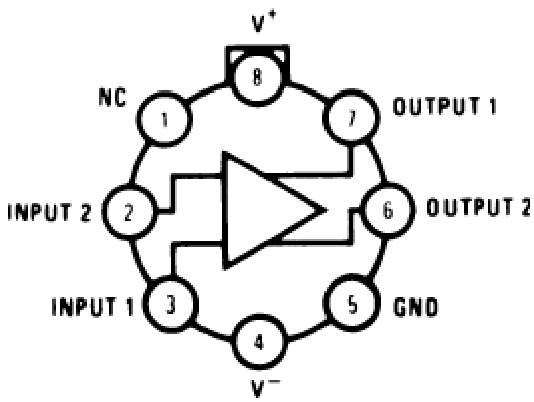
1. Introduction to Elementary Particles, Griffiths.
2. Radiation Detection and Measurement, G.F Knoll
3. Art of Electronics, Hozowitz
4. IC datasheets of Fairchild Semiconductor, Motorola, ST Microelectronics and National Semiconductor.

APPENDIX

LM360: LM360 is a very high speed differential input, complementary TTL output voltage comparator. Typically delay varies only 3 ns for overdrive variations of 5 mV to 400 mV.

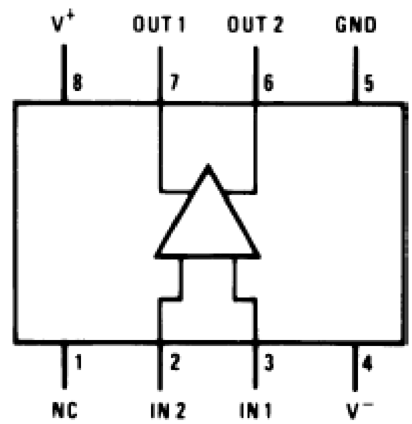
Connection Diagrams:

Metal Can Package



TOP VIEW

Dual-In-Line Package



TOP VIEW

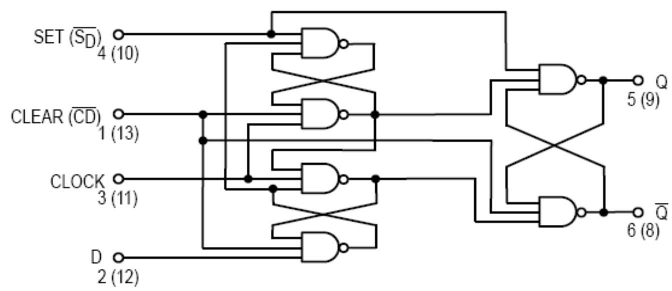
Features

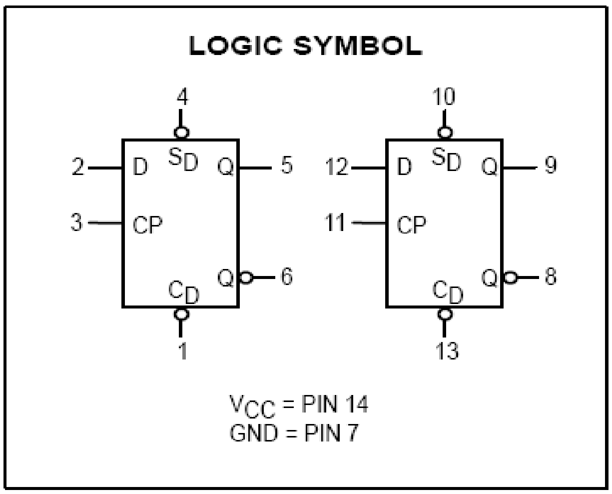
- Guaranteed high speed: 20 ns max
- Tight delay matching on both outputs
- Complementary TTL outputs
- High input impedance
- Low speed variation with overdrive variation
- Fan-out of 4
- Low input offset voltage
- Series 74 TTL compatible

74LS74: It is a dual edge-triggered flip-flop 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 Q outputs.

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

LOGIC DIAGRAM (Each Flip-Flop)





Truth table:

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	$\overline{Q}_0$

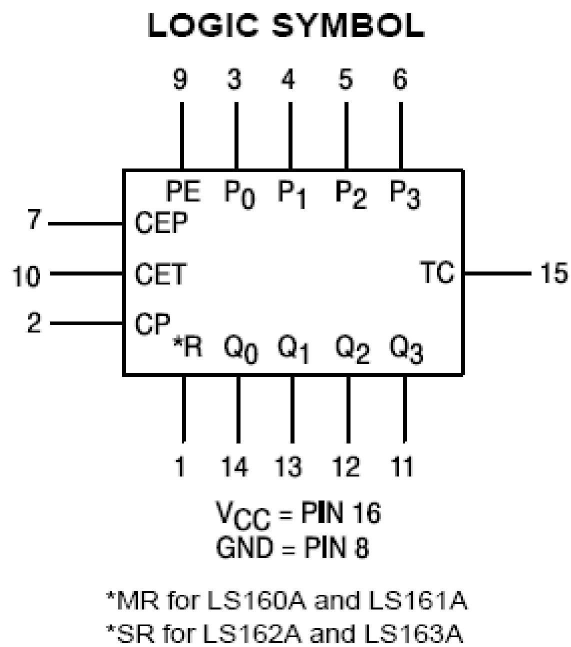
X = LOW or HIGH Logic Level
H = HIGH Logic Level
L = LOW Logic Level
↑ = Positive-going Transition

Q_0 = The output logic level of Q before the indicated i/p conditions were established.

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

74LS161: It is a high-speed 4-bit synchronous counter 16 pin configuration. It is edgetriggered, synchronously presettable and contains internal look-ahead.

CONNECTION DIAGRAM DIP:



GUARANTEED OPERATING RANGES

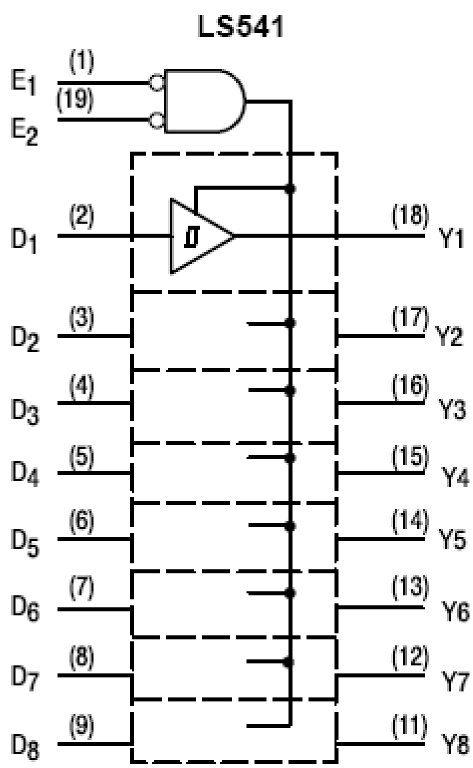
Symbol	Parameter		Min	Typ	Max	Unit
V_{CC}	Supply Voltage	54 74	4.5 4.75	5.0 5.0	5.5 5.25	V
T_A	Operating Ambient Temperature Range	54 74	−55 0	25 25	125 70	°C
I_{OH}	Output Current — High	54, 74			−0.4	mA
I_{OL}	Output Current — Low	54 74			4.0 8.0	mA

74LS541: It is an octal buffer with 20 pin configuration.It takes 4 bit output from each counter and gives 8 bit output to the PC.

Features:

- Hysteresis at Inputs to Improve Noise Margin
- PNP Inputs Reduce Loading
- 3-State Outputs Drive Bus Lines
- Inputs and Outputs Opposite Side of Package, Allowing Easier
- Interface to Microprocessors
- Input Clamp Diodes Limit High-Speed Termination Effects

BLOCK DIAGRAM:



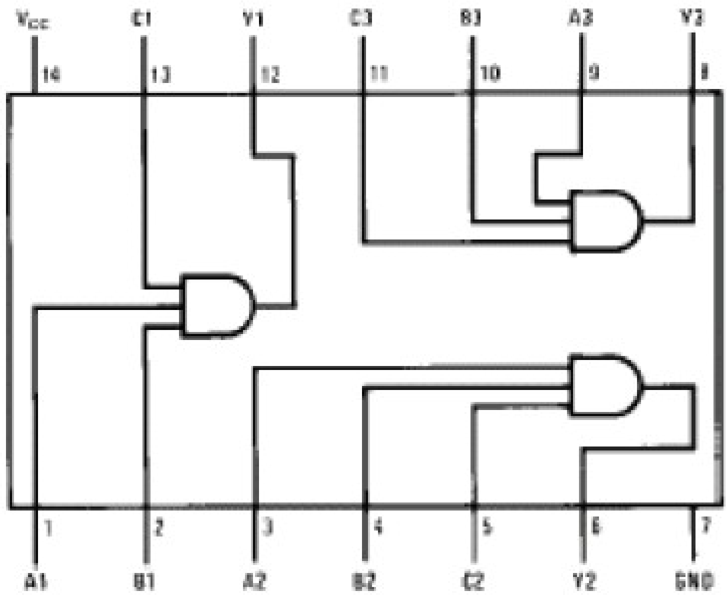
TRUTH TABLE

INPUTS			OUTPUTS	
E_1	E_2	D	LS540	LS541
L	L	H	L	H
H	X	X	Z	Z
X	H	X	Z	Z
L	L	L	H	L

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

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

Pin diagram:



Function Table

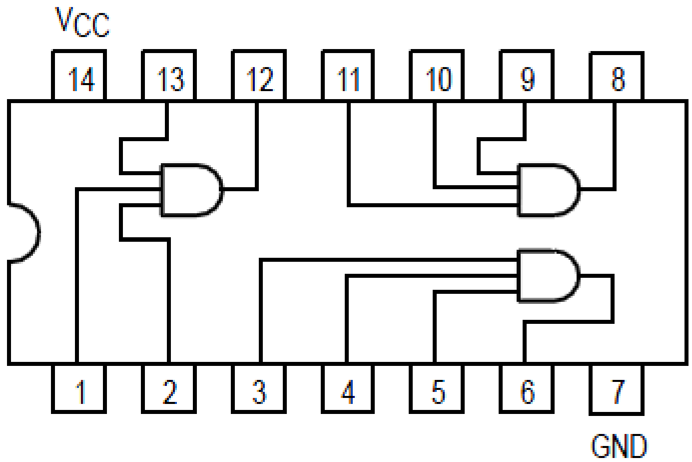
Y = ABC

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

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

CONNECTION DIAGRAM



Recommended Operating Ranges

Symbol	*Parameter*	*Min*	*Nom*	*Max*	*Unit*
Vcc	Supply Voltage	4.75	5	5.25	V
T_A	Operating Ambient Temperature range	0		70	ºC
I_{OH}	Output current - High			-0.4	mA
I_{OL}	Output current - Low			8	mA
V_{IH}	Input voltage - High	2			V
V_{IL}	Input Voltage - Low			0.8	V

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.

Absolute Maximum Ratings

Parameter	***Symbol***	***Value***	***Unit***
Input Voltage (for V_O = 5V to 18V) (for V_O = 24V)	V_I V_I	35 40	V V
Thermal Resistance Junction-Cases (T O-220)	R θJC	5	°C/W
Thermal Resistance Junction-Air (TO-220)	R θJA	65	°C/W
Operating Temperature Range (KA78XX)	TOPR	0 ~ +125	°C
Storage Temperature Range	TSTG	-65 ~ +150	°C

7905: It is a threeterminal negative voltage regulator with thermal overload protection and short circuit protection.

Absolute Maximum Ratings

Parameter	***Symbol***	***Value***	***Unit***
Input Voltage (for V_O = 5V to 18V) (for V_O = 20,24V)	V_I V_I	- 35 - 40	V V
Output Current	I_{OUT}	Internally limited	
Power Dissipation	P_O	Internally limited	
Operating Temperature Range (KA78XX)	TOPR	0 to 150	°C
Storage Temperature Range	TSTG	-65 to 150	°C