Determination of the Muon Lifetime Using Cosmic Ray Muon
Introduction

Leptons are a class of fundamental building blocks of matter as proposed by the Standard Model of Particle Physics. There are three generations of leptons with the electron and electron neutrino (1st generation), muon and muon neutrino (2nd generation) and tau and tau neutrino (3rd generation). These are all fermions with spin $\frac{1}{2}$, and all particles other than neutrinos carry one unit of negative charge, where as the corresponding anti-particles carry one unit of positive charge.

Muon has a mass of 105.66 MeV/c$^2$ and interact only via weak and electromagnetic interactions. Due to this large mass, it is unstable. While passing through matter it can undergo either of the following interactions: capture of muon by nuclei or spontaneous decay as follows, which is a weak decay:

\[
\begin{align*}
\mu^- &\rightarrow e^- + \nu_\mu + \bar{\nu}_e \\
\mu^+ &\rightarrow e^+ + \bar{\nu}_\mu + \nu_e
\end{align*}
\]

Cosmic ray muons

Cosmic rays are high-energy particles—mostly protons and alpha particles with a small fraction of heavier nuclei and other subatomic particles such as electrons, positrons and antiprotons. Their origins in supernovae, quasars, and other exotic astronomical events and how they acquire their sometimes colossal energy (over $10^{20}$ eV) is a topic of current research.

Cosmic ray muons are created when cosmic rays enter earth’s atmosphere where they eventually collide with an air molecule and initiate a hadronic shower a cascade of particles (mostly pions) that may undergo further nuclear reactions. Neutral pions ($\pi^0$) decay in into two gamma rays with a very short lifetime less than $10^{-17}$s, which in turn generate electromagnetic showers ($e^+$, $e^-$, $\gamma$) that are not very penetrating. Charged pions ($\pi^+$,$\pi^-$) that do not undergo further nuclear reactions will decay in-flight into muons ($\mu^+,$$\mu^-$) and neutrinos with a lifetime of 26ns. The muon and its corresponding neutrino are classified as leptons particles that do not participate in nuclear reactions. The neutrinos have an extremely tiny interaction cross-section, and most of them pass through the Earth without any further interactions.

Muons were discovered in cosmic rays by C. Anderson and S.H. Neddermeyer in 1937. There are two kinds of muon, the negative $\mu^-$ and its antimatter partner, the positive $\mu^+$. They are essentially heavy versions of the electron and its antimatter partner, the positron, having the same spin and charge, but with a mass $m_\mu = 105.66$ MeV/c$^2$ approximately 207 times larger than the electron. Muons are unstable decaying into an electron or positron and two neutrinos: with an average lifetime $\tau_\mu = 2.197$ $\mu$s about 100 times longer than that of the charged pion.

Because the muon undergoes a 3-body decay, the kinetic energy of the emitted electron or positron is not fixed but has a broad distribution of values with a maximum (endpoint energy)
of 53 MeV in the rest frame of the muon. In fact, the neutrino’s existence was first postulated to explain why electrons from beta-decay are not emitted with a fixed energy as would be predicted if the neutron decayed into only a proton and electron.

Once created, the muon decay is a completely random event that does not depend on its past history. The probability, \( dP \) of decay in the next infinitesimal time interval \( dt \) is independent of how long it has lived since creation and is given by:

\[
dP = \Gamma dt \tag{3}
\]

where the decay rate \( \Gamma \) is the inverse of the lifetime: \( \Gamma = 1/\tau_\mu \).

This decay process implies that the probability of a muon decay in the interval from \( t \) to \( t + dt \) (given that the muon exists at \( t = 0 \)) follows the exponential probability density function:

\[
dP_e(t) = \Gamma \exp(-\Gamma t) dt \tag{4}
\]

Here, the time \( t \) represents the time for a particular decay to occur and will be called a decay time. In one part of this experiment, you will measure a large sample of decay times and compare with this exponential distribution and determine the muon lifetime.
Experimental Setup

The experimental setup consists of plastic scintillator, photomultiplier tube, a timing measuring circuit and high voltage supply as shown in fig 1.

Working Principle of organic scintillator

The fluorescence process in organics arises from transitions in the energy level structure of a single molecule and therefore can be observed from a given molecular species independent of physical state.

A large category of practical organic scintillators is based on organic molecules with certain symmetry properties which give rise to what is known as a π electron structure. The π electronic energy levels of such a molecule are illustrated in figure 2. Energy can be absorbed by exciting the electron configuration into any one of a number of excited states. A series of singlet states (spin 0) are labeled as $S_0$, $S_1$, $S_2$, ... in the figure 2. A similar set of triplet (spin 1) electronic levels are also shown as $T_0$, $T_1$, $T_2$, ... For molecules of interest as organic scintillators, the energy spacing between $S_0$ and $S_1$ is 3 or 4 eV, whereas spacing between higher lying states is usually somewhat smaller. Each of these electronic configurations is further subdivided into a series of levels with much finer spacing that correspond to various vibrational states of the molecule. Typical spacing of these levels is of the order of 0.15 eV. A second subscript is often added to distinguish these vibrational states, and the symbol $S_{00}$ represents the lowest vibrational state of the ground electronic state.

Because the spacing between vibrational states is large compared with average thermal energies (0.025 eV), nearly all molecules at room temperature are in the $S_{00}$ state. In the Figure 2, the absorption of energy by the molecule is represented by the arrows pointing upward.
In the case of a scintillator, these processes represent the absorption of kinetic energy from a charged particle passing nearby. The higher singlet electronic states that are excited are quickly (on the order of picoseconds) de-excited to the S1 electron state through radiationless internal conversion. Furthermore, any state with excess vibrational energy (such as S1\textsubscript{11}, S1\textsubscript{22}) is not in thermal equilibrium with its neighbours and again quickly loses that vibrational energy. Therefore, the net effect of the excitation process in a simple organic crystal is to produce, after a negligibly short time period, a population of excited molecules in the S1\textsubscript{0} state. The principal scintillation light (or prompt fluorescence) is emitted in transitions between this S1\textsubscript{0} state and one of the vibrational states of the ground electronic state. These transitions are indicated by the downward arrows in figure 2. If $\tau$ represents the fluorescence decay time for the S1\textsubscript{0} level, then prompt fluorescence intensity at a time ‘t’ following excitation should simply be
\[ I = I_0 \exp \left( -\frac{t}{\tau} \right) \]  

In most organic scintillators, \( \tau \) is a few nanoseconds, and the prompt scintillation component is therefore relatively fast. The lifetime for the triplet state T1 is characteristically much longer than that of singlet state S1. Through a transition called intersystem crossing, some excited singlet states may be converted into triplet states. The lifetime of T1 may be as much as \( 10^{-3} \) s and the radiation emitted in a de-excitation from T1 to S0 is therefore a delayed light emission characterized as phosphorescence spectrum will be longer than that for the fluorescence spectrum. While in the T1 state, some molecules may be thermally excited back to the S1 state and subsequently decay through normal fluorescence. This process represents the origin of the delayed fluorescence sometimes observed for organics. Figure 2 can also be used to explain why organic scintillators can be transparent to their own fluorescence emission. The length of upward arrows corresponds to those photon energies that will be strongly absorbed in the material. Because all the fluorescence transitions represented by the downward arrows (with the exception of S10 - S00) have a lower energy than the minimum required for excitation, there is very little overlap between the optical absorption and emission spectra (often called the Stokes shift), and consequently little self-absorption of the fluorescence.

**Plastic Scintillators**

If an organic scintillator is dissolved in a solvent that can then be subsequently polymerized, the equivalent of a solid solution can be produced. A common example is a solvent consisting of styrene monomer in which an appropriate organic scintillator is dissolved. The styrene is then polymerized to form a solid plastic. Other plastic matrices can consist of polyvinyltoluene or polymethylmethacrylate.

**Basic Principle of Photomultiplier Tube**

A photomultiplier tube is a vacuum tube consisting of an input window, a photocathode, focusing electrodes, an electron multiplier and an anode usually sealed into an evacuated glass tube. Figure 2-1 shows the schematic construction of a photomultiplier tube.

![Fig 3: Construction of a photomultiplier tube](image)
Light which enters a photomultiplier tube is detected and produces an output signal through the following processes.

1) Light passes through the input window.

2) Light excites the electrons in the photocathode so that photoelectrons are emitted into the vacuum (external photoelectric effect).

3) Photoelectrons are accelerated and focused by the focusing electrode onto the first dynode where they are multiplied by means of secondary electron emission. This secondary emission is repeated at each of the successive dynodes.

4) The multiplied secondary electrons emitted from the last dynode are finally collected by the anode.

**Photoelectron Emission**

Photoelectric conversion is broadly classified into external photoelectric effects by which photoelectrons are emitted into the vacuum from a material and internal photoelectric effects by which photoelectrons are excited into the conduction band of a material. The photocathode has the former effect and the latter are represented by the photoconductive or photovoltaic effect.

Since a photocathode is a semiconductor, it can be described using band models as shown in Figure 4: (1) alkali photocathode and (2) III-V compound semiconductor photocathode. In a semiconductor band model, there exist a forbidden-band gap or energy gap (EG) that cannot be occupied by electrons, electron affinity (EA) which is an interval between the conduction band and the vacuum level barrier (vacuum level), and work function (ψ) which is an energy difference between the Fermi level and the vacuum level. When photons strike a photocathode, electrons in the valence band absorb photon energy (hv) and become excited, diffusing toward the photocathode surface. If the diffused electrons have enough energy to overcome the vacuum level barrier, they are emitted into the vacuum as photoelectrons. This can be expressed in a probability process, and the quantum efficiency η(υ), i.e., the ratio of output electrons to incident photons is given by
\[ \eta(\nu) = (1 - R) \frac{P_\nu}{k} \left( \frac{1}{1 + 1/kL} \right) P_s \]   

(6)

Where

R : reflection coefficient
k : full absorption coefficient of photons
P_\nu : probability that light absorption may excite electrons to a level greater than the vacuum level
L : mean escape length of excited electrons
P_s : probability that electrons reaching the photocathode surface may be released into the vacuum
\nu : frequency of light

In the above equation, if we have chosen an appropriate material which determines parameters R, k and P_\nu, the factors that dominate the quantum efficiency will be L (mean escape length of excited electrons) and P_s (probability that electrons may be emitted into the vacuum). L becomes longer by use of a better crystal and P_s greatly depends on electron affinity (EA).

Figure 4(2) shows the band model of a photocathode using III-V compound semiconductors. If a surface layer of electropositive material such as Cs_2O is applied to this photocathode, a depletion layer is formed, causing the band structure to be bent downward. This bending can make the electron affinity negative. This state is called NEA (negative electron affinity). The NEA effect increases the probability (P_s) that the electrons reaching the photocathode surface may be emitted into the vacuum. In particular, it enhances the quantum efficiency at long wavelengths with lower excitation energy. In addition, it lengthens the mean escape distance (L) of excited electrons due to the depletion layer.

Photocathodes can be classified by photoelectron emission process into a reflection mode and a transmission mode. The reflection mode photocathode is usually formed on a metal plate, and photoelectrons are emitted in the opposite direction of the incident light. The transmission mode photocathode is usually deposited as a thin film on a glass plate which is optically transparent. Photoelectrons are emitted in the same direction as that of the incident light. The reflection mode photocathode is mainly used for the side-on photomultiplier tubes which receive light through the side of the glass bulb, while the transmission mode photocathode is used for the head-on photomultiplier tubes which detect the input light through the end of a cylindrical bulb.

Electron movement in a photomultiplier tube is influenced by the electric field which is dominated by the electrode configuration, arrangement, and also the voltage applied to the
When designing a photomultiplier tube, the electron trajectory from the photocathode to the first dynode must be carefully designed in consideration of the photocathode shape (planar or spherical window), the shape and arrangement of the focusing electrode and the supply voltage, so that the photoelectrons emitted from the photocathode are efficiently focused onto the first dynode. The collection efficiency of the first dynode is the ratio of the number of electrons landing on the effective area of the first dynode to the number of emitted photoelectrons. This is usually better than 60 to 90 percent. In some applications where the electron transit time needs to be minimized, the electrode should be designed not only for optimum configuration but also for higher electric fields than usual. The dynode section is usually constructed from several to more than ten stages of secondary-emissive electrodes (dynodes) having a curved surface. The potential distribution and electrode structure of a photomultiplier tube is designed to provide optimum performance. Photoelectrons emitted from the photocathode are multiplied by the first dynode through the last dynode, with current amplification ranging from 10 to as much as 108 times, and are finally sent to the anode. Major secondary emissive materials used for dynodes are alkali antimonide, beryllium oxide (BeO), magnesium oxide (MgO), gallium phosphide (GaP) and gallium phosphide (GaAsP). These materials are coated onto a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. When a primary electron with initial energy Ep strikes the surface of a dynode, δ secondary electrons are emitted. This δ, the number of secondary electrons per primary electron, is called the secondary emission ratio. Ideally, the current amplification or gain of a photomultiplier tube having the number of dynode stages n and the average secondary emission ratio δ per stage will be $δ^n$. Anode of a photomultiplier tube is an electrode that collects secondary electrons multiplied in the cascade process through multi-stage dynodes and outputs the electron current to an external circuit.

**Time Measurement Circuit**

A stopped muon decaying inside a scintillator gives rise to two signals; one due to itself and the other due to the electron into which it decays. The time measurement circuit is used to determine the delay between the two signals and then it is passed to a PC via USB interface.

When the muon passes through the detector, it produces a light signal, which is fed to a PMT, to produce a negative analog pulse. The decay electron also gives a similar pulse, but of smaller height. The two pulses are shown in Fig.5.

The time difference between the entering of a muon into the detector and its decay into the subsequent products should be measured. For this a 'clock' is needed. The electronic circuit designed for this purpose is shown in Fig.6.
The main components of this circuit are the following:

(a) Comparator  (b) Flip-flops  (c) Counters  (d) Oscillator  (e) Latches  (f) a buffer IC and (g) a standard Parallel Port interfacing with the computer where the data is recorded.

The names and uses of the different ICs used in this circuit are listed in the following table.

<table>
<thead>
<tr>
<th>IC name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM360 (8 PINS)</td>
<td>Comparator</td>
</tr>
<tr>
<td>74LS74 (14 PINS)</td>
<td>D Flip Flop</td>
</tr>
<tr>
<td>74LS161 (16 PINS)</td>
<td>Counter</td>
</tr>
<tr>
<td>74LS541 (20 PINS)</td>
<td>Buffer</td>
</tr>
<tr>
<td>74LS11 (14 PINS)</td>
<td>AND Gate</td>
</tr>
<tr>
<td>74LS04 (14 PINS)</td>
<td>NOT Gate</td>
</tr>
<tr>
<td>7805 (3PINS)</td>
<td>Positive Voltage Regulator</td>
</tr>
<tr>
<td>7905 (3 PINS)</td>
<td>Negative Voltage Regulator</td>
</tr>
<tr>
<td>LM317</td>
<td>Positive Voltage Regulator</td>
</tr>
<tr>
<td>DB103 (4 PINS)</td>
<td>Bridge Rectifier</td>
</tr>
</tbody>
</table>

The small light pulse produced when a muon stops in the scintillator is detected and amplified by the PMT, the output of which is fed to a comparator. The comparator acts as a noise filter, which will allow only signals with amplitudes greater than a certain threshold value to pass through. Once there is a signal at the comparator output, it starts a counter, which counts at a rate of 10MHz, giving a resolution of 0.1μs. If a second pulse from a decaying muon arrives soon after the first, the counter is stopped and the PC is signalled that the data is to be read. The PC, after reading the data, resets the circuit ready for more decays. If there's is no second pulse following the first pulse after a certain period, the circuit resets itself and waits for the second pulse to come.
The LM360 high speed comparator is the first stage of the electronic circuit. A potential divider is used to set the threshold for the comparator. The comparator filters out noise by allowing only those signals which have a voltage higher than the reference voltage, of 42mV, set at the non-inverting terminal of the IC, to generate a high logic pulse. 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.

This pulse acts as the clock of the first D-FF. Two flip-flops are used in this circuit. In the cleared state, the Q o/p is low and Q’ o/p is high. Q’ o/p of the 1st F/F is connected to its D-i/p. When the clock comes, Q goes high and Q’ goes low. The positive high o/p of the LM360 comparator acts as the clock for the 1st F/F. When the clock is present, the Q o/p of the 1st F/F goes high, goes to the ENT of the 1st 4-bit synchronous counter and starts counting at 10MHz. The Q o/p of the 2nd F/F is low and is fed to the clock of the 2nd F/F. Since the clock is low, Q o/p of the 2nd F/F is low and its Q’ o/p is high.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
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<tbody>
<tr>
<td>PR</td>
<td>CLR</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
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<td>H</td>
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<td>H</td>
<td>H</td>
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</tbody>
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Table 1: D-FlipFlop Truth table

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.

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

There are two cases,

Case 1: Muon decays into an electron

When a muon decays into an electron, a 2nd pulse comes from the PMT and passes through the comparator soon after the first. Now, the 1st F/F’s Q o/p goes low and stops the counter. Meanwhile the Q’ o/p, which is the clock of the 2nd F/F, goes high, making the Q o/p of the 2nd F/F high and its Q’ o/p low. This low Q’ o/p clears the 1st F/F as well as the counter. The low Q’ is read as the time when the data from the buffer (IC-74LS541) is to be read by the interfacing program. Q’ after buffering is sent to the BUSY
Fig 11: Schematics for time measurement circuit
pin of the PC parallel port. On receiving the BUSY signal, the DATA_STROBE is pulled low to enable the data buffer, which passes the count from the counter to the PC, which reads the data. After reading data, the DATA_STROBE line goes high and the RESET line is pulled low for a few microseconds. This clears the F/F back to the waiting state and the counter is ready for the next PMT signal.

**Case 2: Muon doesn’t decay into an electron**

The counter will count up to 255, i.e. if a second pulse is not received within 25.5μs, the RCO (Ripple Carry Output) goes high. This is inverted to clear the counter and the F/Fs, to wait for the next PMT pulse.

**Data Analysis**

The lifetime of a muon as seen by us is not a constant quantity. The decay of the muon is a statistical process. Therefore the aim of this experiment is to determine the average lifetime of the muon. We do it by stopping muons in a plastic scintillator and detecting its decay. The time information is collected from the time measuring circuit on a PC, with the use of a parallel port. A computer program is written, which takes a note of the time interval between the muon’s arrival and its decay on a text file. The experiment is run till sufficient number of counts is obtained. The recorded time intervals follow an exponential distribution. The distribution of the events is governed by the relation

$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$$  \hspace{1cm} (7)

where, $N_0$ is the initial population of muons, $N$ is the population muons at time $t$ and $\tau$ is the lifetime of the muon. However background events are also present in the readings. They might be due to natural radioactivity, PMT after pulses, and other through going muons. The background pulses arising due to entry of one muon and due to the entry of another muon within the time interval of 25.5 μs is quite negligible as the avg. muon flux at the sea level is about 1 muon/sq. cm/min. The background is also exponential but the time constant is very high so, we assume that the background is constant over a period of time, the decay spectrum could be written as

$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right) + b$$  \hspace{1cm} (8)

where $b$ is the number of background events.
Studies & Measurement

1) Observe signal in oscilloscope
2) collect time difference with the setup and calculate the muon lifetime
3) collect signal in oscilloscope and estimate charge of muon signal as well as electron signal

Precaution:

1) Do not increase the PMT voltage beyond 1750V
2) Take precaution while measuring high voltage, Connect first ground probe to HV connector. While probing high voltage, make sure you are in contact with any metal surface.
3) Do not touch any ICs with out ESD strap.
4) Take additional care when you handle devices during cold weather. Indoor humidity tends to decrease in cold weather, causing an increase in static electricity.
5) Do not touch solder joints, pins, or exposed printed circuitry.