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

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INTRODUCTION:

The muon is one of the fundamental particles and belongs to the fermion family. It behaves very much like an electron, participating in weak and electromagnetic interaction, except that it is much heavier (m_μ=105.66 MeV) than electron and is unstable. The intent of this experiment is to measure the average muon lifetime. 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.**[1]**

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

The probability of capture by nucleus is low for low Z materials. Plastic scintillators (used in the present experiment) are made of chains of carbon and hydrogen polymers. For hydrogen the capture probability is very low while for carbon the effect has been well studied in literature. In the present case however we have not considered this effect in our analysis.
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.

Source of Muons:

The constant bombardment of atmosphere by the primary cosmic ray containing high energy charged particles gives rise to showers of secondary particles which include protons, neutrons, charged and neutral pions, kaons, photons, electrons and positrons. The pions decay and produce highly energetic muon particles which travel almost at the speed of light. Studies[2] show that the muon production height is at about 15 kms from sea level and it takes 50µsec for them to reach sea level. The fact that this transit time of 50µsec is more than 20 times the muon lifetime at rest corroborates the effect of time dilation for particles travelling at speed of light. Also the muons are highly penetrating particles. This is because of their heavier mass which limits the bremsstrahlung radiation it emits when it passes through the matter. The flux of the muons at sea level is approximately 1 muon per minute per cm^2 at sea level[2]. For the experiment only those muons are considered which slows, stops in the detector and decays subsequently.

Detector:

The detector used is a (24cm x 24cm x 14.5 cm) plastic scintillator detector wrapped using a light reflecting material called “Tyrek”, followed by a black paper called “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 and atomic excitation of the scintillator molecules (the Bethe Bloch[3] equation gives a more accurate measure of the energy loss of charged particles in matter). 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 (type 9807B, Electron tubes Ltd made) 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 focussed 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.

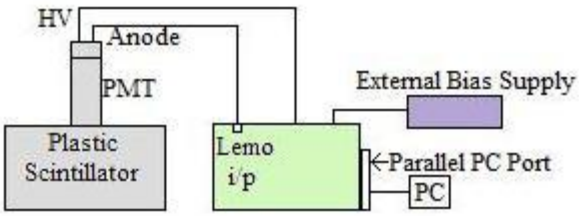

Fig1: Schematic Diagram of Muon Lifetime counter circuit

Life Time Measurement:

For the measurement a “clock” is needed which can tell the time difference between the entering of the muons in detector and the ensuing decay of the muons. The block diagram of the electronic readout imprinted on the PCB which just does this job is shown in Fig:2.

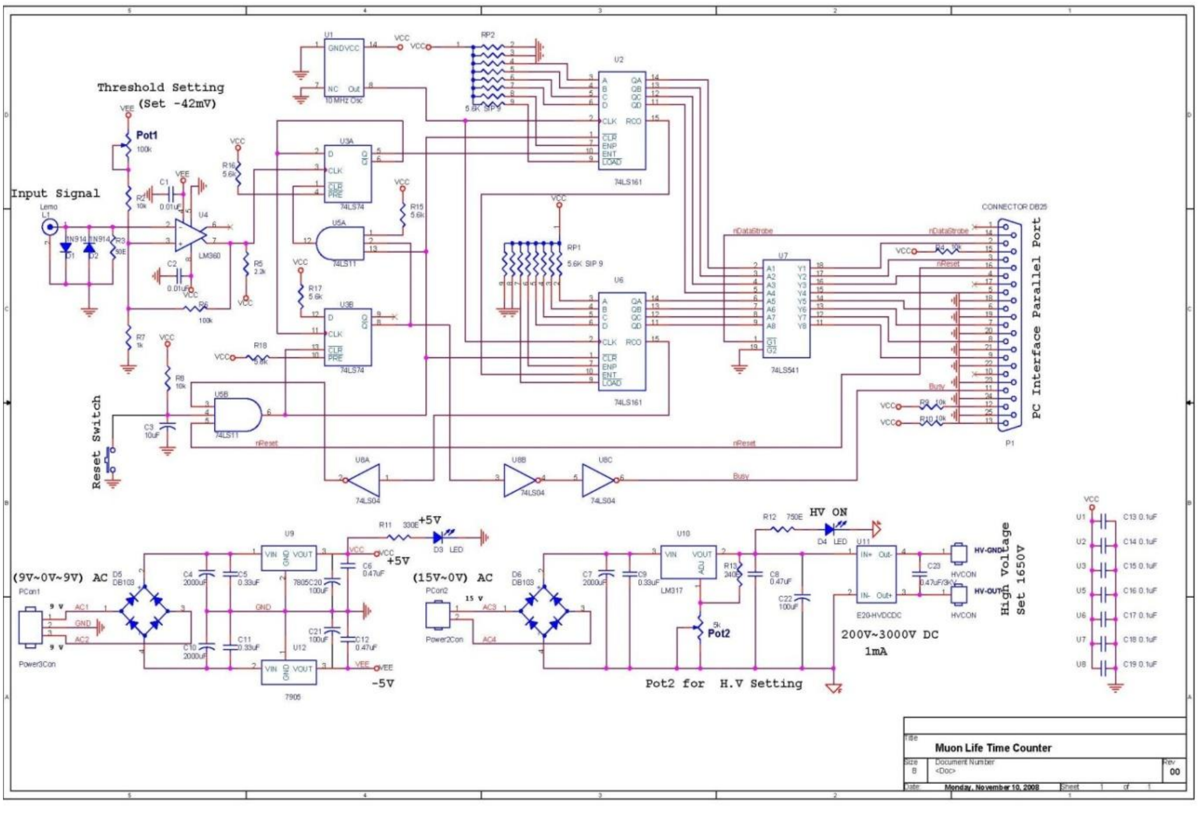

Fig2: Muon Lifetime counter circuit

The two circuits shown below the main circuit in Fig2 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.

The interfacing program is attached at the end of this report. First it initializes the Standard Parallel Port Byte mode and subsequently enables the bi directional port. It then sends HIGH -LOW-HIGH signal through nReset to IC74LS11 (AND gate) to clear the FLIP FLOPS (IC-74LS74) of previous states. In clear states the Q outputs of the F/F's are set to low while $\bar{Q}$ is set to high. The D of first flip flop is set to high and the clock of the second flip flop is high . However the output state of second flip flop doesn't change state because of the clear signal . The $\bar{Q}$ of second F /F is still high sending high signal to the PC. After the clear state the positive edge triggered IC's wait for their respective clock signals.

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 2.2μsecs and 25.6 μsecs is more than good enough time window to detect the decay.

When the second signal arrives the CLK of 2^{nd} 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 (36000 data points in the present case). The components used are listed in the table below. The timing circuit is shown in Fig3. (Clr1,Q1,D1,Clk1 correspond to 1^{st} FF and Clr2,Q2,D2,Clk2 correspond to 2^{nd} FF.)

1) IC Details:

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

2) Oscillator(4 Pins) : Frequency = 10 MHz

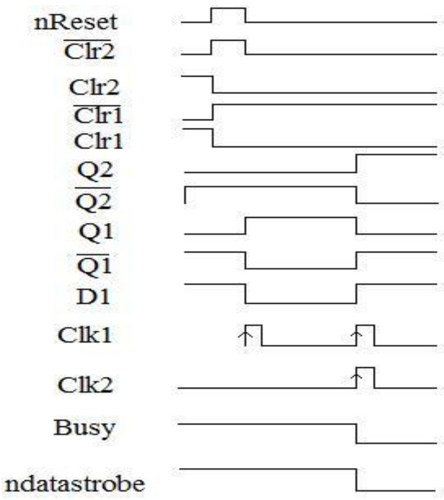

Fig3: Timing Diagram for the signals

Analysis:

The analysis of data requires fitting of data with appropriate functions. The measured quantity is the time lag between the start event and the stop event. For the distribution, the time difference is sampled and the events binned and then fitted. The sampled data is not free from the background events. The detector doesn't know if the events produced are from the stopping of muon and its decay or from starting from some other radioactive source or light leakage and stopping from another of the same. These will be random and will be inherently present in the sample data points. The background events which are produced due to start from one muon and stop from another one will be very small as the flux reaching down at sea level is very small when compared to the 25.6μsecs window we have put in for counting. 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

$$N = N_0 \exp(-t/\tau) + b$$

The data is fitted with the above function using ROOT[5] and the fitting parameters obtained are :

$$N_0 = 887.13 \pm 0.51$$
$$b = 14.75 \pm 0.07$$
$$\tau = (2.123 \pm 0.002)\mu secs$$

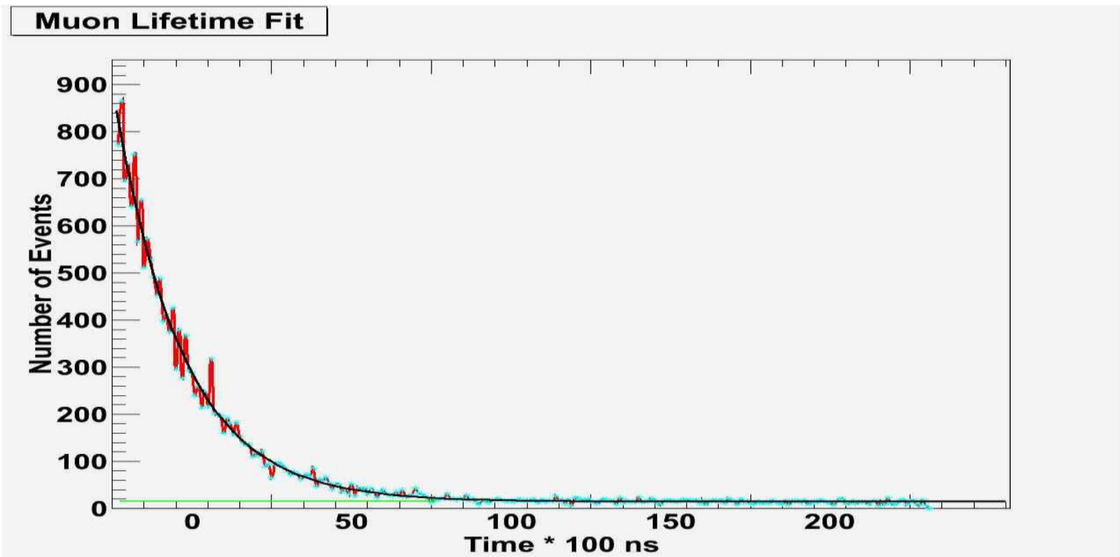

Fig2: Muon Lifetime Distribution with background.

The average muon life is hence determined to be $(2.123 \pm 0.002)\mu secs$.

Fermi Coupling Constant:

The universal constants for a process provides a tool to validate experimental results. 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 [1]

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

The value of G obtained for the above value of τ is

$$G = 1.2026 * \ 10^{-5}\ GeV^{-2}$$

The standard uncertainty in the above value is $0.00050 * \ 10^{-5}\ GeV^{-2}$.

References:

[1] Introduction to Elementary Particles, Griffiths.

[2] http://pdg.lbl.gov

[3] Radiation Detection and Measurement, G.F Knoll

[4]Art of Electronics, Hozowitz

[5] http://root.cern.ch/

Appendix:

```
/* Program to interface a Muon Life Time Counter with SPP of IBM PC in WIN XP Environment */
/* "muonlife.c",    26-09-2007      L.V.Reddy, DHEP, TIFR. */
/* "muonlife.exe" */


#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include <windows.h>
#include <time.h>


#define BASE 0x378                  /* Definning the BASE ADDRESS of Parallel Port LPT1 */
#define ECR  BASE + 0x402



/***** This Code is meant for to Run Parallel Port in WIN XP environment. *****/

typedef short (_stdcall *inpfuncPtr) (short portaddr);
typedef void (_stdcall *oupfuncPtr) (short portaddr, short datum);

void test_read8(void);
void test_write(void);
void test_writ_datum(short datum);

inpfuncPtr inp32fp;
oupfuncPtr oup32fp;

short Inp32 (short portaddr)
{
        return (inp32fp) (portaddr);
}

void  Out32 (short portaddr, short datum)
{
        (oup32fp) (portaddr, datum);
}

/***** The above Code is meant for to Run Parallel Port in WIN XP environment. *****/



int main (void)            /* Main C Program is starting from here */
{
   int statusbits;
   int busystatus;
   int data;
        int loop = 0;
   int sample = 1;

   char filename [200];      /* For filename getting */
        FILE *FilePointer;

        time_t starttime;        /* For Time and Data printing */
```

```
        struct tm *stime;

    char hotkey = ' ';        /* For key testing and assigned to blank */


/***** The below Code is meant for to Run Parallel Port in WIN XP environment. *****/


    HINSTANCE hLib;

        hLib = LoadLibrary("inpout32.dll");

        if (hLib == NULL) {
                fprintf(stderr, "LoadLibrary Failed. \n");
                return -1;
        }

        inp32fp = (inpfuncPtr) GetProcAddress(hLib, "Inp32");

        if (inp32fp == NULL) {
                fprintf(stderr, "GetProcAddress for Inp32 Failed. \n");
                return -1;
    }

        oup32fp = (oupfuncPtr) GetProcAddress(hLib, "Out32");

        if (oup32fp == NULL) {
                fprintf(stderr, "GetProcAddress for Oup32 Failed.\n");
                return -1;
    }

/***** The above Code is meant for to Run Parallel Port in WIN XP environment. *****/



/*** The Muon Data Taking Program is starting from here. ***/


        printf("****** Program is running ******\n\n");

        Out32 (ECR, 0x01);        /* Initialisation to SPP Byte Mode */

    Out32 (BASE + 2, 0x24);   /* Enable Bi-directional port and Reset = H */
    Out32 (BASE + 2, 0x20);   /* Enable Bi-directional port and Reset = L */
        Out32 (BASE + 2, 0x24);   /* Enable Bi-directional port and Reset = H */


    printf("Enter Data File [c:\\muonlifedata\\filename.txt]: ");
        scanf("%s", filename);                          /* Getting Data File Name */

        FilePointer = fopen(filename, "a+");            /* Openning Data File Name */

        if (FilePointer == NULL) {                      /* Checking Data File Name */
                printf("Can not open filename.txt file.\n\n");
      return 1;
        }
```

```
        fprintf(FilePointer, "SAMPLE      DATA     TIME       DATE \n");     /* Data File Header */

   printf("     \n");
        printf("SAMPLE      DATA     TIME       DATE \n\n");

        do {

                statusbits = Inp32 (BASE + 1);           /* Read the Status Port */
           busystatus = (0x80 & statusbits);        /* Busy is 7th Bit */

                if (busystatus == 0x80)
                {
                        Out32 (BASE + 2, 0x26);              /* Making Data Strobe = L */
                        data = Inp32 (BASE);                 /* Reading data from Port */

                        time (&starttime);                   /* To grab and store Current System Time */
                        stime = localtime (&starttime);      /* To convert Time to struct tm */


                        fprintf(FilePointer,"%06d         %03d     %02d:%02d:%02d    %02d-%02d-%4d \n",
sample, data, stime->tm_hour,stime->tm_min, stime->tm_sec, stime->tm_mday, stime->tm_mon+1, stime-
>tm_year+1900);
                        fflush(FilePointer);                 /* Writing data into a Data File */

                        printf("%06d         %03d     %02d:%02d:%02d     %02d-%02d-%4d ", sample, data,
stime->tm_hour,stime->tm_min,      stime->tm_sec,      stime->tm_mday,      stime->tm_mon+1,      stime-
>tm_year+1900);
                        printf("    Press 'q' to end the Program.  \n");

                        Out32 (BASE + 2, 0x24);      /* Making Data Strobe = H and Reset = H */
                        Out32 (BASE + 2, 0x20);      /* Making Data Strobe = H and Reset = L */
                        Out32 (BASE + 2, 0x24);      /* Making Data Strobe = H and Reset = H */

                        sample = sample + 1;

                }
                if( _kbhit() )                   /* Checking for any key pressed */
                {
                        hotkey = _getch();           /* Getting the pressed key */
       hotkey = toupper(hotkey);
                }

        } while ((1) && (hotkey != 'Q'));     /* Evaluating DO LOOP Condition for 'q' key pressed*/

        fclose(FilePointer);                 /* Closing Data File */

        FreeLibrary(hLib);                    /* Freeing from WIN XP Library */
        return 0;
}
```