The Mindanao Forum, Vol XV, No. 2 (December 2000)

Advanced Modular System in Data Acquisition for Muon Lifetime Measurements of Cosmic Ray Muon

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Abstract

Muons are created in the upper atmosphere when highly energetic cosmic ray primaries of extra-terrestrial origin collide with the atmosphere's molecules. Cosmic ray muons decay via weak interaction with particles of absorbing matter producing an electron and a partner neutrino in the process. At MSU-IIT's high-energy physics laboratory, five different material absorbers were used to capture a decaying muon: lead, aluminum, wood, copper and iron. The muon decay lifetime is measured by timing the observation of a signal from an incoming muon and its decay electron in the absorber using an assembly of high-precision scintillation detectors and advanced electronic modular systems of nanosecond accuracy.

Analog pulses generated by the scintillator detectors are directed using coaxial signal cables into several nuclear instrumentation modules (NIM) such as the discriminator, coincidence module and gate generator that eliminate noise and ensure purity of desired muon signals. The NIM output digital signals which then go into the input channel of a time-to-digital converter module or the TDC. The TDC belongs to another instrumentation standard called the Computer Automated Measurement and Control (CAMAC). Both the NIM and CAMAC are internationally accepted advanced modular systems for data acquisition and control.

Analysis of data sets from various material absorbers each reveal that the

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This paper was read before the 18th National SSP Physics Congress at Palawan.

decay of muons conform to the characteristic exponential decay law $N(t)= N_0 e^{-t/\tau\mu}$*; with* $\tau\mu$ *as the muon lifetime. Using lead absorber,* $\tau\mu= 2.059\pm0.068$ *μs; wood absorber,* $\tau\mu= 2.180\pm.042$ *μs; aluminum absorber,* $\tau\mu= 2.121\pm0.045$ *μs; copper absorber,* $\tau\mu= 2.059\pm.047$ *μs and iron absorber,* $\tau\mu= 2.052\pm0.055$ *μs. These values are all comparable to the standard value as published in The European Physical Journal C (15), 2000.*

Keywords: *muon decay, scintillation detectors, NIM, CAMAC, TDC*

1 Introduction

It is of considerable importance to be able to observe the muon directly. The muon, also called mu-lepton, is one of the fundamental constituents of matter. The microscopic basis for all known physical phenomena, with the exception of gravity, is explained by the modern theory of particle physics called the standard model [1]. The standard model describes nature in terms of the properties and interactions of a small number of particles of three distinct types: the leptons, quarks and the mediating particles called the gauge bosons.

The most familiar example of a lepton is the electron which is bound in atoms by electromagnetic interaction. Much less familiar but of equal importance in the standard model is the muon. Apart from its heavier mass and instability, the muon has all the properties of the electron.

The muon mass is measured to be 105.6 MeV/c^2; about two hundred times heavier than the electron. It was first identified in cosmic ray experiments by Anderson and Neddermeyer in 1936 [2]. Cosmic rays reaching the surface of the earth are now known to be secondary particles which are byproducts of the collisions between the primary, high-energy particles of extraterrestrial origin with the nuclei in the earth's atmosphere. Very penetrating particles, the muons constitute about 75% of the cosmic rays at sea level. While the cosmic ray flux depends at the 10% level on the latitude [3], there has been no known dependence for the muon lifetime. The mouns are also artificially produced at accelerator laboratories.

The positive muon decays via the weak interaction into a positron and two neutrinos; the negative muon into an electron and two neutrinos as shown in Figure 1.

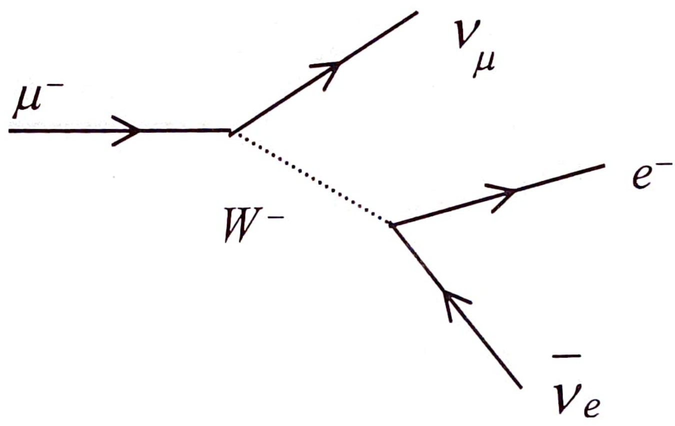


Figure1. Muon decay occurs via the weak interaction.

The strength of the weak interaction in muon decay is described by the phenomenological weak constant called the Fermi constant. This same parameter describes the more familiar phenomenon of nuclear β-decay. The Fermi constant can be calculated when the value of muon lifetime is known. The presently accepted value of the muon lifetime is 2.19703 ± 0.00004 μs as given by the Particle Data Group [6].

2 Objectives

This study is designed purposely to measure the decay lifetime of cosmic ray muon using the technique of particle scintillation detection and delayed pulse timing measurements. Specifically, it intends to process the signals generated by the scintillation counter, detect the existence of muons hitting the earth's surface and analyze the muon decay lifetime using different material absorbers.

3 Experimental Details

3.1 Detector's Assembly

In the laboratory, plastic scintillators are glued to a plastic light guide. First covered with aluminum, they are made light-tight by wrapping it with thick black cloth. The anode signals from the scintillator-photomultiplier tube assembly are tested using a 100-MHz digital oscilloscope.

The detector set up for measuring the muon lifetime is shown in Fig. 2. Cosmic ray muons are detected by a stack of three, horizontal plastic scintillator counters and a layer of absorber. Each scintillation counter consists of a 20 cm x 20 cm x 1.0 cm plastic scintillator which is optically coupled via a light guide to a Hamamatsu photomultiplier tube. The two upper counters are kept at a high voltage of – 1750 V while the bottom is kept at -2100 V. Each layer of absorber has a volume of 21.5 cm x 21.5 cm x 1.0 cm.

Most of the incoming cosmic ray muons will penetrate through the bottom counter. But in some cases the muon will be stopped at the absorber after passing through the two upper scintillator counters. The muon disintegrates and the decay products are an electron or positron and two neutrinos. The electron or positron then discharges the bottom scintillator counter and thus gives the signature of a decay electron.

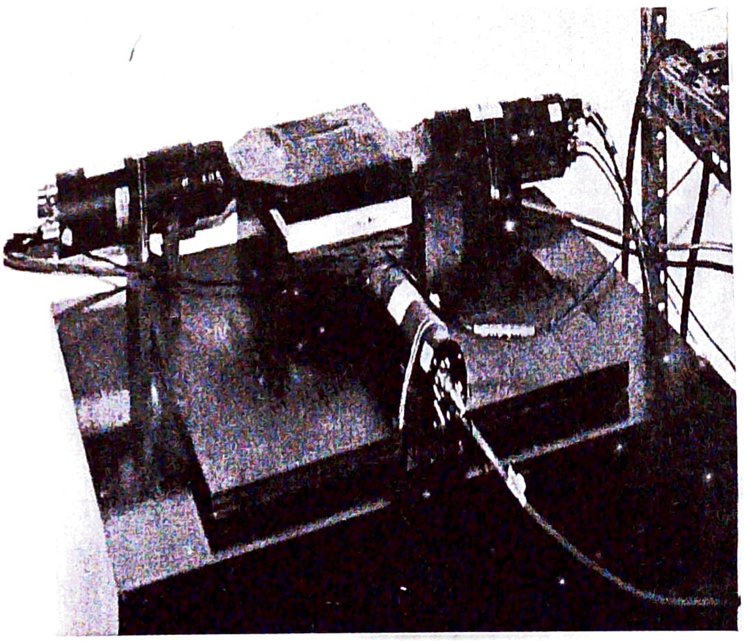


Figure 2. The Assembly of Plastic Scintillation Detectors

3.2 Calibration of the Instruments

A large part of the experiment involved signal processing in order to practically eliminate the probability of measuring false muon decay due to random noise inside the electronics and scintillators [4]. To minimize the noise and other background signals, two detectors composed of the same type of photomultipliers and a third detector providing a veto pulse are stacked on top of each other. The coincidence unit checks the pulses for time coincidence and to make it sure that it is the same particle passing through both detectors. Only a particle that traveled through both detectors can cause an event. The signals are then routed to an array of electronic modules in the nuclear instrument modules (NIM) where the analog signals are processed and shaped into a logic pulse.

Photomultiplier Tube (PMT) Base Voltage

In counting applications, where the PMT signal is analyzed by a discriminator, a simple method for finding the optimal base voltage is to make a plateau measurement [12]. This involves measuring the count rate from the scintillation counter to discriminator as a function of the applied PMT voltage.

The high voltage supplied to the PMT can be adjusted to achieve the desired sensitivity of the detectors. To find the optimal voltage of each detector used in this experiment, counts were taken every 10 minutes every time the applied voltage was set. The voltage was incremented by 50 volts starting from –1100 volts to –2400 volts for detectors A and B while the maximum voltage applied to detector C was –2600 volts. During the counting process, the discriminator's threshold voltage level was set at –100 mV. The above steps were repeated to a discriminator's voltage level of –200 mV and –300 mV. Fig. 3 shows the result of the plateau measurement for the three PMT's where the log of counts per 10 minutes was then plotted against applied PMT voltage using Gnuplot software for data analysis for each discriminator setting. An operating voltage of -1750V for PMT A and B and -2100V for PMT C were chosen.

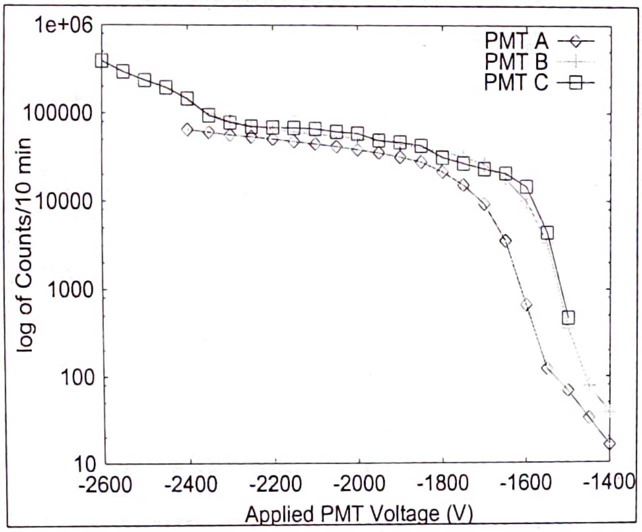


Figure 3. *Counter Plateau Curves of PMT A,B & C*

Setting the NIM Discriminator Threshold Voltage

The discriminator controls the output of the scintillation counter. To ensure that no low amplitude noise will be registered and to minimize excessive rate of accidental coincidences occurring in the circuit, the discriminator threshold voltage was determined. The discriminator standardizes pulses by issuing logic signals when the input exceeds the threshold voltage. The discriminated outputs are then sent to the NIM coincidence module where pulses arriving within an overlap time of 50 ns are registered as coincident. Figure 4 illustrates the electronic logic for coincidence measuring system and figure 5 shows the plateau generated when discriminator module was calibrated. A -200 mV threshold voltage was chosen for each discriminator channel where at this level all of the noise is eliminated while all muon signals are kept.

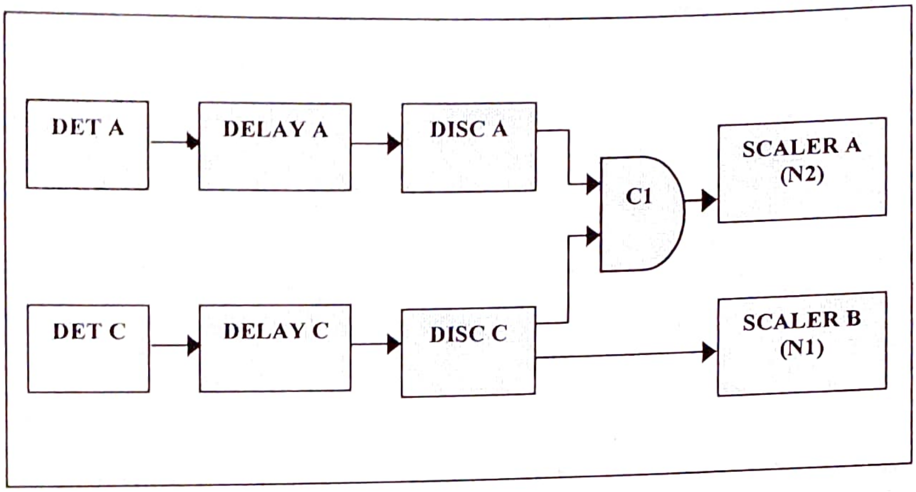


Figure 4. *Flow Diagram for Setting the Discriminator*

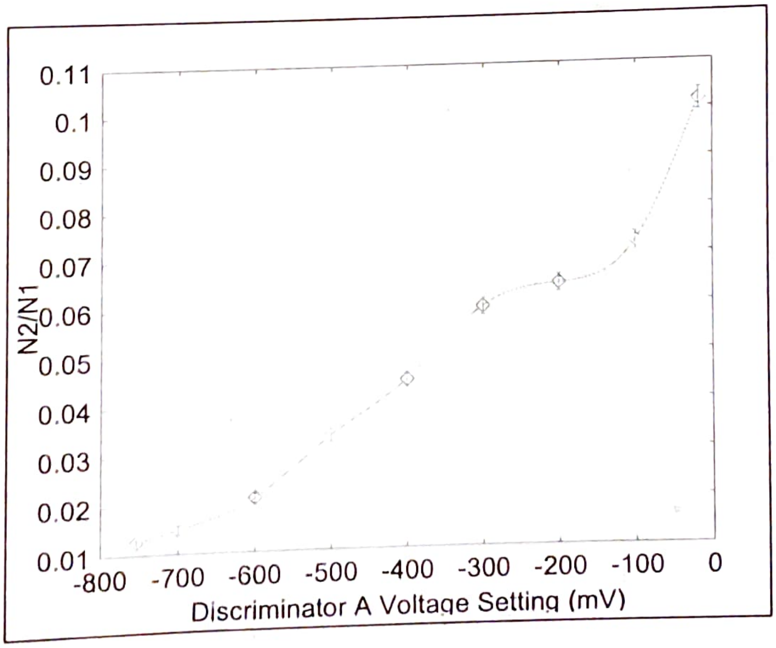


Figure 5. *Threshold Voltage Curve of a Channel in a NIM Discriminator Module*

Signal Delay

Basic coincidence technique was employed in adjusting delay of signals [5]. Figure 6 shows the schematic diagram in measuring the coincidences of signals. The relative values of the delays can be found by measuring the number of coincidences at gate C1 as a function of delay settings. Detectors A and B are operated at the same time. With the use of delay lines, delays on A and B are adjusted and the appropriate threshold voltage of the discriminator was set. The ratios of the counts registered in the scalers (N2/N1) were recorded and plotted against delay settings giving a coincidence curve shown in fig. 7. From this graph, the middle of the plateau corresponds to the correct setting for the delay of signals A and B and hence T_A-T_B = 0 ns is chosen.

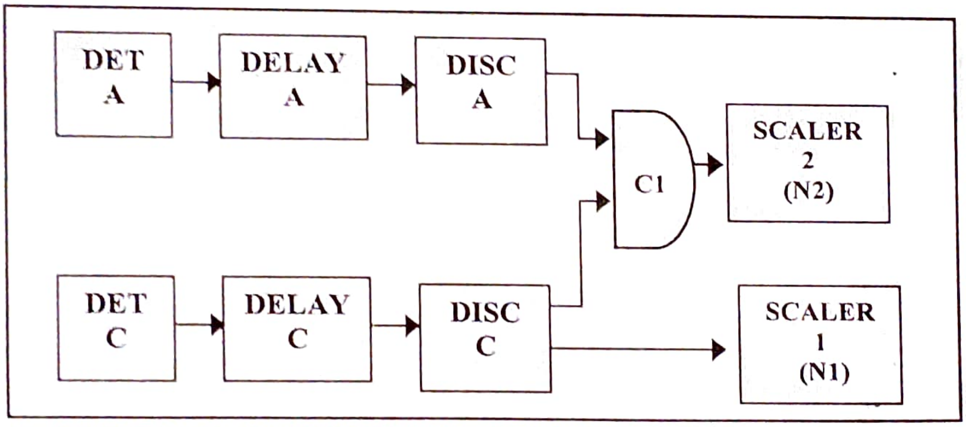


Figure 6. Logic Diagram for Finding the Delay of Signals A & B

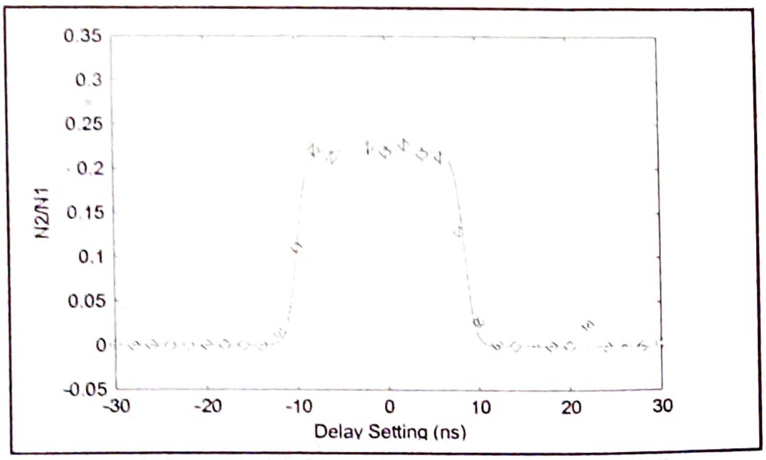


Figure 7. Delay Curve of Signals A & B where T_A-T_B = 0 ns

Schematic diagram shown in fig. 8 is used determine the relative delay between signals A/B and C. An absorber is placed between detectors B & C. Delay lines A & B were fixed at 5 ns since T_A-T_B = 0 ns while delay line C was adjusted. Again, the ratios of the counts N2/N1 were plotted against delay settings as shown in fig. 9 and from the principle of plateau measurement, signal C must be delayed by 8 ns relative to signals A/B.

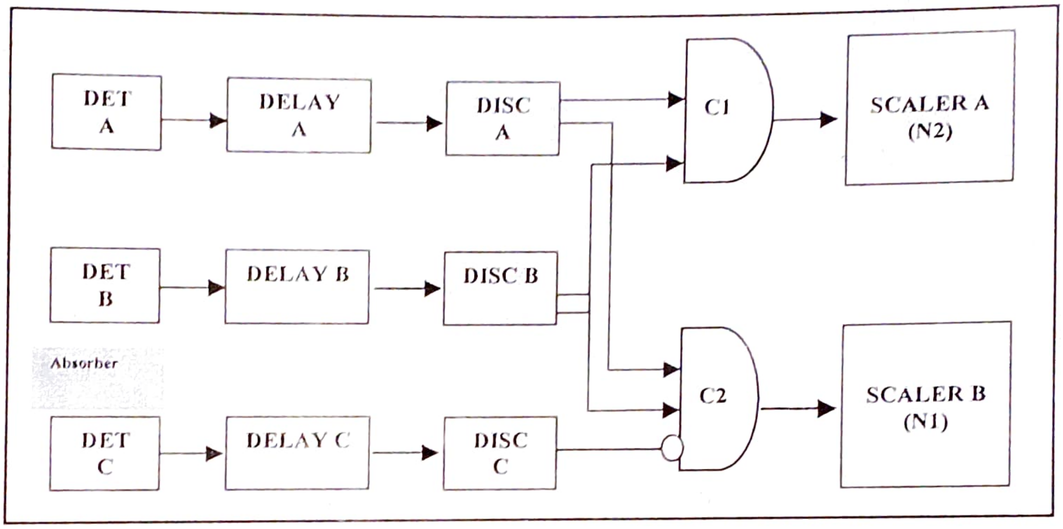


Figure 8. *Logic Diagram for Finding the Delay of Signals A, B & C*

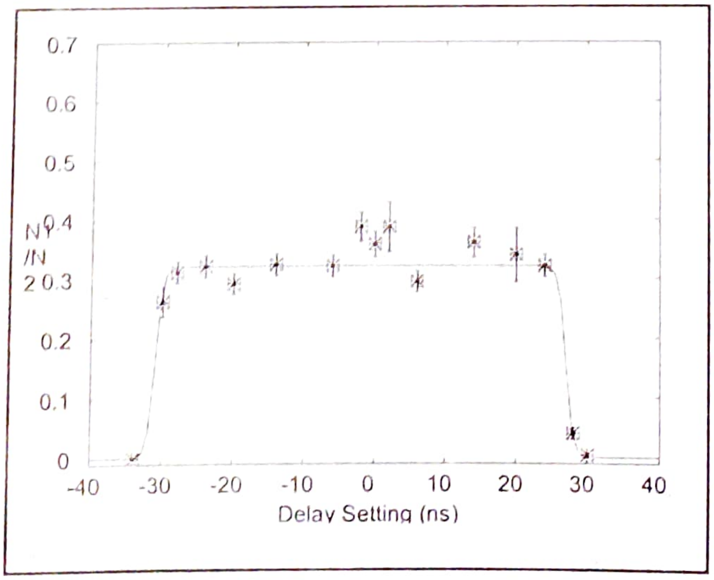


Figure 9. *Delay Curve of Signals A, B & C where T_{AB}-T_C = 8ns.*

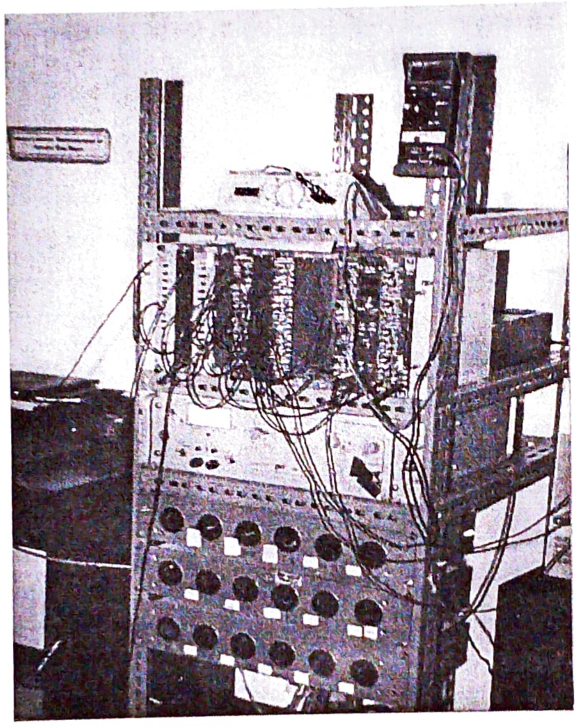


Figure 10. *The Nuclear Instrument Modules*

3.3 Time-to-digital Converter (TDC) Module

The arrival of muon in the detectors assembly is given by the coincidence circuit and a veto pulse from detector C. This issues a START signal to the time-to-digital converter of the CAMAC. Unstable particles like the muon lose energy by collision when they interact with the absorbing material. Hence, the muon stops and has a probability of decaying in the material. To record muon decay, the electron that speeds out from the absorber must exit in the downward direction for it to be captured by the detector C. Output pulse from gate C_3 triggers a STOP signal to the TDC of the CAMAC. The accompanying neutrino leaves the detectors undetected because it has no charge and practically no mass [3]. TDC counts only every START and STOP signals and it outputs counts per muon decay event. The corresponding time interval between two pulses practically implies a muon decay event and this time interval is proportional to the muon decay lifetime when the proper TDC calibration is known.

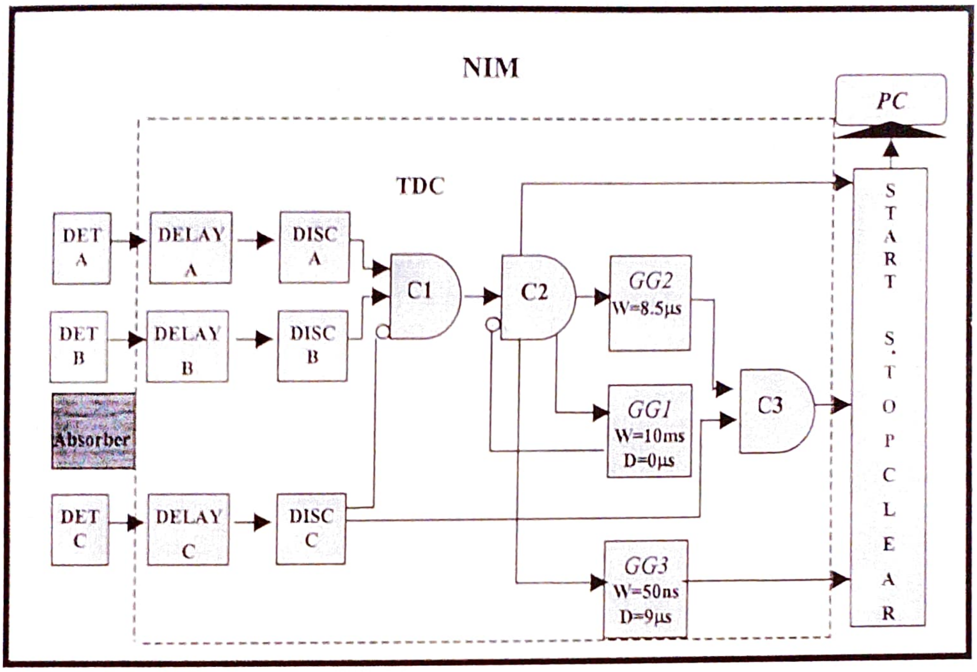


Figure 11. The Electronic Logic used for the Measurement Muon Lifetime

3.4 TDC Time Scale Calibration

A time-to-digital converter generates a binary digital output that is proportional to the time interval between start-stop timing signals. Use of the start-stop type inputs with proper internal gating demands that a stop signal be preceded by a start signal [11]. As soon as the stop pulse is received, the TDC begins an internal cycle that digitizes the time measurement automatically. Start before stop signals means a positive time difference. The TDC module in the CAMAC made use of counting-type TDC in the process of data taking. Reliability of data depends upon the time scale of the TDC channel; hence calibration of this TDC module is necessary.

A simple method for calibrating the Time-to-Digital Converter (TDC) module is shown in Figure 12. The input signals are provided directly from discriminator A. A signal coming from a single detector is fed into the discriminator set at its minimum voltage. An output signal of the discriminator is used to drive both the START and STOP registers input of the TDC module with the STOP channel signal passing through a variable delay. The delay introduced is varied from 1.0 to 8.4 ms. A discriminator output set at a gate width of 10ns triggers a STOP signal to the TDC in the CAMAC. When the full range scale has been exhausted, the timing system resets the clock making ready for the next start pulse. Counts were then taken for every delay of signal introduced into the system.

After each START-STOP has been counted, the internal clock determines the time interval between these two pulses in counts per microsecond. The counts produced are then uniformly distributed on the time scale. The TDC counts are plotted against time distribution. Figure 13 shows the graph of TDC time scale calibration having a slope of 467.1 ± 0.293 in TDC counts/ms. This value represents the conversion factor that is used to obtain the time spectrum of muon decay.

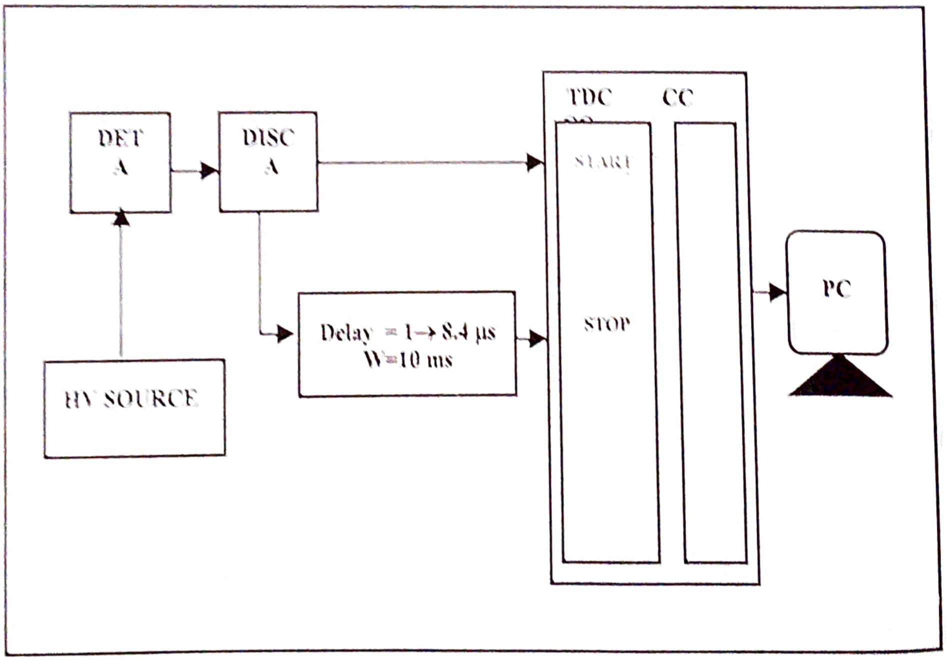


Figure12. TDC Time Scale Calibration Network

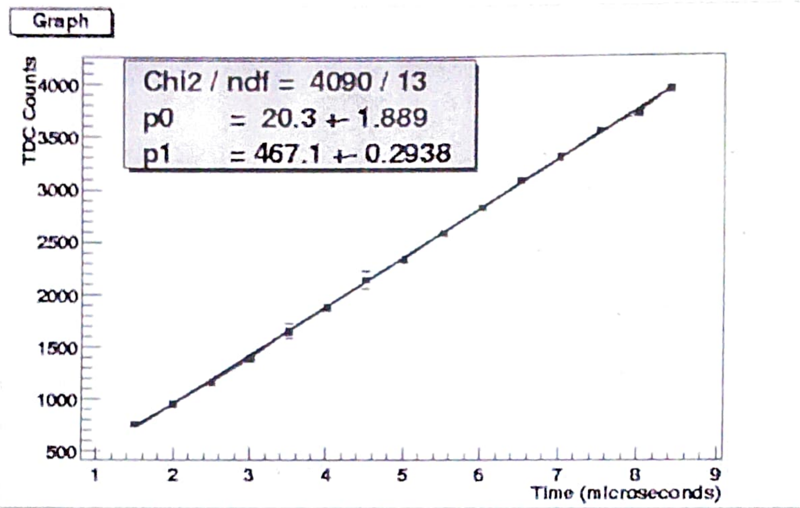


Figure 13. Curve generated from the TDC Time Scale Calibration

3.5 On-*Line Data Acquisition and Control*

CAMAC system is designed as a computer-controlled electronics system. Figure 14 shows such a set-up. The data acquisition computer is an old 486 IBM Compatible PC which is used for monitoring this time-interval measurement. A high-level language in FORTRAN 77 handled the data acquisition process. The application program makes decision on the CAMAC data since it includes a number of CAMAC routines, coded in assembly language written to perform fundamental CAMAC command operations [12]. In the program, the location of the TDC module and stop input channel are specified. TDC module is placed at CAMAC crate station 4 and TDC stop channel used is channel 0. The digital time signal is sent to the personal computer via an interface board for data storage and the program outputs the run number, event number, total events to date and TDC data. Every two-muon decay events are stored to files in the computer hard disk to assure an optimum data storage since data can be lost due to erratic power trips. At the end of every 100 data runs, the program is terminated and a run summary is accessed showing the number of decay events recorded with the corresponding TDC counts per muon decay event. The computer program is rerun until a large number of decay events are detected and recorded. An hourly monitoring of data is done in order to evaluate the performance of the experimental set-up.

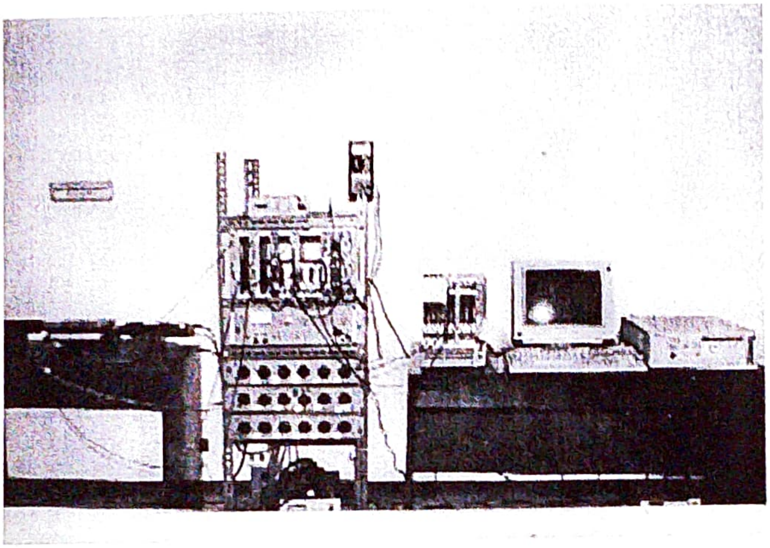
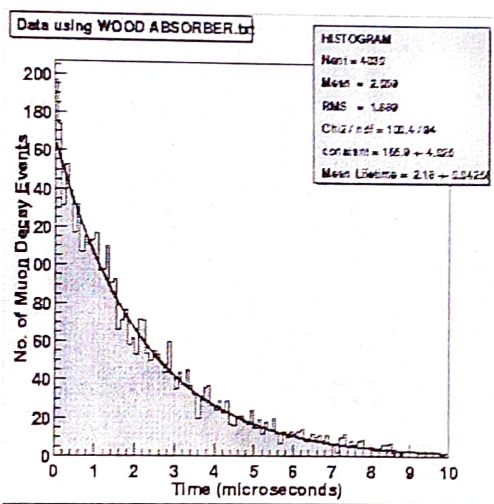


Figure 14. *The actual experimental set-up of the lifetime Measurement*

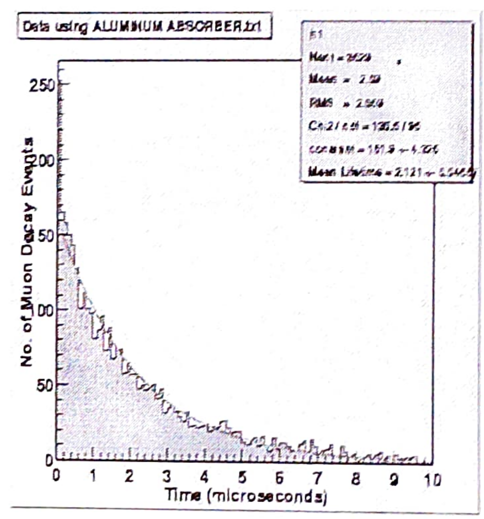
4 Results and Discussions

The approach to the data analysis requires non-linear curve fitting, evaluation of statistical significance including evaluation of error in the fitted parameters. We use the suite of programs called the ROOT; a free software provided by the European High Energy Physics Laboratory called CERN. ROOT is an object-oriented data analysis framework that allows the researchers to do a straightforward analysis in evaluating the collected data. The raw data in counts per decay obtained using each of the absorber used is converted to time in microsecond per decay by dividing the raw data with the magnitude of the slope of the TDC calibration curve. These are then read and analyzed by a ROOT macro coded in C++ developed for constructing and fitting histogram.

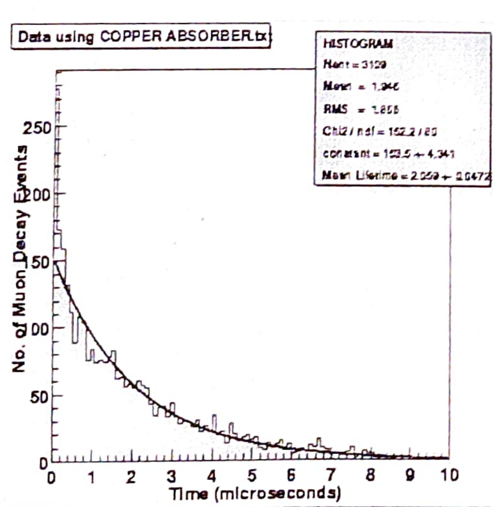
To obtain statistically significant data, data is accumulated for a longer period of time and the set-up was left running for a continuous hours of measurement. The time distribution of muon decay events using five different absorbers are histogrammed and fitted giving a lifetime shown in Table 1. In all these measurements, the average rate of muon decay events observed in the scintillation counters is 3 decays/hour and all the five time spectra obtained reflect an exponential decay curve conforming to the radioactive decay law: N (t) = No exp (-t/tm) giving a mean lifetime value consistent with the existing standard muon decay lifetime [8,9,10]. The reduced c^2 in each measurement is in the order of unity which shows reasonably fitting. Figures 15a – 15e show the time spectra of muon decay using five different absorbers.



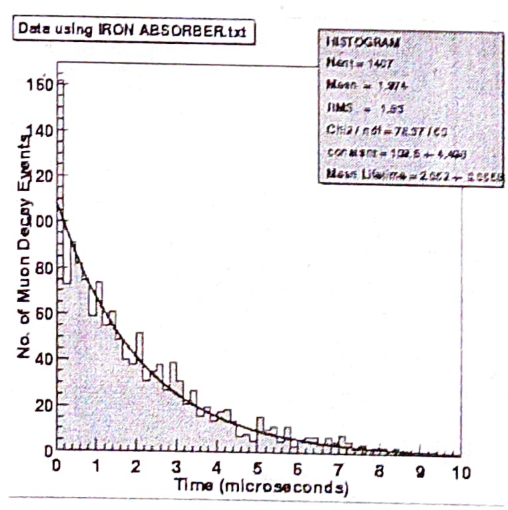
(a)



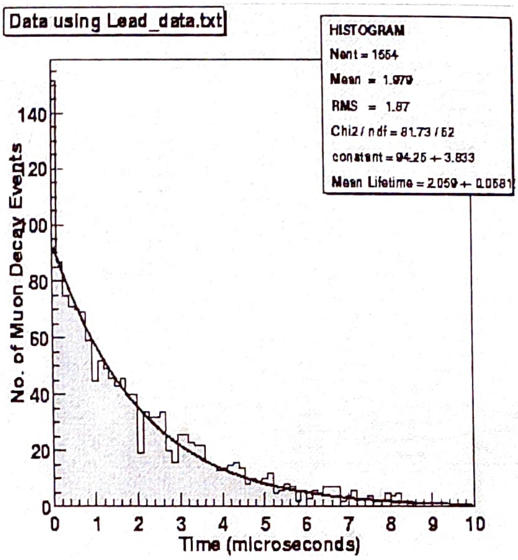
(b)



(c)



(d)



(e)

Figure 15. *Time spectra of muon decay using (a) wood absorber and (b) aluminum absorber (c) copper absorber (d) iron absorber (e) lead absorber.*

Table 1. *Measured Muon Lifetimes*

Absorber	No. of Events	Muon Lifetime, τ_μ (μs)	χ^2 /ndf
Wood	4030	2.18 ± 0.042	1. 02
Aluminum	3529	2.121 ± 0.045	1. 37
Copper	3109	2.059 ± 0.047	1. 90
Iron	1407	2.052 ± 0.055	1. 56
Lead	1564	2.059 ± 0.068	1.31

5 Summary and Conclusion

The existence of muons has been detected using the assembled plastic scintillation detectors, NIM and CAMAC instrumentation at the MSU-IIT Laboratory. The lifetime of muons has been measured precisely as presented in Table 1 in Iligan City in the southern Philippines with geographical coordinates: $3^{0}29'$ N latitude and $124^{0}39'$ E longitude [7]. The associated error in the decay lifetime is statistical in nature and the measured lifetime agrees with the world-wide accepted value as given in Reference [6].

6 Implications and Recommendations

Because of economy and convenience, the use of advanced modular systems such as the NIM and CAMAC are so widespread in many laboratories and industries all over the world. It is thus quite beneficial to adapt these technologies in desk-top experiments at university laboratories to provide advanced training to students to prepare them for more practical work later. Indeed, this research project demonstrates just one of the many important measurements that are made possible through the use of these advanced modular systems that are not possible otherwise.

Acknowledgement

We express our deepest appreciation to Prof. Kazuo Abe of the High Energy Accelerator Research Organization (KEK), Tsukuba, Japan whose effort made possible the donation to MSU-IIT of all NIM and CAMAC equipment used in this study. The Commission on Higher Education with its Mindanao Education Advanced Project is also greatly appreciated for the financial support extended to this study especially the scholarship granted to the first author. The generous support of the National Research Council of the Philippines through the NRCP grant is also gratefully acknowledged.

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