Measurement of Mean μ-Lifetime

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Abstract:

The average muon lifetime is determined in the experiment by stopping muons in a plastic scintillator, where they subsequently decay into electrons. From these stopping muons we get two pulses: one from the entry of a muon and a second one a short time later from the electron arising from the muon decay. The time delay between the two signals is measured for a large number of decays and produces an exponential distribution. To get the lifetime we measure the decay constant which on a logarithmic scale is 1/slope of the line.

Introduction

Muon is an elementary particle and one of the fundamental constituents of matter. Muons belong to the family of leptons (second generation) together with electrons and taus. They behave much like electrons but are heavier than them, with mass of about 105.7Mev/c^2, carry one unit of fundamental charge and are unstable. Muons participate in electromagnetic and weak interactions and are not subjected to strong interactions. On passing through matter, muons (or anti-muons) decay spontaneously via weak interaction into a neutrino-anti-neutrino pair, and an electron (or positron), as shown below:

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

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

Muons can also be captured by nucleus. They are highly penetrating particles .Owing to their large mass; emission of Bremsstrahlung radiation is limited on its passage through matter.

Cosmic Muons

Most of the primary cosmic rays consist of protons (92%) , alpha particles(7%) and some heavier nuclei(1%). To produce muons, primary cosmic ray protons interact in the upper atmosphere with atmospheric nuclei like oxygen and nitrogen to produce secondary particles like 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 “radioactively” into muons .Neutral pions decay into a pair of gamma rays.The muons that are so produced, due to their longer lifetime (10^{-6}secs) and almost complete absence of nuclear interactions, are the principle components of penetrating particles produced by cosmic rays that are observed at sea levels; the sequence of events is illustrated in fig.1.

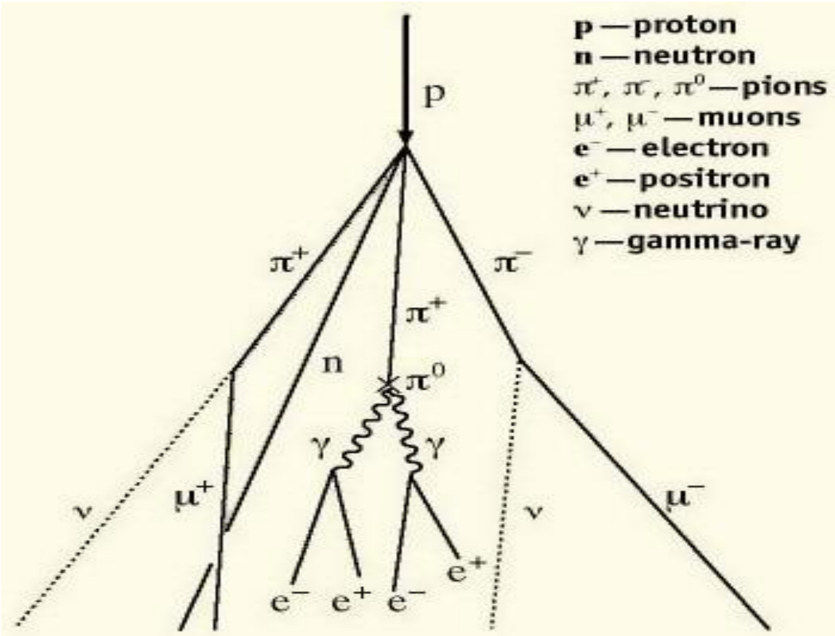

Figure 1. A typical interaction between a cosmic ray proton and an atmospheric nucleus.

Many of the new particles formed are short lived and do not survive to reach sea level but muons are detectable at ground level. The total secondary flux at sea level is $1cm^{-2}min^{-}$ .Roughly 75% consists of positive and negative muons and only 25% electrons and positrons.

If the mean lifetime of the free muons is a few μs then according to classical physics, they should travel a few hundred meters when travelling at the speed of light after being created in the upper atmosphere and many fewer than that indicated above would be expected to reach the ground. Relativistic time dilation effect can explain this.

We know that,

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

where, t is the time measured in the laboratory system,
t' is the time measured in the rest frame of the system,
v is the velocity of the system, and
c is the speed of light.

Thus to an observer on Earth, the muons have a lifetime equal to γt'. Hence if v=0.99c the average distance travelled by muons as measured by an observer on Earth is 4712.4m for t'=2.2μs.

Aim

The aim of this experiment is to determine the average muon-lifetime. This is accomplished in the experiment by stopping the muons in a plastic scintillator, where they subsequently decay into electrons.

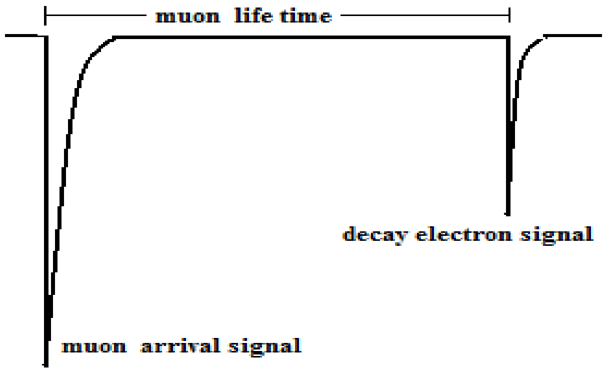

Figure 2: Output of PMT

A short light pulse is produced by the stopping muon which is detected and amplified by a PMT .When the muon decays a second pulse is produced by the emitted electron or positron.The signals for the PMT are fed into an electronic circuit which determines the time delay between the two pulses. The circuit is connected to a PC which is used to read out the data. The distribution of the muon spontaneous decay is governed by the general radioactive decay law,

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

The average muon- lifetime is then determined by fitting exp(-t\\τ) to distribution of the time intervals between entry of muon stopped in the scintillator and their subsequent decay. Hence for the experiment only those muons are considered which slows, loses all their kinetic energy and stops in the detector and decay subsequently.

Experimental Setup

The basic components of the experimental set-up are:

- Plastic scintillator
- Photomultiplier tube
- Time measuring circuit
- PC

1. Plastic scintillator: We are using a plastic scintillator (refractive index =1.58) of dimensions (24cm x 24cm x 14.5cm).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. It is wrapped carefully in highly reflecting (Tyvec) paper to minimize the light loss and then wrapped in Tedlar sheets to prevent the ambient light from entering the scintillator and hence minimizes stray scintillation. When a charged particle like muon passes through this detector, it loses some of its kinetic energy by ionization and atomic excitation of the scintillator molecules. The de-excitation of molecules then produces radiation near the blue and below UV region of electromagnetic spectrum.

2. Photomultiplier tube: The plastic scintillator is directly coupled to the PMT. A 2 inch diameter PMT with 21 pin base (type 9807B, Electron tubes Ltd. manufactured) is used to convert the light signals obtained from scintillator into amplified electrical signals. The incident photons from the scintillator strike the photocathode of the PMT producing photo electrons, these electrons are directed by focussing electrode on Dynodes where secondary electron emission takes place. The final charges are accumulated and then collected at the anode, which gives rise to a sharp and strong electrical output.

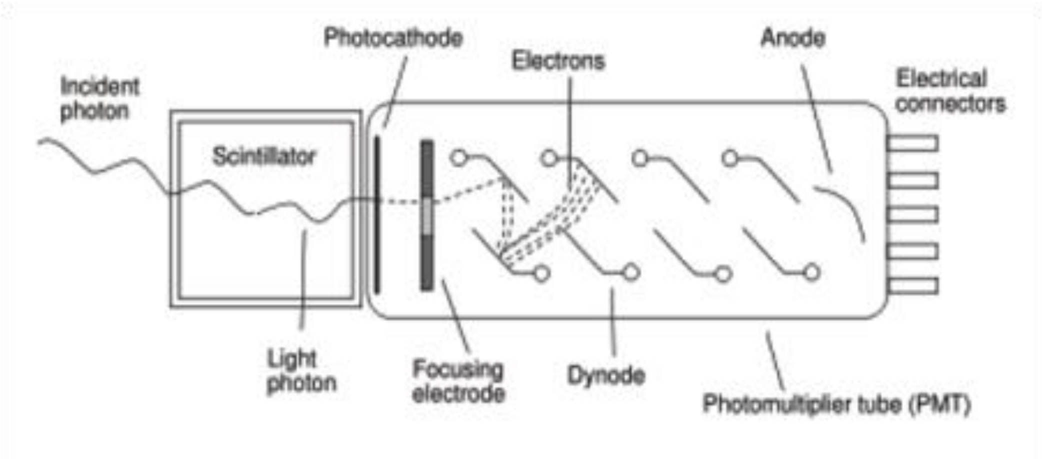

Figure 3: Schematic of a PMT coupled to a scintillator

The PMT base is applied a high voltage of 1.7kV by means of high voltage dc to dc converter (E20-HVDCDC).Negative pulses with a rise time of few nanoseconds are obtained at its output.

3. Time measuring circuit: 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.

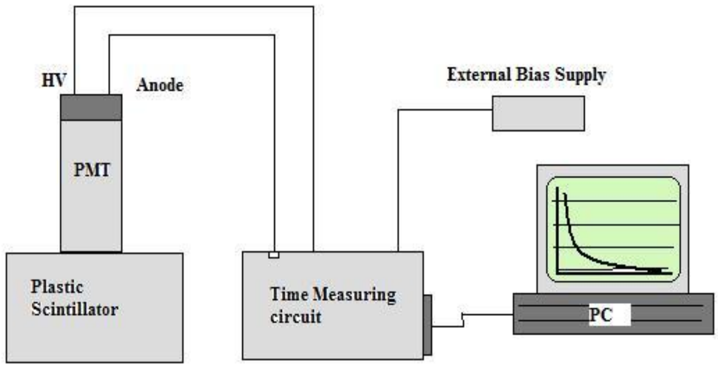

Figure: 4 Schematic diagram of muon life time measurement counter circuit

The Electronic components used are listed below:

IC details:

IC NAME	DESCRIPTION
LM360(8 pins)	Comparator
74LS74(14 pins)	D-Flip Flop
74LS161(16 pins)	4-bit 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
DB103(4 pins)	Bridge rectifier

A crystal oscillator of frequency 10MHz is used to generate the clock for both LSB and USB counters, thus giving the resolution of 0.1µs.

Electronic Circuit Operation: The 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).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 signal is not free of noise and the actual signal rides over this noise. If present, the noise can trigger the counters giving spurious results. Hence the negative pulse from PMT is fed to a comparator (IC LM360). It filters out the noise by allowing only those signals to generate high logic pulse whose levels are above the threshold voltage, - 42mV (in the present case), set at the non-inverting terminal of the IC. The output of the comparator is positive high (since, the negative input signal is fed to the inverting terminal) logic pulse of 5 volts.

The comparator output is then fed to the clock pin of the first F/F (IC 74LS74).The Q o/p of this positive edge-triggered F/F goes high which enables the 4-bit LSB counter (IC 74LS161) and it starts counting at 10 MHz. The $\overline{Q}$ o/p goes low which is taken to the clock input of the second F/F. Hence its $\overline{Q}$ remains high. When the LSB counter reaches binary 15 ,the RCO pin goes high which enables the USB 4-bit counter(IC 74LS161) and it starts counting at 10MHz.

If the muon decays into an electron, a second pulse comes from the PMT, the Q o/p of the first F/F goes low and the LSB counter is stopped. It's $\overline{Q}$ o/p goes high and makes the clock i/p of the second F/F high. Thus the $\overline{Q}$ o/p goes low of the second F/F, is read by the interfacing program as the time when the data from the buffer (IC-74LS541) is to be read. 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 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. 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 and the time and date of writing of file.

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, and to wait for the next pulse from the PMT.

The program is run till required number of data points for good statistical measurement is obtained (48500 data points in the present case).

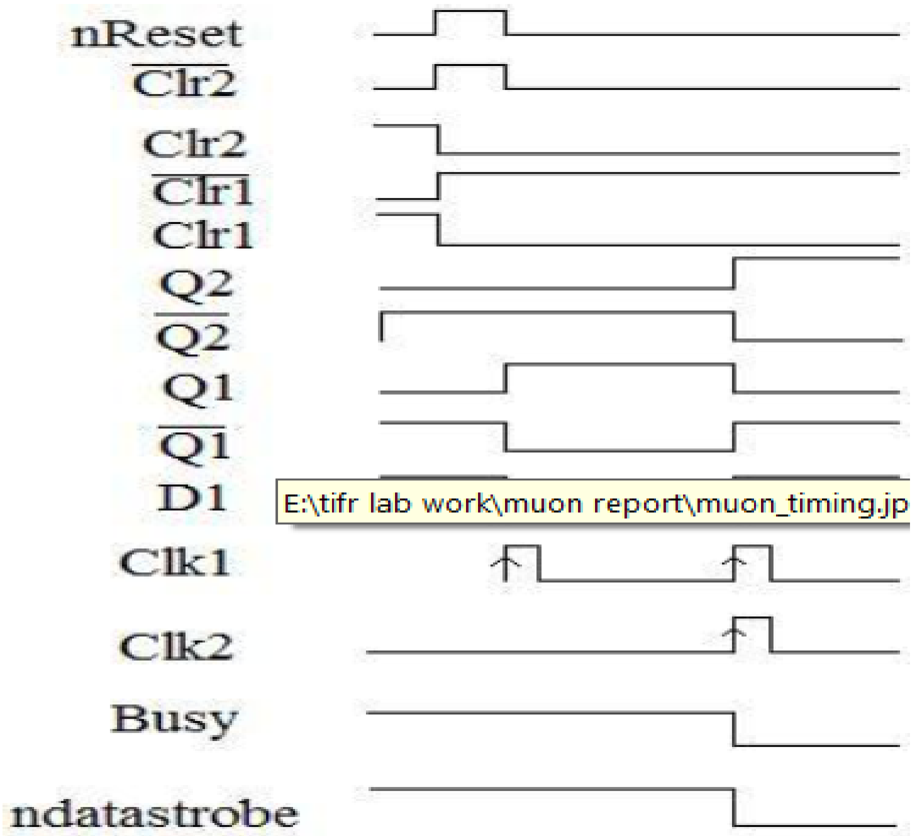

Figure 5: Timing Diagram for the signals

The timing diagram shown above in fig.5 gives the output waveforms for the flip flops with respect to the clock inputs. (Clr1,Q1,D1,Clk1 correspond to the first flip flop and Clr2,Q2,D2,Clk2 correspond to second flip flop.)

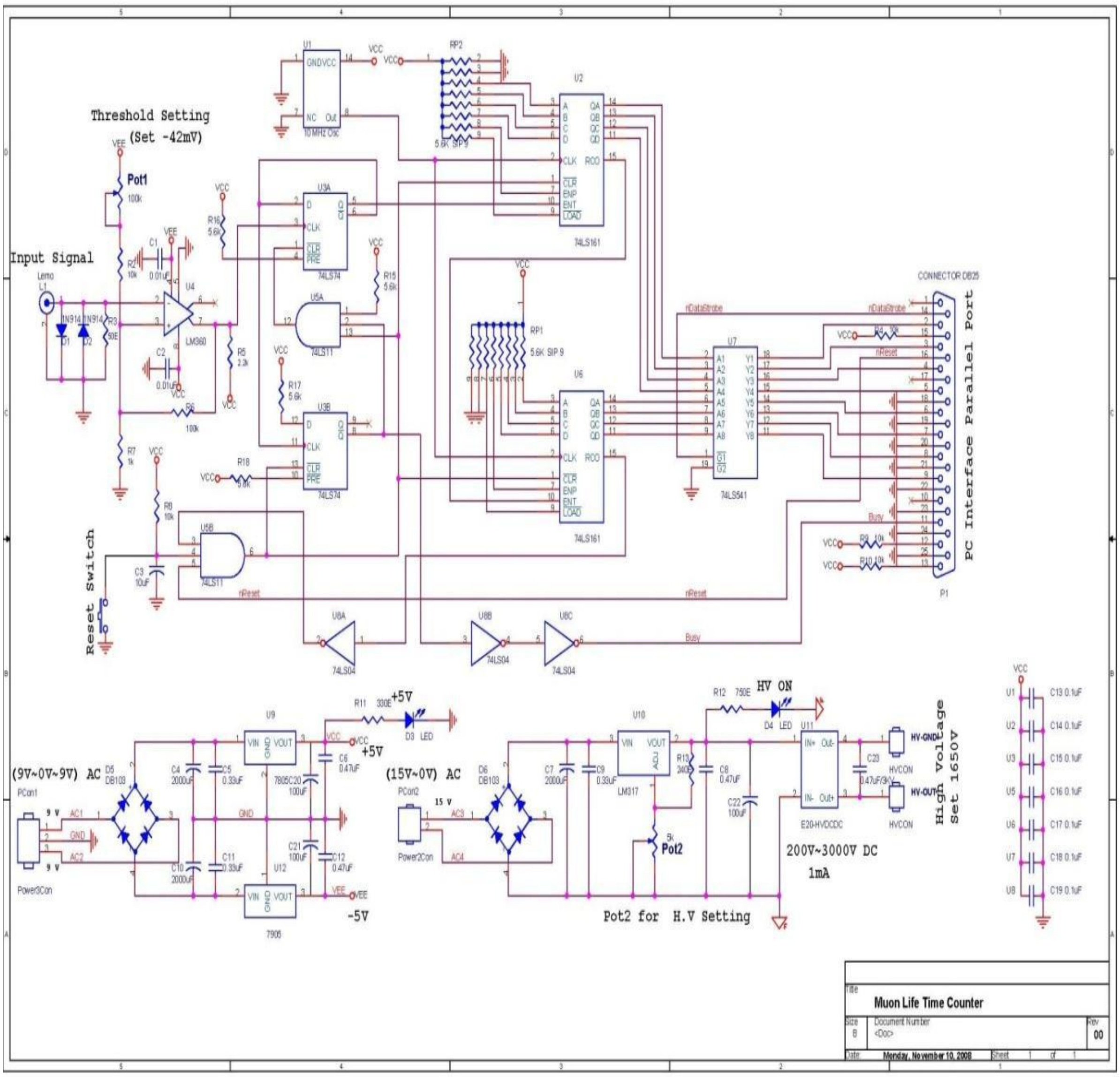

Figure 6.Electronic circuit diagram

The two circuits shown below the main circuit in Fig.6 employs the voltage regulators for providing voltages to IC's (+5 volts and -5 volts) and PMT base (rated1700V)

Analysis

The file saved contains a column of data which are the different time intervals for each muon decay, i.e., the time lag between the start event and stop event. The analysis of data requires fitting of data with appropriate exponential functions, taking background events into account. For the distribution, the sampled data is sampled and the events binned and fitted. The background events are random coincidences of signals not arising from muon decays. These are mainly due to natural radioactivity, through-going muons and PMT after-pulses. 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.

If the background for the data is assumed to be constant over a period of time , then the measured decay spectrum follows the law:

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

where, N_0 is the normalisation parameter,
b is the number of background events per time bin.

The data is fitted with the above function using ROOT and the fitting parameters obtained are:
$N_0 = 855.9 \pm 9.8$
$b = 9.54 \pm 0.27$
$\tau = (2.19 \pm 0.02)\mu s$

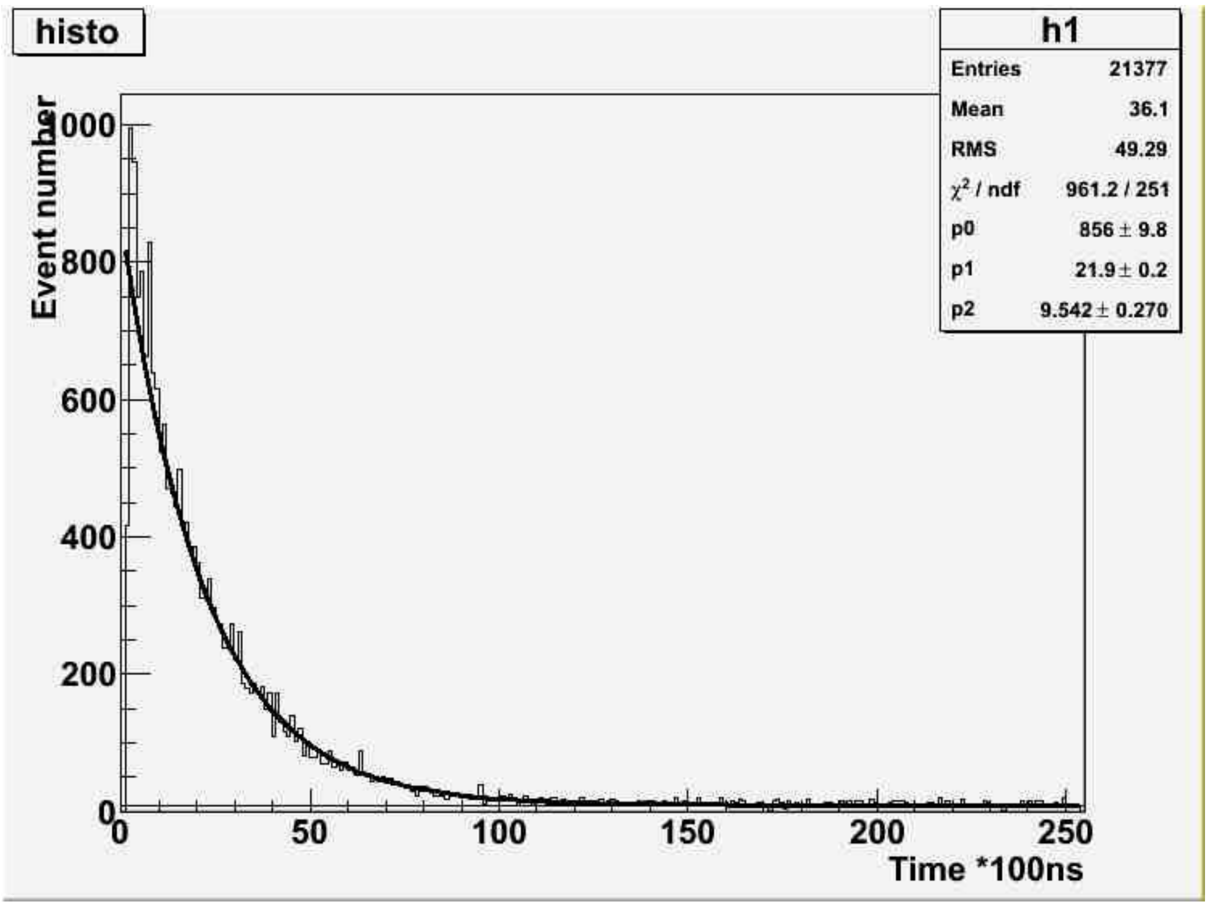

Figure 7: Muon lifetime distribution with background

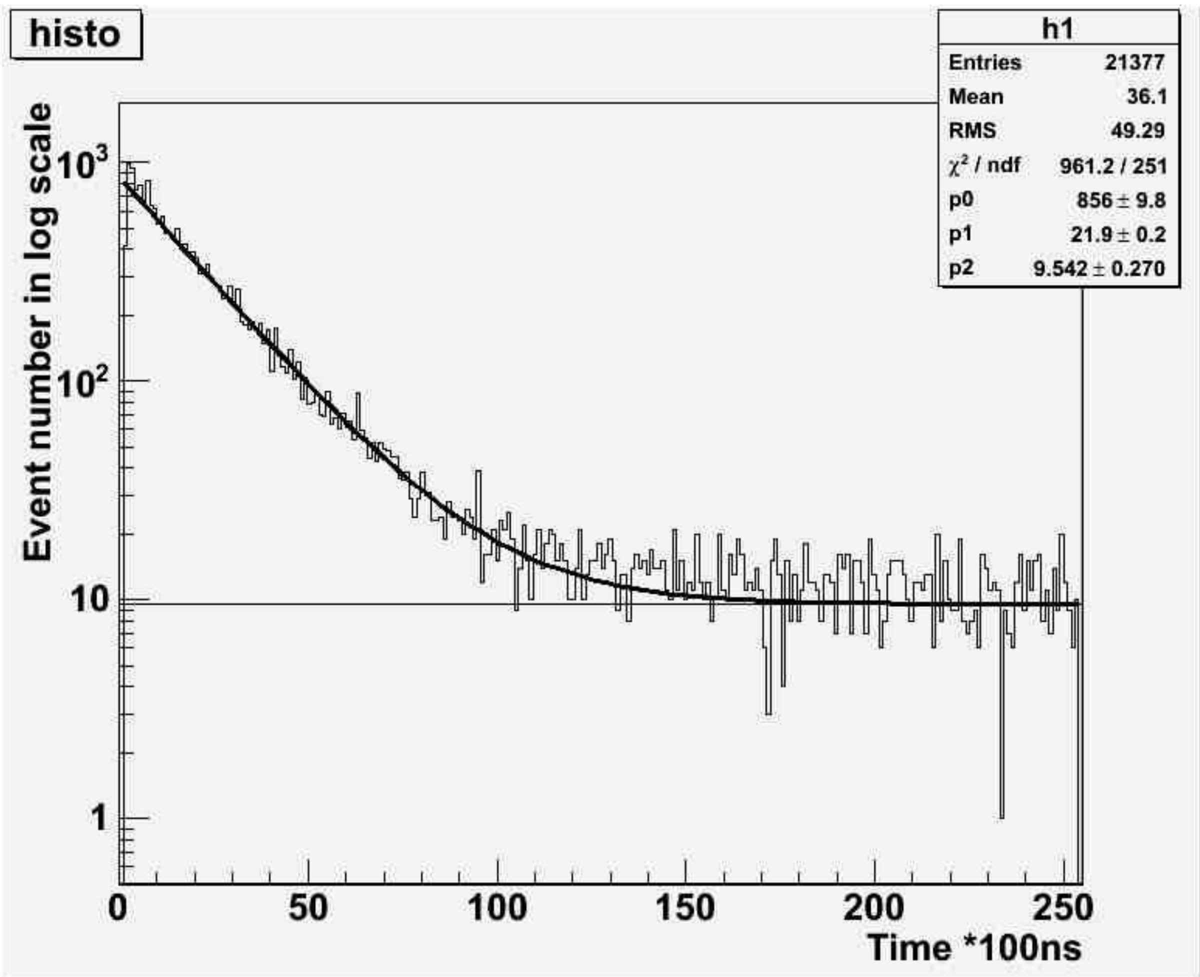

Figure 8: Muon lifetime distribution with background taking event numbers in Log scale

Hence the average muon lifetime is obtained as:

$$\tau = (2.19 \pm 0.02)\ \mu s$$

Fermi Coupling Constant: The universal constants for a process provide a tool to validate experimental results. The Fermi Coupling Constant plays a key role in all precision tests of electroweak model standard model .In the theory of muon decay , which is an electroweak process, the expression for average lifetime of muon is given as:

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

By putting the above value of $\boldsymbol{\tau}$ in the following relation,

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

The value of G_F in natural units is obtained as:

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

where m_μ is taken as 105.66 MeV.

References

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