Experiment 10:
Muon Decay with Custom Electronics

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1 Introduction

Muons, discovered in cosmic rays by Carl D. Anderson and Seth Neddermeyer in 1936, are fascinating subatomic particles that have since been instrumental in advancing our understanding of particle physics. Despite their short lifetime, muons play crucial roles in various natural phenomena and have become indispensable tools for scientists studying fundamental particles and their interactions.

Muons are elementary particles categorized as leptons, similar to electrons but with a much greater mass. They are often referred to as the "heavy cousins" of electrons. Muons are negatively charged and are denoted by the Greek letter μ. They have a mean lifetime of approximately 2.2 microseconds and decay into electrons and neutrinos through weak interactions.

Due to time dilation effects from their relativistic speeds, muons created at high energies in the upper atmosphere can travel significant distances before decaying. The primary mode of decay for muons is through weak interactions, specifically into an electron, an electron antineutrino, and a muon neutrino.

This decay process is mediated by the weak force and is similar to beta decay, where a W boson is exchanged between the muon and the resulting electron, neutrinos, or antineutrinos. A diagram of how muons are created from collisions in the atmosphere can be seen in Figure 1 [1].

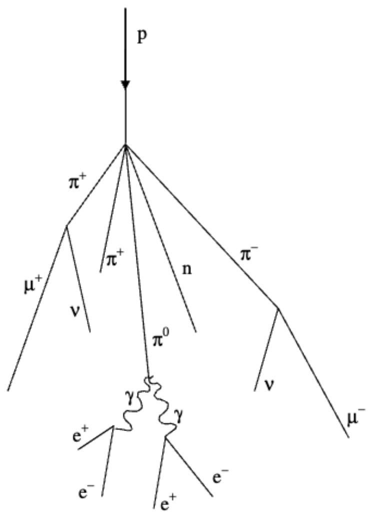

Figure 1: Cascade of particles created from a cosmic ray proton colliding with a nucleus in the upper atmosphere.

Calculating the exact number of muons reaching the Earth's surface involves various factors, including the energy spectrum of cosmic rays, the density of the atmosphere, and the distance traveled by muons before decaying. However, it's estimated that approximately one muon per square centimeter per minute reaches the Earth's surface at sea level. This estimation can vary depending on location, altitude, and other environmental factors.

The ability of muons to penetrate Earth's atmosphere and reach the surface plays a crucial role in their detection and study. Muon detectors positioned at or near the Earth's surface take advantage of this penetration to observe and analyze the properties of these particles, providing valuable insights into cosmic ray interactions and fundamental particle physics.

In this lab, custom electrical equipment was used to detect the presence of muons and to track their lifetime. Some unique equipment used includes scintillators and photomultiplier tubes. Plastic scintillators are made from organic polymers that contain fluorescent molecules. When charged particles pass through the scintillator, the fluor molecules are excited and emit photons. These photons are detected by photomultiplier tubes (PMTs) thats outputs a negative voltage when photons are detected. Using these pieces of equipment, the presence of muons can be detected along with the presence of the decayed electrons.

2 Materials and Methods

This lab involved the use of many unique electrical equipment, each of which is important to understand the uses and limits of. Before starting the lab, the instruction manuals of each piece of equipment was read and understood. A labeled diagram of the setup can be seen in Figure 2.

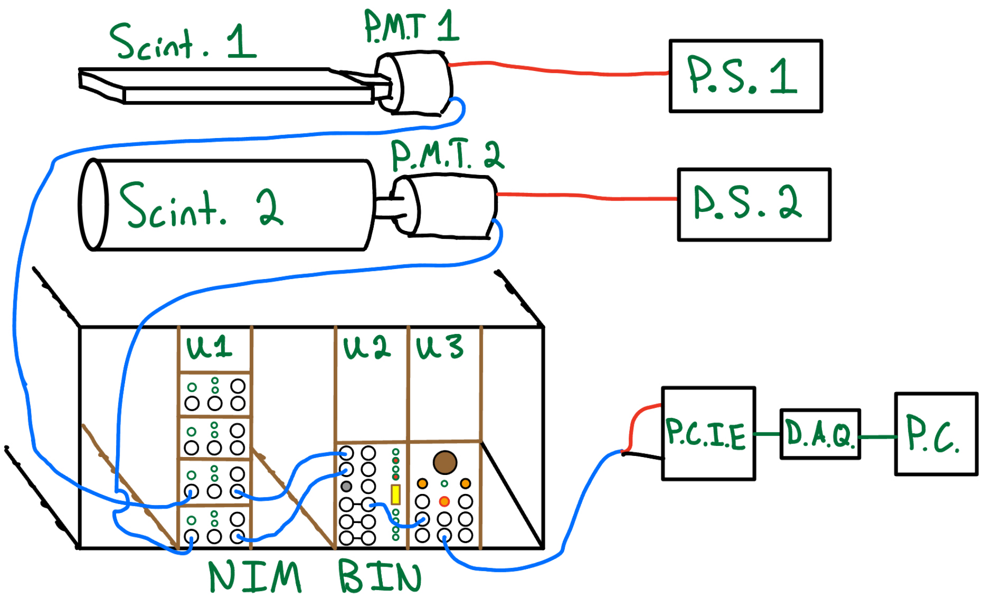

Figure 2: General Diagram of Muon Lab Set up

The first part of the lab was to collect counts of muons that went through both scintillators and to adjust the voltages being used to power the photo multiplier tubes. Since there are high voltages at work in this lab, every time the phrase "turned off" is used, it means that both the internal switches are off and the device was completely unplugged. The opposite is true for being "turned on". The NIM box was turned on. Within the NIM box, there were three units that were regularly used. This included the discriminators (U1), the 4 fold logic unit (U2), and the dual gate generator (U3). Diagrams of each are found in Figure 3.

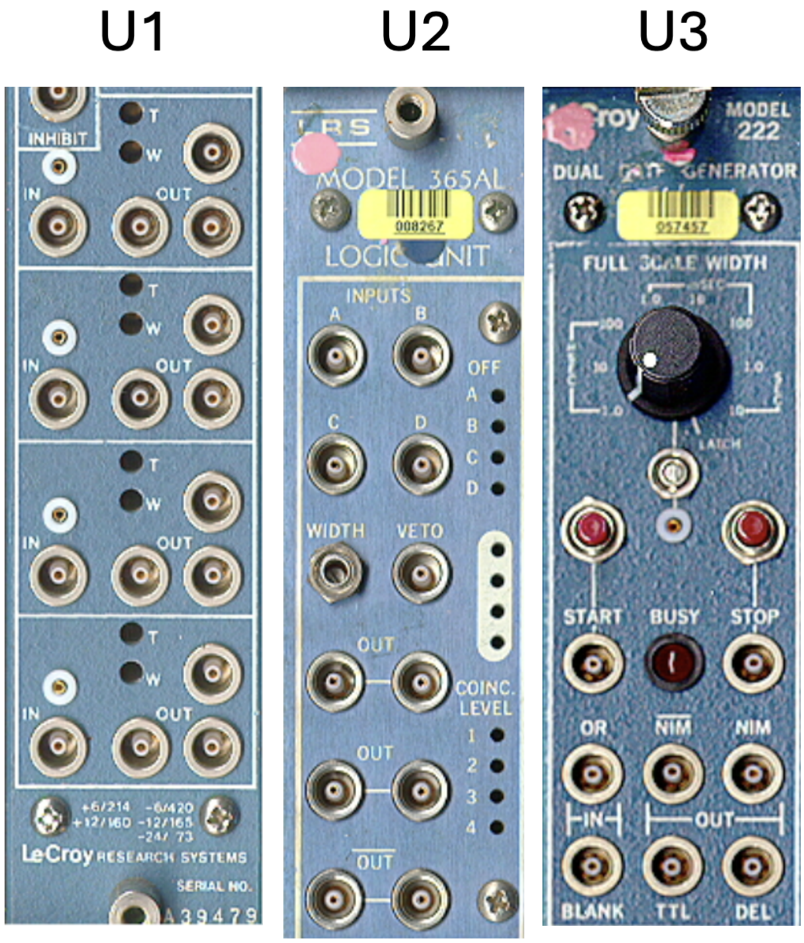

Figure 3: Expanded view of the NIM box which includes half of each unit. The NIM box is made of U1 (LeCroy 623B Octal Discriminator), U2 (LeCroy 365AL Dual 4 Fold Logic), and U3 (LeCroy 222 Dual gate generator)

The discriminator takes in voltage signals from a PMT and turns it into NIM logic which has true at -0.8 Volts and false at 0 volts. The first thing done was to set the threshold value for the discriminator. The given value to set this threshold to was negative 70 mV but after experimentation, the threshold value of the discriminator connected to the small scintillator was set to -36 mV. On the discriminator there is a probe hole surrounded by white rubber that probes this threshold value. There is also a hole labeled "T" which contains a screw to adjust said voltage. The probe hole was connected to the positive end of a GW Instek digital multimeter. The ground was connected to the metal housing of the NIM Bin. This was found to be the best ground for getting a stable value. It is important to note the probe hole outputs the threshold value times a value of 10. An oscilloscope and function generator were used to verify the discriminators used were working. This was done by sending square pulses of negative 0.15 Volts to the discriminator and verifying the output was pulses of NIM logic. The discriminators also have a hole labeled "w" which controls the pulse width of its output. Using the oscilloscope, both pulse widths were set to their maximum values between 100 and 150 nanoseconds. This width and the affects of it will be discussed later in this lab. This NIM logic then needs to be converted to TTL logic so the DAQ can understand it. To do this, the outputs of both discriminators (and in essence the outputs of both scintillators) were connected to input A and input C of the four fold logic gate, although any of the four inputs would work. The pins on the logic unit were then inserted into pin holes B and D to turn them off. Two more pins were inserted into coincidence level pin holes 1 and 2. This turns the unit into an and gate. One of the four normal outputs was chosen to connect to the "or" input of the dual gate generator. The "TTL" output of the dual gate generator was then connected to the oscilloscope to verify an output of positive pulses at 1.5 Volts. The wires shown in Figure 2 show the correct pathway just described.

The next step involved turning on the high voltage power supplies. Before this was done, all metal was removed from one's person (i.e. necklaces, watches, rings). The Stanford Research System (SRS) power supply, labeled PS 2, which was already connected to PMT 2 was verified to be in negative polarity by checking the screw position in the back. The wires from the PMT to the discriminator and through out the rest of the circuit were verified to still be in place before turning the SRS on. The SRS was set to -1900 Volts as recommended by the lab manual. The smaller grey supply (PS1) was turned on. There as a test voltage probe on PS 1 that was connected to a DMM to verify its output voltage. PS 2 was set to a recommended value of -1250 Volts. It is important to note that every cable used in this experiment carries along with it some signal delay on the order of magnitude of 10's of nanoseconds.

The TTL output was connected to the correct pins on the PCIE connector block and with code found in Appendix A, count rates were observed for time periods of three minutes. The "correct" pins will be discussed more in depth late in this lab. The voltage of PS 1 was varied from -1100 V to -1375 V to find its peak operating voltage. Then PS 1 was set to this operating voltage as PS 2 got count data at voltages from -1700 V to -2000 V. Once both peak operating voltages were found, each PS was set to this voltage for the remainder of the lab.

The next step was to collect data to find the half-life of muon decays. To do this, the time between muon detection by both scintillators and electron detection (decay byproducts) solely in scintillator 2 needs to be calculated. To do this a second output from discriminator 2 was connected to a the second dual gate generator ”or” input. The TTL output of this generator was connected to the appropriate pins on the PCIE connector block. Code was developed to find edge separation of these outputs and can be found in Appendix A. The code basically starts a timer when a muon passes through both scintillators and then stops the timer the next time the bottom scintillator picks up a charge (ideally this would be the electron byproduct from decay). The set up was left to run for three days to collect around 1000 decay events before analysis in MATLAB.

3 Results

By keeping the voltage of PS 1 at negative 1250 Volts and varying the voltage of PS2 from negative 1700 Volts to negative 2000 Volts, Figure 4 was obtained. This shows a maximum counts per minute value corresponding to a large PMT (PMT 2) supply voltage of around negative 1950 volts. This was kept as PS 2’s operating voltage for the remainder of the lab.

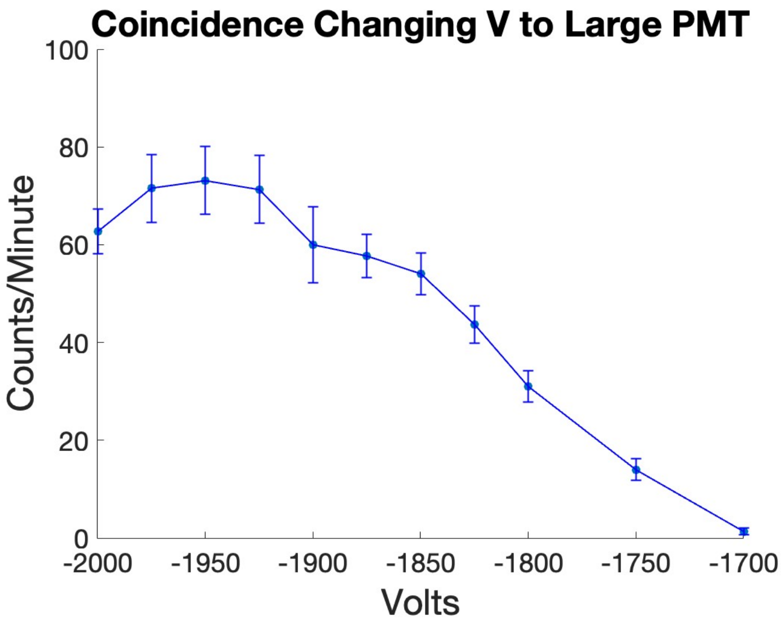

Figure 4: Counts per minute vs voltage supplied to PMT 2

With PS 2 set to negative 1950 Volts, the supply voltage from PS 1 to PMT 1 was varied from negative 1100 to negative 1400 volts to obtain Figure 5/ This shows a ”knee” around negative 1340 Volts which was said to be its operating voltage.

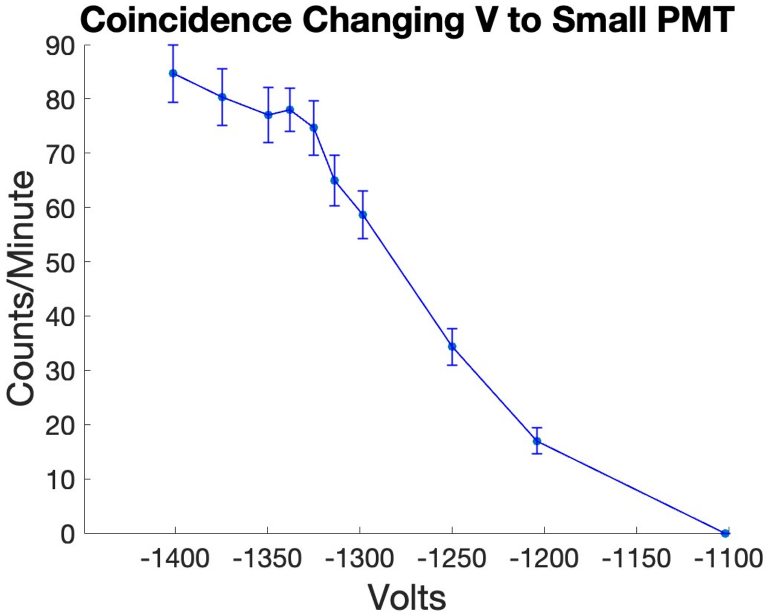

Figure 5: Counts per minute vs voltage supplied to PMT 1

Once all the muon decay data was collected, it was put into a histogram using MATLAB with bin sizes of 250 nanoseconds and using the binned maximum likelyhood method, the mean lifetime of muons was determined to be $2.19 \pm 0.09 \mu s$. There was also a + C constant in the fit that accounts for background activity. This constant had a value of 0.0011 ± 0.0007 counts. The histogram of the muon decays can be seen in Figure 6.

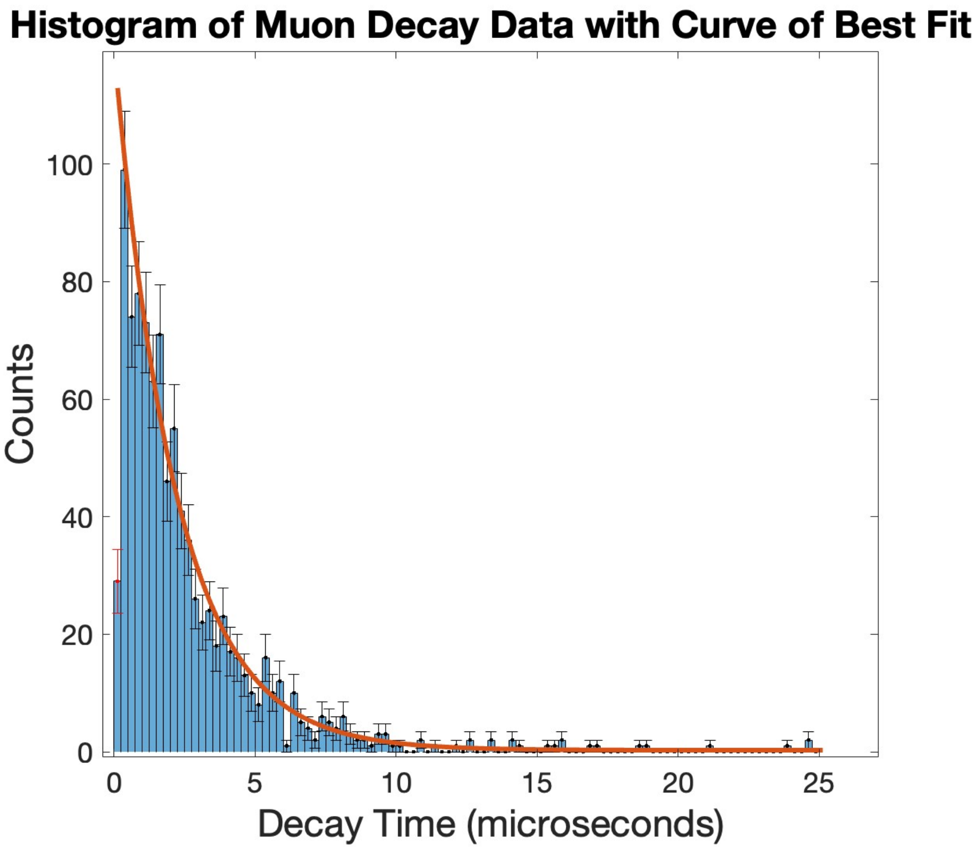

Figure 6: Histogram of decay times of muons with bin width of 250 nanoseconds and a curve fit shown in red.

4 Discussion

The first part of this lab involved collecting count data from each scintillator using custom C# code. To do this each piece of equipment needed to be tested. During testing it was found that one must ground the DMM to the NIM box casing in order to get a stable threshold value read out. This threshold was originally set to negative 70 mV for both discriminators but this led to sub-optimal muon counts. To increase the muon counts, the threshold value was decreased for discriminator 1 to negative 36 mV because after using an oscilloscope it was confirmed that any "dark pulses" from the PMT are lower than that threshold. This increased the muon count. It was also found that one of the logic gates did not work. If both logic gates worked, the edge to edge detection used to get muon decay could have been switch to a pulse width measurement using an XOR gate as the pulse stop signal. It was also noticed during this setup that many of the coax wires used were not very reliable. There would be many instances where a single wire would cause significant ringing in signals even with a 50 Ohm terminator added. Because

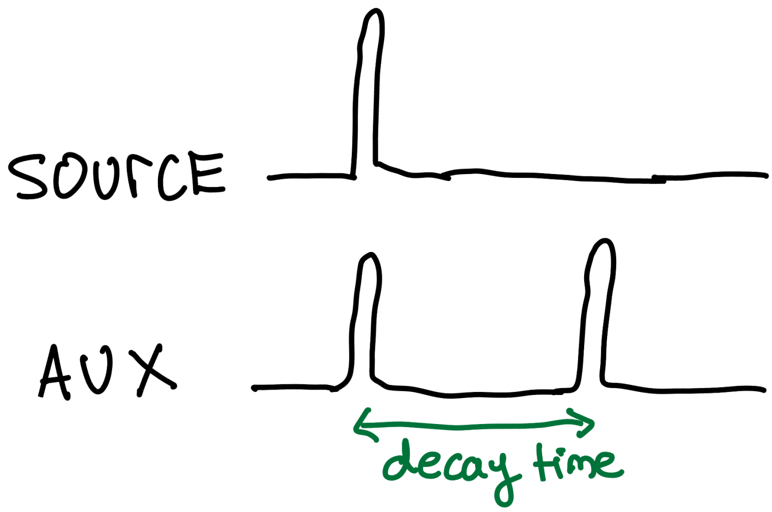

Figure 7: What the computer "sees" when a muon goes through both scintillators (SOURCE) and then decays in the bottom scintillator (AUX).

of this, the outputs were constantly monitored during each set up to confirm all wires were working consistently and reliably. With all this setup done, the output of the dual gate generator was connected to virtual ground and channel 36 of the PCIE board which acts as "SOURCE". This is what allowed for the collection of data in Figures 4 and 5. The results found in Figure 4 were as expected from the given manual which showed a curve that peaked around negative 1950 Volts. However, the results obtained in Figure 5 differed from the expected data. In this graph, there should be increasing counts per minute as the magnitude of the voltage increases until it hits a knee. After the knee, the counts continue to increase but this is from PMT noise and not from increased muon counts. The given manual says this knee should occur at a voltage of negative 1250 Volts, however the knee in this experiment occurred around negative 1340 Volts. This difference is believed to be from damage done to the top scintillator. Damage to this scintillator would also give reasoning behind the need for the discriminator threshold to be decreased.

Once the operating voltages for each PMT were found, it was time to collect muon decay data. The output that was originally put into "SOURCE" at channel 36 was not put into "GATE" at channel 44. A second output from discriminator 2 was put into "AUX" at channel 3. It is important to note that documentation on the board said that "AUX" was the first peak in the detection and "GATE" would be the second. However, after further testing, it was found that the opposite was true. An example of what the computer sees when a muon is detected and decays in the bottom scintillator is shown in Figure 7.

One problem that was faced is that when the initial signal from the source and aux were coinciding within some tolerance, the clock was not starting. To fix this, longer wire was added to the source signal to give it delay on the order of 10 ns. This allowed the initial aux signal to not block out the start signal from source. Since the decay time was on the order of microseconds, this added delay wasn't thought to be significant to results. Once the machine collected data for around three days, there was a data pool of 962 decay events. In the C# code, there were a couple of mistakes made that should be fixed in future iterations of this experiment. There is a part of the code that limits data intake to any decay time between 100 ns and 25 μs. This was done thinking it would reduce any noise and there wouldn't be any data loss but that was incorrect. One can notice in Figure 6 that the very first bin has less counts that expected compared to the curve. That is because limiting the data intake to anything more than 100 ns got rid of any decay event in 40% of that bin. Instead, the minimum count could be set to the physical limit of the 80 MHz clock which is 12.5 ns. To adjust for this loss of data, the first bin was ignored during the curve fitting process and the second bin was treated as time = 0. This can be done because of the nature of data being collected. The initial start time of the calculations does not affect how long it takes for half the initial amount to be gone. Binned maximum likelihood was then used to get the decay value of $2.19 \pm 0.09\mu s$ and a background noise value of 0.0011 ± 0.0007 counts. The standard errors for these were found using the jack knife method. The decay value fits with the value found in literature of 2.2 μ s. The experiment handout also asked to calculate the muon flux for the detector used. With a given surface area of scintillator 1 of 721 square cm, that means that muons could go through half of that area (just the top of the scintillator). With a given flux value of 1 muon per square cm per minute, our scintillator would have a flux rate of around 360 muons per minute or 6 muons per second. It is important to note that one other factor that can lead to loss of data in the first bin is the pulse widths that feed into the 4 fold logic gate. Both widths were set to 100 ns so any decay that happened withing that pulse width would also be ignored. In the future, the pulse widths should be decreased as much as possible while still keeping the and gate functional. It is also important to note that even if one cannot do this, the statistical methods to adjust for the loss of data are perfectly adequate in getting correct results.

5 Conclusion

Muons are elementary particles that can be created in the atmosphere from cosmic ray collisions. Muons have a recorded lifetime in literature of 2.2 μs and with the effects of time dilation, reach the surface of the earth and can be analyzed. This experiment used electrical equipment including scintillators and photo multiplier tubes to detect the presence and mean decay time of muons. A mean lifetime of muons was found to be $2.19 \pm 0.09\mu$s which is within the known value. A background noise value of 0.0011 ± 0.0007 counts was also found. Optimum supply voltages for both the top and bottom PMT were found to be -1340 V and -1950 V respectively. The Binned Maximum likelihood method was used to analyze the decay data and obtain mean lifetime.

References

[1] ”Muon Physics,” *T.E. Coan and J. Ye* http://www.phys.utk.edu

APPENDIX A

```
%Code for Counting Muons
using NationalInstruments;
using NationalInstruments.Analysis;
using NationalInstruments.Analysis.Conversion;
using NationalInstruments.Analysis.Dsp;
using NationalInstruments.Analysis.Dsp.Filters;
using NationalInstruments.Analysis.Math;
using NationalInstruments.Analysis.Monitoring;
using NationalInstruments.Analysis.SignalGeneration;
using NationalInstruments.Analysis.SpectralMeasurements;
using NationalInstruments.UI;
using NationalInstruments.UI.WindowsForms;
using NationalInstruments.Visa;
using NationalInstruments.DAQmx;
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace JustCount
{
    public partial class Form1 : Form
    {
        public Form1()
        {
            InitializeComponent();
        }

        private void QUIT_Click(object sender, EventArgs e)
        {
            this.Close();
            Application.Exit();
        }

        private void START_Click(object sender, EventArgs e)
        {
            timer1.Start();
            COUNTS.Value = 0;
            NationalInstruments.DAQmx.Task risingEdgeCounterTask = new
NationalInstruments.DAQmx.Task();

risingEdgeCounterTask.CIChannels.CreateCountEdgesChannel("Dev1/ctr0","",CICountEdgesActiveEdge
.Rising, 0, CICountEdgesCountDirection.Up);
            CounterSingleChannelReader reader = new
CounterSingleChannelReader(risingEdgeCounterTask.Stream);
            risingEdgeCounterTask.Start();
            while (TIMER.Value > 0)
            {
```

```
            Int32 read = reader.ReadSingleSampleInt32();
            COUNTS.Value = read;
            Console.WriteLine(read);
            Application.DoEvents();

        }
        risingEdgeCounterTask.Stop();
        risingEdgeCounterTask.Dispose();
        timer1.Stop();
    }

    private void timer1_Tick(object sender, EventArgs e)
    {
        TIMER.Value = TIMER.Value - 1;
    }

    private void TIMER_AfterChangeValue(object sender, AfterChangeNumericValueEventArgs e)
    {

    }
  }
}
```

```
%Code for Counting Lifetime of Muon Decay
using NationalInstruments;
using NationalInstruments.Analysis;
using NationalInstruments.Analysis.Conversion;
using NationalInstruments.Analysis.Dsp;
using NationalInstruments.Analysis.Dsp.Filters;
using NationalInstruments.Analysis.Math;
using NationalInstruments.Analysis.Monitoring;
using NationalInstruments.Analysis.SignalGeneration;
using NationalInstruments.Analysis.SpectralMeasurements;
using NationalInstruments.UI;
using NationalInstruments.UI.WindowsForms;
using NationalInstruments.Visa;
using NationalInstruments.DAQmx;
using System;
using System.IO;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace MuonDecayAcq
{
  public partial class Form1 : Form
  {
```

```
        public Form1()
        {
            InitializeComponent();
        }

        static bool acquiring = false;
        static List<double> readValues;

        private void START_Click(object sender, EventArgs e)
        {
            acquiring = true;

            readValues = new List<double>();

            NationalInstruments.DAQmx.Task sepEdgeTask = new NationalInstruments.DAQmx.Task();
            sepEdgeTask.CIChannels.CreateTwoEdgeSeparationChannel("Dev1/ctr0", "", 1E-7, 5E-6,
CITwoEdgeSeparationFirstEdge.Rising, CITwoEdgeSeparationSecondEdge.Rising,
CITwoEdgeSeparationUnits.Seconds);
            //sepEdgeTask.Timing.ConfigureSampleClock("/Dev1/20MHzTimebase", 2E7,
SampleClockActiveEdge.Rising, SampleQuantityMode.ContinuousSamples);
            sepEdgeTask.Stream.Timeout = 100;
            CounterSingleChannelReader reader = new
CounterSingleChannelReader(sepEdgeTask.Stream);

            sepEdgeTask.Start();

            while (acquiring)
            {
                double read;
                try
                {
                    read = reader.ReadSingleSampleDouble();
                } catch
                {
                    read = 0;
                }

                if ((read != 0) & (read < 25E-6))
                {
                    Console.WriteLine(read);
                    Console.WriteLine();
                    readValues.Add(read*1E6);
                }

                Application.DoEvents();
            }
            sepEdgeTask.Stop();
        }

        private void STOP_Click(object sender, EventArgs e)
        {
            acquiring = false;

            SaveFileDialog saveFileDialog = new SaveFileDialog();
            saveFileDialog.Filter = "Text Files (*.txt)|*.txt|All Files (*.*)|*.*";
```

```
            saveFileDialog.Title = "Save Read Values";
            if (saveFileDialog.ShowDialog() == DialogResult.OK)
            {
                using (StreamWriter sw = new StreamWriter(saveFileDialog.FileName))
                {
                    foreach (var value in readValues)
                    {
                        sw.WriteLine(value);
                    }
                }
            }
        }

        private void QUIT_Click(object sender, EventArgs e)
        {
            this.Close();
            Application.Exit();
        }

    }
}
```