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

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Introduction:

Muons are one of the most fundamental particles of the Universe, belonging to the 2nd generation of the lepton family. Its properties are very similar to that of an electron except that its about 200 times heavier than electron (m_μ=105.66MeV). The following report describes an experimental technique to measure the lifetime of muons using a plastic scintillator detector. The intent of this experiment is to determine the distribution of time intervals between entry of a muon into the scintillator (in which the muon stops) and its subsequent decay. A fit of the distribution to the *exp(-t/τ)* then gives the average muon lifetime.

Source of muons:

Cosmic rays are highly energetic particles originating from the outer space impinging on Earth's atmosphere. The primary flux of the cosmic rays consists of extremely high energy protons (E>1GeV). These protons interact with earth's atmosphere to a shower of secondary particles which mainly consist of proton, neutrons and charged and neutral pions. The neutral pions decay quickly into photons which multiply into showers, while the charged pions decay into a muon and a neutrino or anti-neutrino

$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \pi^+ \to \mu^+ + \nu_\mu$$

These are often referred as 'cosmic muons' and are highly energetic travelling almost with the speed of light. The average flux of the muons at sea level is 1 muon per minute per cm^2 and their average energy is about 4GeV.

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

$$\mu^{-} + p \rightarrow n + \nu_{\mu}$$

or by spontaneous decay to an electron ans a neutrino and anti-neutrino pair.

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

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

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

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.

Interaction of muon with matter:

The fundamental principle of detecting any ionizing radiation is the transfer of energy from the radiation to the matter. In our case the muons lose their energy to matter by Coloumb interactions between the muons and the atomic electrons and to some extend the atomic nucleus. The principal modes for energy are:

- ***Inelastic Collisions:*** with energy transferred to the electrons of the materials. Primary mechanism for electrons and muons.
- ***Bremsstrahlung:*** emission of electromagnetic radiation by a decelerating particle. Main source of energy loss relativistic particles ($E >> m_0c^2$). Not important for muons because of their large mass.

The rate of energy loss, is determined by the initial energy and the Z of the material and is governed by the Bethe Bloch equation for heavy charged particle:

$$\frac{dE}{dx} = 4\pi NZ \frac{z^2 e^4}{mv^2}\left[\ln\left(\frac{2\gamma^2 mv^2}{\hbar\omega}\right) - \frac{v^2}{c^2}\right]$$

m, e: mass and charge of electron respectively

z, v: the charge and the velocity of the ionizing particle

Z, N: the electron number and neutron number of the target material

$\hbar\omega$: the average excitation energy of the target material.

Detector:

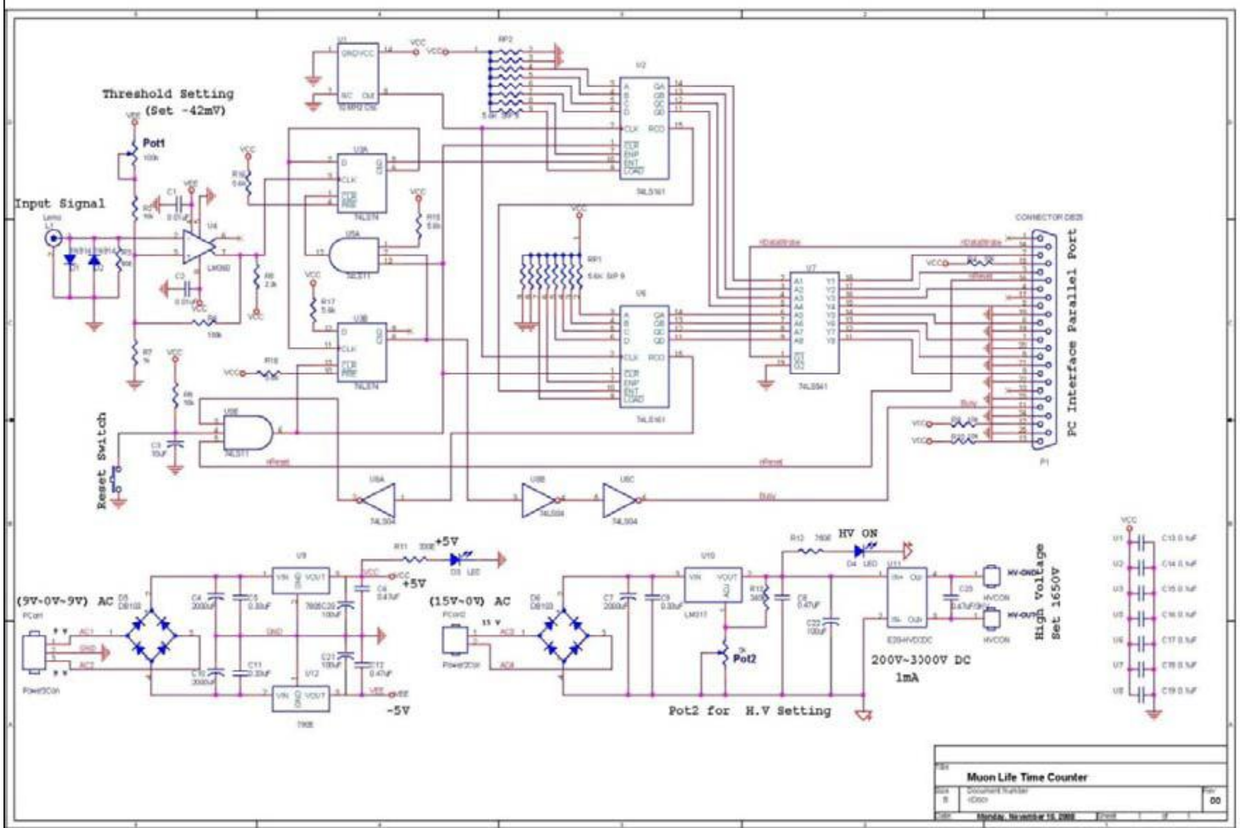
A plastic scintillator (24cm x 24cm x 14.5cm), wrapped reflecting material ‘Tyrek’ followed by a black paper ‘Tedler’. Tedler prevents ambient light to enter the detector and hence minimizes stray scintillation. When a charged particle like muons passes through it loses some of its kinetic energy by ionization (as per the Bethe Bloch equation) and atomic excitation of the scintillator molecule. The de excitation of the molecules then produces radiation near the 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.

A 2 inch diameter Photomultiplier tube (PMT) with 21 pin base is used to convert these light signals into electrical signals. 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. The PMT base is applied a high voltage of 1700 Volts for the same purpose. The rise time of the pulse is a few nanoseconds.

Lifetime measurement:

For the measurement, we need a clock that measures the time difference between the enrty and decay of muon. Fig(1) shows the circuit that was used for this purpose.

The two circuits shown below the main circuit in Fig(1) employs the voltage regulators for providing voltages to IC’s (+5 volts and -5volts) and PMT base (rated 1650 volts). The main counter circuit mainly consists of comparator, flip flops, counters, oscillator, latches, a buffer IC and a Standard Parallel Port interfacing with the computer where the data is recorded[3]. The circuit was first tested with a double PULSER kept at frequency of 1kHz and varying the delay between 4μsecs to 20μsecs checking that the circuit is counting correctly as required.



Fig(1): Circuit diagram of the muon lifetime counter circuit

The signal arriving after the PMT amplification is not free of noise and the actual signal rides over this noise. If present the noise will trigger the counters giving spurious results. The noise level is however of the order of tens of millivolts while the actual signal is of the order of few hundreds of millivolts and hence can be removed by using a discriminator. The comparator (IC-LM360) filters out this noise by allowing only those signals to generate a high logic pulse which has a voltage higher than the reference voltage set at the non-inverting terminal of the IC. The threshold voltage set at the non inverting terminal is 43mV in the present case. The output of the comparator is positive high (the negative input signal is fed to the inverting terminal) digital pulse of 5 Volts.

The comparator output is then fed to the clock of first F/F. When the first signal arrives the D of first F/F which was high before is transferred to the Q of the flip flop and $\bar{Q}$ goes to low making

D low. The Q of first F/F goes to the ENT of 4 bit LSB counter (IC-74LS161). Both the LSB and USB counters are clocked by a 10MHz crystal oscillator. The oscillator gives us a resolution of 0.1µsecs which means we can count for only 25.6µsecs after which the ripple carry output (RCO) from the USB counter will again reset the Flip-Flops without further waiting for the next pulse. This is done with a hindsight of the knowledge that the required event of decay has lifetime of about $2.2\mu s$ and $25.6\mu s$ is more than good enough time window to detect the decay.

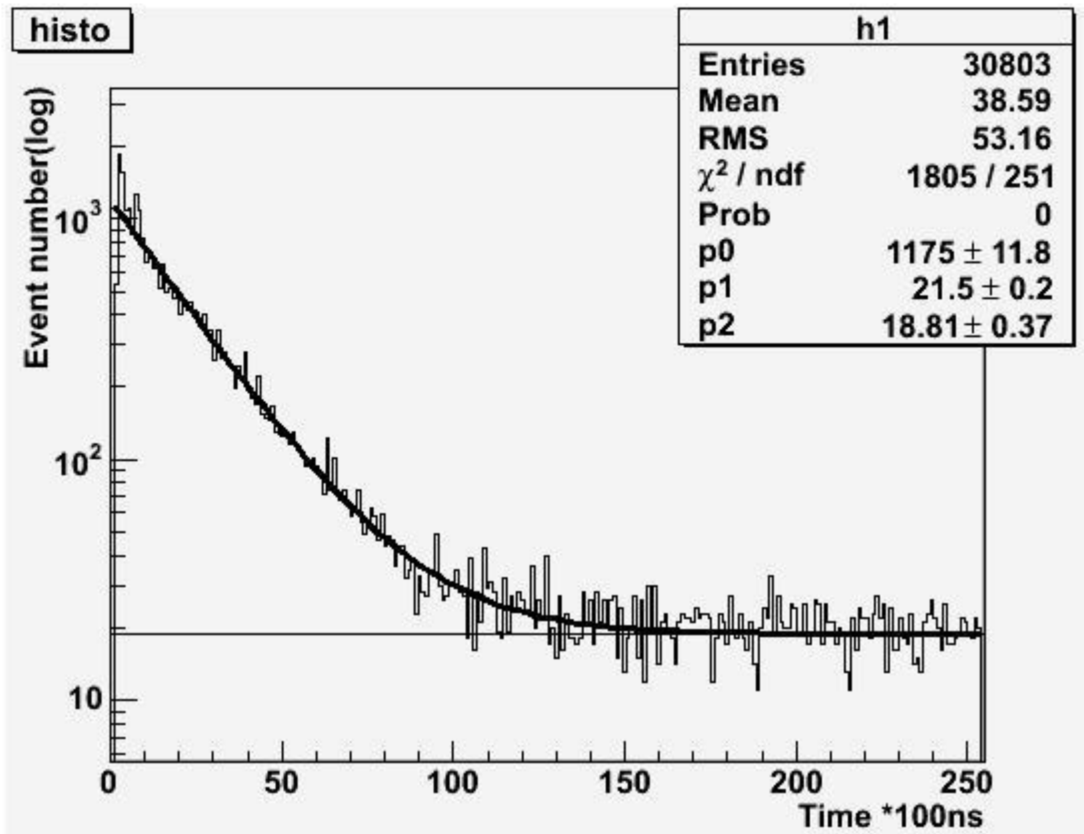
When the second signal arrives the CLK of 2nd F/F goes high making its $\bar{Q}$ state low. The $\bar{Q}$ low then is read by the interfacing program as time when the data from the buffer (IC-74LS541) is to be read. The NDataStrobe is made low and all the bit information is passed by the buffer to the Parallel Port. The interfacing program writes the total number of counts and the time and date of writing of file. The program is run till required number of data points for good statistical measurement is obtained. The components used are listed in the table 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

Analysis:

Measured quantity is the time lag between the START of an event and the STOP of the event. For the distribution, the data is sampled, events are binned and the fitted. A number of background events are recorded due the light leakage in the scintillator, a muon passing through the scintillator without decaying, 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 the period of the period of the time, then the distribution of the muon lifetimes would follow the Radioactive decay law, and is given by:

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



Fig(2): Muon lifetime distribution with background

The data was plotted and fitted in ROOT. From obtained values of the fitting parameters, we have:

N_0 =1 175 ±11.8
τ = 2.15±0.02μs
b = 18.81±0.37

Fermi Coupling Constant:

The muon decay is an electroweak process and the strength of this interaction would be given by Fermi's coupling constant *G*. From the theory, the expression for average muon lifetime of the muon is given by

$$\tau = \frac{192\pi^3}{Gm_\mu^5} \text{ (in Natural units)}$$

Substituting the obtained value of lifetime we get the value for *G* as

$G = 1.176\times10^{-5}\,\text{GeV}^{-1}$

Results:

The average muon lifetime is $\tau = 2.15\pm0.02\,\mu\text{s}$
The value of Fermi's coupling constant obtained $G = 1.176\times10^{-5}\,\text{GeV}^{-1}$

Reference:

(1) Radiation Detection and Measurement, Glenn. F. Knoll

(2) Introduction to Elementary Particle Physics, David J. Griffiths.

(3) Art of Electronics, Hozowitz.