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Measuring the muon lifetime using stopped cosmic muon's in a plastic scintillator detector.

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20/02/2010

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Introduction:

The muon is an elementary particle similar to the electron, with negative electric charge and a spin of 1/2. Together with the electron, the tauon, and the three neutrinos, it is classified as a lepton . It is the unstable subatomic particle with the second longest mean lifetime (2.2 µs), behind the neutron (~15 min). Like all elementary particles, the muon has a corresponding antiparticle of opposite charge but equal mass and spin: the anti muon (also called a positive muon). Muons are denoted by μ^{-} *and antimuons by* μ^{+}*. Muons have a mass of 105.7 MeV/*c^2*, which is about 200 times the mass of the electrons. Even so, muons amongst the lightest particles of matter, after the electrons and neutrinos. Since the muon's interactions are very similar to those of the electron, a muon can be thought of in most ways as simply a much heavier version of the electron. The muons while passing through matter can disappear in either of the two ways , by capture by 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. In this experiment we are considering only spontaneous decay.*

The distribution of the muon spontaneous decay is governed by the general radioactive decay distribution.

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

where,
N(0)- Initial number of muons.
N(t)- Final number of muons after the expiry of time "t".
t- time elapsed.
τ- Decay constant.

In this experiment the average muon life time is determined by fitting exp (-t/τ) to the distribution of the time intervals between entry of muon stopped in plastic scintillator (which produces a signal) and their subsequent decay (which gives signal production of electron during the decay).

Source of muon and its decay:

Since the production of muons requires an available center of momentum frame energy of 105.7 MeV, neither ordinary radioactive decay events nor nuclear fission and fusion events (such as those occurring in nuclear reactors and nuclear weapons) are energetic enough to produce muons.

On Earth, all naturally occurring muons are apparently created by cosmic rays, which consist mostly of protons, many arriving from deep space at very high energy.

When a cosmic ray proton impacts atomic nuclei of air atoms in the upper atmosphere, pions are created. These decay within a relatively short distance (meters) into muons (the pion's preferred decay product), and neutrions. The muons from these high energy cosmic rays, generally continuing essentially in the same direction as the original proton, do so at very high velocities. Although their lifetime without relativistic effects would allow a half-survival distance of only about 0.66 km at most, the time dilation effect of special relativity allows cosmic ray secondary muons to survive the flight to the earth's surface. Muons don't participate in strong interactions but take part in weak and electromagnetic interaction. The interactions for production and decay of the muon are given below,

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

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

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

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

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

Fig-1: *Production and decay of muon .*

And the diagrammatic representation for the production of muon and its decay (commonly called as cosmic ray shower) is shown below,

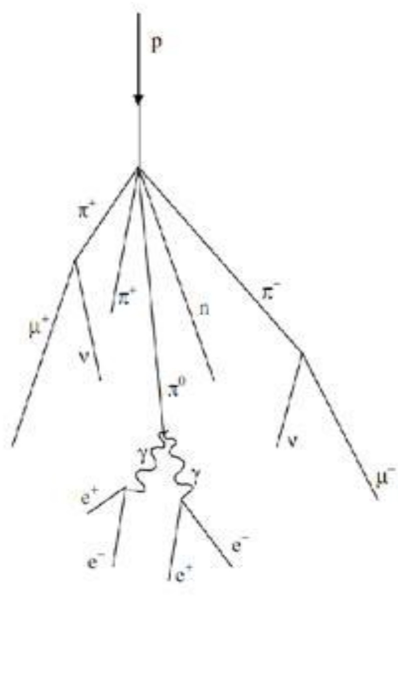

Fig-2: *Production and decay of muon shown diagrammatically .*

Indeed, since muons are unusually penetrative of ordinary matter, like neutrinos, they are also detectable deep underground and underwater, where they form a major part of the natural background ionizing radiation.

Detector Setup, principle and working:

The detector we used is a plastic scintillator coupled with a photomultiplier tubes on it's end. The dimensions of the plastic scintillator bar are 24cm x 24cm x 14.5cm and it is wrapped by a light reflecting paper called "Tyrek" followed by a black paper called "tedler". These wrapping is done to minimize the external light passing through the detector causing a signal.

When a muon pass through the scintillator it produces a photon (due to the loss of kinetic energy of muon for the excitation of scintillator molecules and the photons are produced by the de-excitation of the excited molecules). This photon produced strikes the photomultiplier tube and gets amplified by it to produce a electrical signal. This signal is used as a start signal for the measuring the decay time intervals.

Once the muon entered the scintillator and stopped it undergoes decay into electron and neutrino as per the interactions given above. This electron produced will also give a signal in the plastic scintillator , which is used as a stop signal. Thus by calculating the time interval between the arrival and decay of the muon the average muon life time can be calculated.
The start and stop signals are diagrammatically shown below,

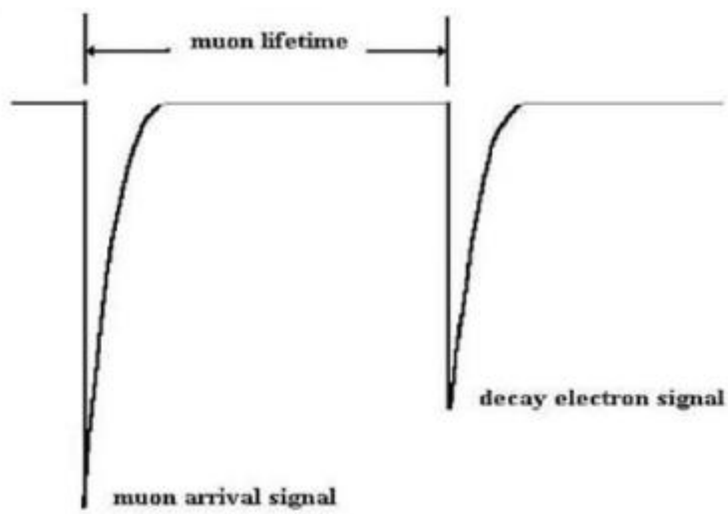

Fig-3: *Time interval between start and stop given to counter.*

The block diagram for the above said time interval calculation is shown below,

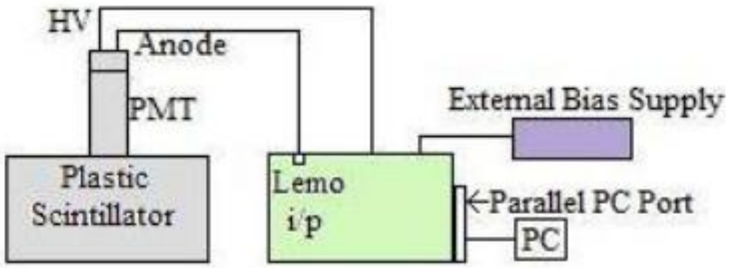

Fig-4: *Block Diagram of the circuit.*

The signals produced by the arrival of muon and the electron produced by the decay of muon can be sensed by a suitable electronic readout interfaced with the plastic scintillator through a photo multiplier tube.

Life time measurement:

The basic thing that is needed for measuring the time difference between the entry and decay of muon into electron is the "clock". It has the frequency of 10 MHz. The block diagram of the electronic readout is shown below,

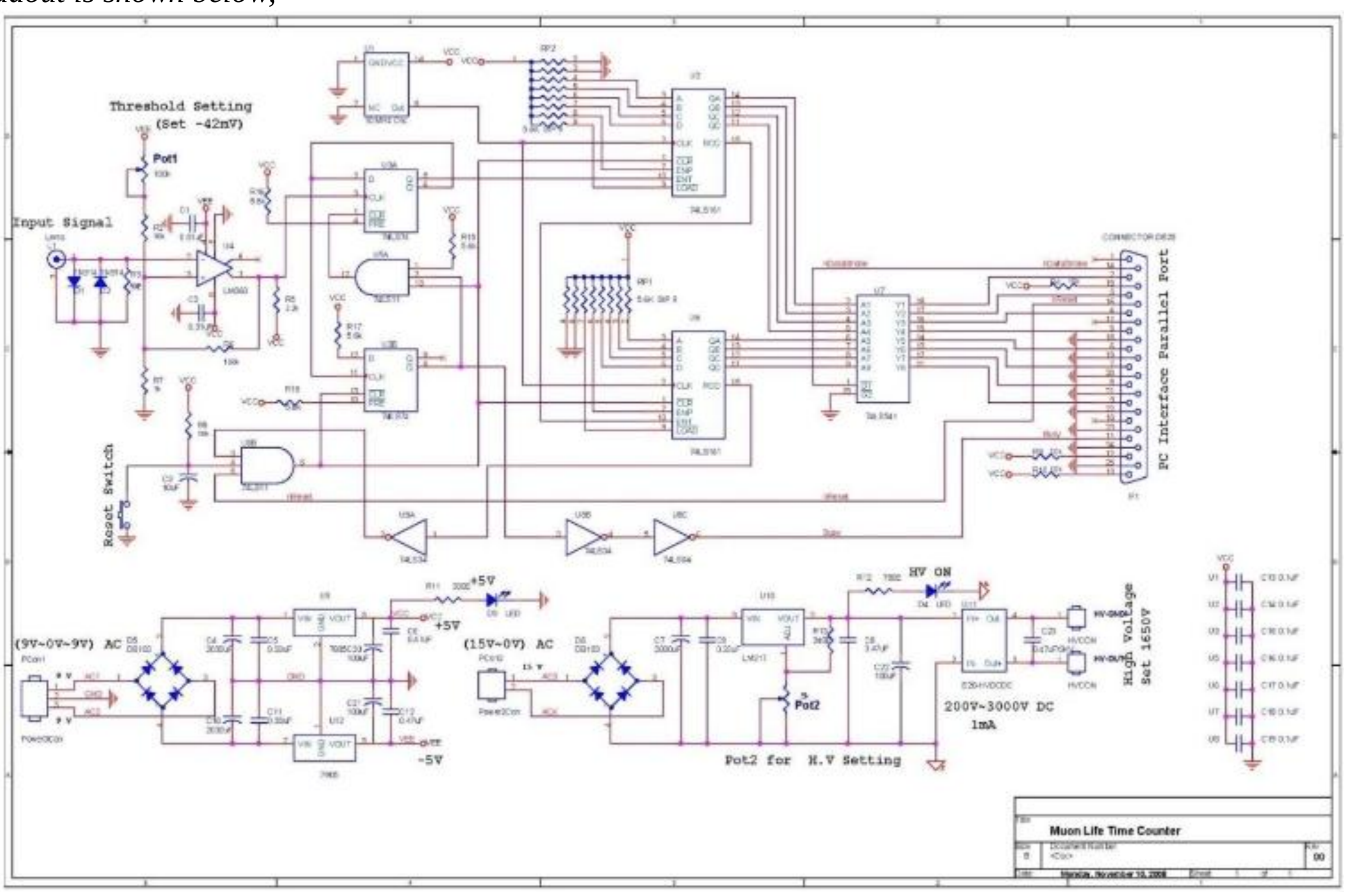

Fig-5: *Detailed electronic circuit of counter.*

The circuit shown in the above diagram consists of two parts (lower and upper). The lower part of the circuit is the power supply circuit which gives the power supply to the IC's (+5 and -5 volts) and PMT (1650 volts) and is mainly consists of voltage regulators. The main circuit i.e the upper part of the diagram is the actual circuit which measures the time interval that is discussed earlier and is mainly consists of comparator, flip flops, counters, oscillator, latches, a buffer IC and a Standard Parallel Port interfacing with the computer.

The IC pin details and the components used in the muon life time measurement circuit is shown below:

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

A Constant threshold voltage is applied to the non-inverting terminal and the negative pulse from the PMT is applied to the inverting terminal of the comparator. This Comparator compares the signal pulse with the threshold voltage and produces an output positive pulse whenever the signal exceeds the threshold voltage.

This output pulse is given as a clock signal to 1st Flipflop, it makes output of Q as high and output of Q' as low. Now the first counter starts counting at the rate of 10MHz as soon as Q is high because the the output of Q is connected to the ENT of the first counter. As soon as the 4-bit counter reaches its maximum counting capacity, its RC0 becomes high which is feed to ENT of the second counter and the second counter starts counting.

If the muon decays into electron, this produces a signal in the output of the comparator (calling it as a second signal).when the second signal arrives at the clock of first flipflop, D will become low (because Q' of first flipflop is low which in turn connected to D). Now output Q will become low and stops the counter.

After the arrival of the second signal 'Q' of first flipflop becomes high, which makes clock of second flipflop high which in turn makes 'Q' of second flipflop as low and the signal is sent to the parallel port through BUSY PIN. After PC receives the send signal, it makes DATA_STROBE to low enabling data buffer. So data buffer will now transfer the counts from counter to PC. When the data's are completely transfered to the PC, the DATA_STROBE is again made high and the reset line becomes low and resets all the flip flops. This makes the counter ready for next muon. Suppose if the muon doesn't decay into electron then the counter will reach its maximum count of 255 bits(25.5μs)which makes the RC0 high. This RC0 signal is inverted and fed to NAND gate which in turn clears all the flip flops and counters making the circuit ready for next muon arrival.

Analysis:

Once the experiment got over and the data's are collected. The next part in the project is the analysis of the obtained data to get the results. Here also we did the analysis on the computerized data obtained (Mainly consist of the number of events and the time interval) by binning and fitting it with appropriate functions. While doing the analysis the background due to the stray light, arrival of a muon before the decay of a muon etc are corrected by considering the background as a constant.
So the function will get the form,

$$N(t) = N(0) * \exp(- t / \tau) + b$$

After doing this we plotted the data points and the fitted curve with the help of "root" software and plot looks as follows,

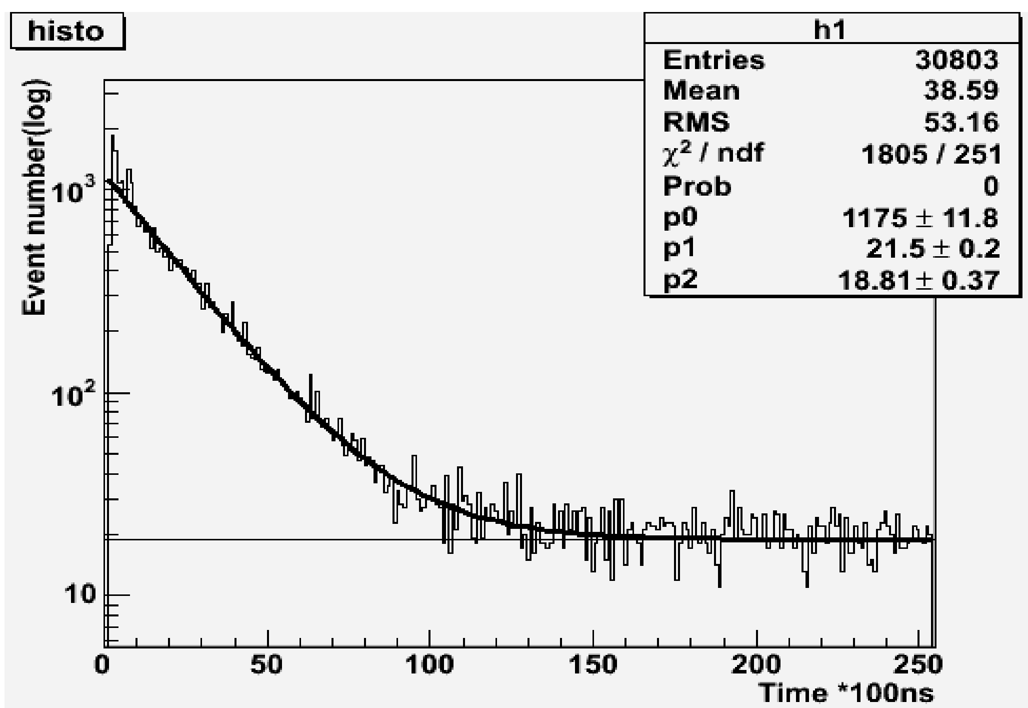

Fig-6: *fitted curve with data points.*

From the graph, we found the mean life time of muon by multiplying the time parameter obtained with time scale on x-axis. The mean life time of muon= 21.5 x 100ns = 2.15 μs =2.2 μs .

Fermi coupling constant:

In order to ensure that we did the experiment correctly we need to check the results with the theoretical values. Here this can be done by calculating the Fermi coupling constant GF of the weak interaction using the formula,

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

where,

$\boldsymbol{\tau}$ *– mean life time,* $\mathbf{G_F}$ *– Fermi coupling constant,* $\mathbf{m_\mu}$ *- mass of muon.*

The obtained value of G_F *is 1.16533 X* 10^{-5} GeV^{-2}*, where,* $\mathbf{m_\mu}$ *= 105MeV.*

Teams:

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References:

1) *"Introduction to Elementary particle physics" by D.J. Griffiths*
2) *"Muon Physics" by T.E.Coan and J.Ye*
3) *Radiation Detection and Measurement, G.F Knoll*
4) *http://pdg.lbl.gov*