

LAB 2: Experiments in Nuclear Physics

John A. J. Matthews, Michael P. Hasselbeck, and Paul R. Schwoebel

Purpose

Introduce the student to some of the basic techniques and approaches used in nuclear and particle physics.

Reading Assignment

Reading required as per references in text of experiment.

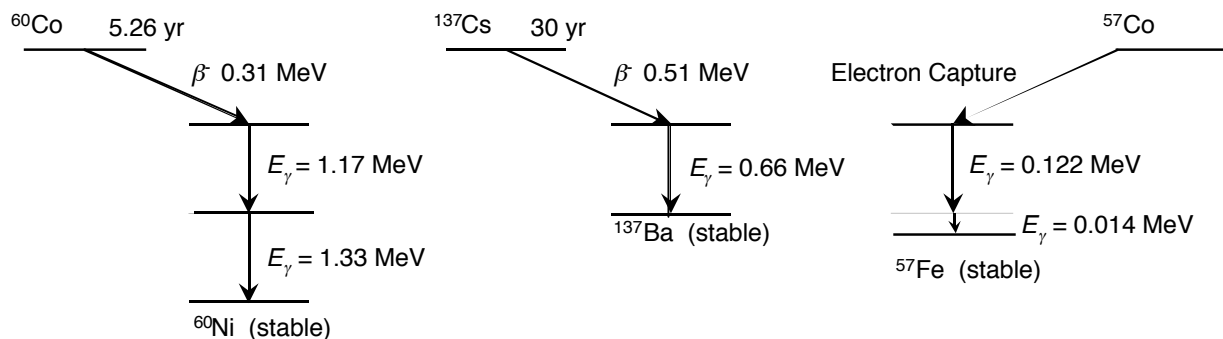
Preface

This laboratory is divided into two sections. The first section is an introduction to gamma-ray spectroscopy. γ -ray spectroscopy is of both fundamental and applied interest. The techniques introduced in γ -ray spectroscopy will be expanded upon and used in the second section to measure the mean-life of the muon. The mean life of the muon is directly related to the fundamental strength of the Weak Nuclear Force; one of the four fundamental forces in nature.

Part 1: Gamma-Ray Spectroscopy

Introduction

The decay of many radionuclides involves the emission of γ -rays. Processes that leave the daughter in an excited state can lead to gamma emission. Alpha emission and beta emission precede gamma decay in the natural radionuclides. For example, there can be a large difference between the nuclear spin of the ground states of the parent and the daughter. Then the beta transition directly to the ground state of the daughter is forbidden and therefore most of the transitions leave the daughter in an excited state. Decay schemes for some radionuclides are shown below.



Often the half-life of the parent is very long relative to the half-life of the daughter. In this case gamma decay is in transient equilibrium with the decay of the parent and the γ -ray intensity falls off with the half-life of the parent. This is the reason it is customary to name the parent as the γ -ray source.

γ -ray spectroscopy has a number of important uses in the applied sciences. For example, it can be used to identifying much of the elemental composition of an unknown sample. To do this the unknown sample is irradiated with neutrons which makes the sample radio active. This is so-called ‘neutron-activation’. One can then measure the γ -rays (and β -rays) and sample half-life to determine the constituents and their relative concentrations. This technique is used in the petroleum industry and areas of geology, medicine, and criminology, to name a few.

To learn about γ -ray spectroscopy and standard instrumentation used in nuclear physics you will:

1. Observe γ -ray energy spectra,¹
2. Identify the processes taking place,²⁻⁸
3. Complete an energy calibration of the apparatus.^{9, 10}
4. Determine the identity of an unknown isotope.
5. Determine the attenuation coefficients of γ -rays as a function of γ -ray energy.^{2, 10, 11}

Procedure:

A radioactive γ -ray source is placed near a NaI(Tl) scintillation detector. The NaI(Tl) absorbs the γ -ray and gives a light burst proportional to the amount of energy absorbed. The light is converted into electrons by a photocathode mounted on the input of a photomultiplier tube (PMT). The PMT is interfaced by the PMT base to a high voltage power supply and amplifier (or preamplifier plus amplifier). The PMT outputs a current pulse which is proportional to, and much greater than, the initial photoelectron current. Finally a multichannel analyzer (MCA) digitizes the pulses and stores a histogram of the number of pulses versus pulse amplitude. This is shown schematically in Fig. 1.

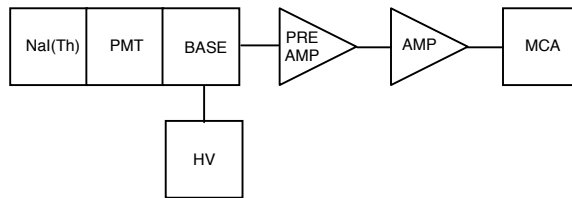


Fig. 1: Schematic drawing of the electronics for γ -ray spectroscopy. The NaI(Tl) scintillator crystal, PMT, and PMT Base are a single unit. The high voltage applied to the base is negative and less than 1500 V. The preamp and amplifier are typically Nuclear Instrumentation Modules (NIM) powered by a NIM crate. The MCA is a stand alone unit.

1. Observe γ -ray energy spectra, identify the processes taking place, energy calibration the apparatus, and determine the identity of an unknown isotope.

The UCS 30 MCA you will be using has an integral high voltage supply. Following the manual (Appendix 3) for the MCA connect it to the high voltage input for the PMT. Using the ¹³⁷Cs source, observe the output from the anode output of the PMT base on an oscilloscope using 50 Ω termination. The pulse will be negative. Set the high voltage on the PMT so that the pulses are > 50-100 mV. Typically ~ *positive* 1200 V is adequate high voltage; **do not exceed +1500V**. Before continuing it is instructive to see the γ -ray line(s) directly on the oscilloscope. Each line will appear as a brighter *band*. To see this you will need to get the correct trigger polarity: negative if you take the signal from the anode output of the PMT base or positive if you take the

signal from the dynode output of the PMT base. You will also need a sweep rate that is matched to the time response of the NaI(Tl) detector. Once you find the signal, vary the high voltage (modestly) to see how the signal magnitude varies with applied high voltage. At this point you may want to determine what voltage change will cause a doubling of the signal amplitude!

The UCS 30 MCA also has an integral preamp and amplifier. Following the manual (Appendix 3) for the MCA connect it to the output of the PMT. For simple applications you should set the MCA to accumulate/display the maximum number of channels. The final choice of high voltage and amplifier gain settings should place the highest energy γ -ray line near the upper end of the MCA range. As different combinations of high voltage and amplifier gain will result in the same amplitude signal you may want to investigate which combination gives you the sharpest signal: i.e. the narrowest line for a fixed signal amplitude. At this point you should also accumulate γ -ray spectra from the ^{60}Co source to learn the range of γ -ray energies and the number of distinct lines. Then you should consider building a cave, from lead bricks, to shield the NaI(Tl) detector from extraneous (i.e. background) γ -rays. Where does this background come from? You should also experiment with the distance between the source and the front of the NaI(Tl) detector. Does this make any discernable difference other than count rate? A good rule of thumb is to place the source at least 2 detector diameters from the detector. Why? The effective solid angle of the detector is then $(\pi r^2)/4\pi d^2$, where r is the detector radius and d is the source-to-detector distance. With your optimal setup you should accumulate a spectrum from each of the γ -ray sources. Do the spectra look different from your first spectra? How and why? Do the spectra look like the text book spectra? Identify as many of the features and lines as you can. Now take individual spectra for a couple sources such as the ^{137}Cs and ^{60}Co . You may also want to try the ^{57}Co source if it is not too old. Do this in as short a time period as is possible. Repeat to be sure that your peaks have not drifted! Determine the channel numbers for the center of each γ -ray line. If the DAQ electronics and the MCA are linear there should be a linear relation between peak channel number and γ -ray energy. To check this make a plot of channel number versus energy. Are the points in a line? Does the curve go through (0,0) or is there an offset? To what energy does channel 1 correspond? Now get an unknown γ source from the instructor. Using references^{2, 10} identify the unknown source.

Other issues you should consider include:

Do you have a circuit diagram including all equipment device types/numbers, SETTINGS, etc. so that you could easily rebuild your setup. Have you sketched pulse shapes at different places in the circuit? What should you check for when looking at pulse shapes? What change in phototube high voltage results in a 100% increase in the observed γ -ray pulse heights (i.e. channel number in MCA)?

To a first approximation the gamma ray line-width, that is its Full-Width at Half-Maximum (FWHM) is 2.35σ , and related to the statistical fluctuations in the number of photo-electrons, N_e , that are collected from the photocathode of the phototube. In turn $N_e \propto E_\gamma$, thus:

$$\sigma/E_\gamma = 1/\sqrt{N_e} \propto 1/\sqrt{E_\gamma}$$

Thus this ratio measures N_e . Check this by plotting $(E_\gamma/\sigma)^2$ versus E_γ . If the plot is linear then our approximation was valid; that is there should be an essentially constant γ -ray energy required per observed photo-electron. What is the average γ -ray energy/photo-electron in your experiment? The inverse question is how many photoelectrons result from a 1 MeV γ -ray?¹² Does this number make sense?

γ -ray (i.e. photon) cross sections for interacting with the NaI(Tl) are rather small in the energy range of a few hundred keV to \sim MeV. The photon interaction processes include the photoelectric effect, Compton scattering and pair production. What photon cross section is most directly related to the total conversion of the γ -ray to visible light in the energy range of this experiment? Is this the dominant cross section at these energies? What is the dominant photon interaction? Does this dominant process result in events in the observed γ -peaks? If not how do events get to be in the peak?

2. Measure γ -ray attenuation coefficients:

Just as γ -rays interact with the NaI(Tl) to be detected or with lead shielding to reduce background counts, γ -rays interact with all matter. The physical processes include the photoelectric effect, Compton scattering and pair production as noted above. These cross sections are combined (in a variety of ways depending on the precise definition) into an absorption or attenuation coefficient, μ . Thus following a distance, X , an initial number of γ -rays, $N(0)$, is attenuated to a final number, $N(X)$:

$$N(X) = N(0) e^{-\mu X}$$

Because the photon cross sections change rapidly with energy and depend on the absorber material's nuclear charge, it is interesting to measure μ at different energies and for more than one absorber material.

To measure the energy dependence of μ , start with the ^{137}Cs source and the MCA. To know $N(0)$ for each γ -ray line, you need to take (and fit) a MCA spectra with no absorber and for a known "live-time" interval. Then take additional spectra with different thickness of absorber and for different types of absorber. Copper and lead are available. Plot $N(X, E_\gamma)$ versus absorber thickness, X , as you accumulate the data. Remember to include the statistical uncertainty in each measurement, δN , in your plot:¹³

$$\delta N = \sqrt{N}$$

Are your statistics sufficient such that $\delta N \ll N$? If not, accumulate spectra for longer periods of time. If spectra are accumulated for different time intervals how do you record them in one plot? Have you taken spectra for enough absorber thicknesses to measure the X -dependence of $N(X)$ at small- X where $N(X) \sim N(0)$, and also at large X where $N(X) \ll N(0)$. Why is this important? Now try the ^{60}Co source. Should your steps in absorber thickness be the same at different γ -ray energies and/or for different absorbing materials? Why or why not?

Do you need to correct for the NaI(Tl) efficiency, ϵ ? Why or why not? Because you expect an exponential decrease with absorber thickness you should plot your data on a semi-log plot. Do your results agree with the exponential dependence on absorber thickness? Do your results agree with smaller values for μ at larger γ -ray energies? If the answer to either of the last two questions is no, then you may want to reconsider the *geometry* of your experimental setup. Can the absorber provide a scattering path for γ -rays not initially directed at the NaI(Tl) detector to scatter into the detector? How can you minimize this experimental problem? Once you have a reliable experimental geometry and analysis procedures, take sufficient spectra to measure μ at several energies and for at least two absorber materials. How do your results compare with tabulated values for μ ?

Part 2: Measurement of the Mean Life of the Muon

Introduction

The muon¹⁴ is an elementary particle indistinguishable from the electron except that its mass is ~ 200 times greater. Muons are produced primarily from the decays of charged pions, π^\pm , which are themselves produced (copiously) in extensive air showers caused by cosmic rays. Primary cosmic rays cover the spectrum from protons to intermediate mass nuclei ($<$ iron). The primary cosmic rays interact with nuclei in the atmosphere creating large numbers of charged and neutral π mesons. These subsequently interact or decay. Depending on the energy of the initial cosmic ray, millions or billions of secondary particles can be produced. This is called an extensive air shower.

Generally the neutral mesons, π^0 , decay before interacting. Depending on their energy, the charged pions may interact with nuclei in the atmosphere or may decay, $\pi^\pm \rightarrow \mu^\pm + \nu$, to charged muons and neutrinos. To understand this behavior look up the lifetimes, τ_π , and masses, m_π , of charged and neutral pions. The average distance they travel (before decaying) depends on their energy, E_π , and is given by:

$$\text{Distance} \sim (E_\pi/m_\pi c^2) c \tau_\pi$$

where c is the speed of light. What are typical distances if $E_\pi = 10^9$ eV or if $E_\pi = 10^{10}$ eV? If this distance is large then it is likely the π interacts before it decays.

Unlike pions, muons do not interact strongly. Thus to first order they will decay before they interact. The distance a typical $E_\mu = 10^9 - 10^{10}$ eV muon travels is thus:

$$\begin{aligned} \text{Distance} &= (10^9 \sim 10^{10} \text{ [eV]}) / (105.7 \text{ [MeV]}) (3 \times 10^8 \text{ [m/s]}) (2.197 \times 10^{-6} \text{ [s]}) = \\ &6.24 \sim 62.4 \text{ [km]}. \end{aligned}$$

Where the muon mass $m_\mu = 105.7$ MeV. This distance is sufficiently great that many muons reach the earth surface. In fact at the earth's surface muons are the dominant component of secondary particles from cosmic ray showers. Most of the muons are of modest energy by the time they reach ground level. Thus some will range out, i.e. stop, in a tank of liquid scintillator. The study of the decay of these stopped muons is the basis of this experiment.

Muons decay via the weak interaction similar to the β -decay of free neutrons and nucleons in nuclei:

$$\mu^\pm \rightarrow \nu_\mu + e^\pm + \bar{\nu}_e$$

Because neutrinos only interact via the weak nuclear force, muon decay is one of very few natural processes that only involves the weak interaction. The decay rate is actually a measure of the strength of the weak interaction, much like the electronic charge is a measure of the strength of the electromagnetic interaction.

As with nuclear β -decay the energy (E_e) spectrum of the resultant e^\pm is that for a typical three body weak decay:¹

$$d\Gamma(E_e)/dE_e = (G_F^2/12\pi^3) m_\mu^2 E_e^2 (3 - 4 E_e/m_\mu).$$

where $d\Gamma$ is the muon decay rate. If this is integrated over possible electron energies:

$$\Gamma = 1/\tau_\mu = G_F^2 m_\mu^5 / 192\pi^3$$

where τ_μ is the muon lifetime and G_F is the Fermi coupling constant. The Fermi coupling constant is the fundamental coupling constant of the charge changing weak interaction. Thus a measurement of the muon lifetime provides a measurement of G_F once the muon mass is known!

A fraction of the muons that reach the earth's surface have just the correct energy to stop in a block or tank of scintillator. As the muons stop they deposit $\sim 2 \text{ MeV}/(\text{gm}/\text{cm}^2)$ in the scintillator. Because the density of scintillator is $\sim 1 \text{ (gm}/\text{cm}^3)$, muons deposit $\sim 2 \text{ MeV}/\text{cm}$ of path length. This is much greater than the $\sim 1 \text{ MeV}/\text{cm}$ of typical γ -rays in Part 1 of this lab. Thus these stopping muons result in a pulse of light (in the scintillator) which is easily detected.

Roughly 5% of the μ^- will be captured into low Bohr orbits and then interact with the nucleus of the scintillator atoms before decaying. Thus the majority of μ^- and virtually all the stopped μ^+ decay before interacting with electrons or nuclei in the scintillator. Each muon decay results in an electron with a energy up to $m_\mu/2 \sim 53 \text{ MeV}$ (i.e. neutrinos are essentially massless). These electrons also can result in a pulse of light (in the scintillator) which is also easily detected.

If one starts a clock each time a muon stops, i.e. this defines $t = 0$, then for a total number of stopped muons, N_{stop} , the number of muons remaining at a time t later is:

$$N(t) = N_{stop} \exp(-t/\tau_\mu).$$

Note: clearly this assumes that muons are not lost due to interactions with the scintillator (see comments above). Process other than weak decays that remove muons will result in a low value for τ_μ . Random accidentals will be flat in time and will result in a high value for τ_μ , unless you analyze your data properly.

The number of muon decays in the time interval from t_1 and t_2 is:

$$\Delta N(t) \Big|_{t=\langle t \rangle} = \Delta N(\langle t \rangle) = N_{stop} (-\Delta t / \tau_\mu) \exp(-t/\tau_\mu) \Big|_{t=\langle t \rangle} = N_{stop} (-\Delta t / \tau_\mu) \exp(-\langle t \rangle / \tau_\mu)$$

where $\Delta t = t_2 - t_1$ and $\langle t \rangle = (t_2 + t_1)/2$. Thus a histogram of the number of the observed decays, $\Delta N(\langle t \rangle)$, binned in time bins of width Δt , is predicted to be a simple exponential in $\langle t \rangle / \tau_\mu$. A semi-log plot of $\Delta N(\langle t \rangle)$ versus $\langle t \rangle$ will have a slope $-1/\tau_\mu$.

Procedure

The muon decay experiment starts with a large tank of liquid scintillator viewed by two phototubes (PMTs). If one PMT is sufficient to trigger on cosmic ray muons and on the electrons from muon decay, why use two PMTs? The basic setup is shown schematically in Fig. 1. As depicted in Fig. 1, the difference between a through going muon and a stopped muon followed by a β -decay, is one pulse versus two pulses.

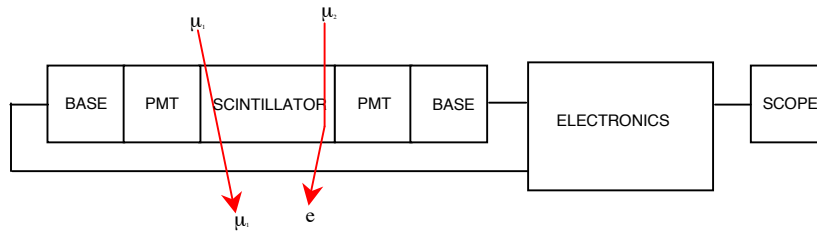


Fig. 1. Schematic setup for muon lifetime experiment. μ_1 passes through the scintillator losing some energy: A single voltage pulse appears on the scope. μ_2 stops in the scintillator and decays after time t to an electron: Two voltage pulses appear on the scope.

You will measure the lifetime of the muon using two different approaches for the ‘electronics’ package shown in Figure 1. The first is based upon Nuclear Instrumentation Module (NIM) electronics. Although no longer routinely used to accumulate the final data in modern particle physics experiments it is often still used to set up such experiments as it allows for oscilloscope validation of each step of the experiment upon which a dedicated board can then be designed, fabricated and used. The second method you will use to measure the muon lifetime is with just such a dedicated board. By making the measurement using both approaches you will see the individual measurements made in nuclear/particle physics via NIM instrumentation and how present day experiments are conducted with dedicated boards.

1. NIM Based Measurement

A sketch of a realistic experimental setup is shown in Fig. 2. The PMTs require **negative HV and NO MORE NEGATIVE THAN ~ -1500 V** should provide adequate output signals. In practice you need to adjust the HV for each PMT to get approximately the same output signals. Typically the PMT output signals are discriminated with $V_{threshold} = 30$ mV. Why is this setting used? Can you rationalize your discriminator setting based on the fact that muons deposit ~ 2 MeV/cm of path length and that the end-point energy of the electrons or positrons resulting from the beta decay of the muon is ~ 53 MeV? Set the discriminator output pulse length to ~ 20 ns. Are the pulse lengths sufficient to allow for the variation in pulse timing between the 2 PMTs and still give a coincidence? Have you adjusted the relative time delay between the two scintillator signals so the signals are in time on average? Set the coincidence unit to require a 2-fold coincidence. The coincidence requires that both PMTs are above threshold to avoid noise triggers or triggers from cosmic ray muons that are clippers.

To monitor and set up your experiment pass signals of interest through the scope; i.e. put the oscilloscope between outputs of interest and the next device in the logic/signal chain.

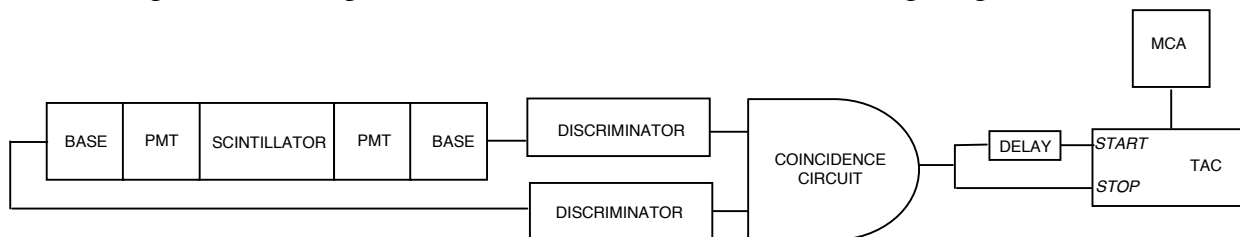


Fig. 2. A practical experimental arrangement for the muon lifetime experiment.

Two outputs are taken from the coincidence unit. One is delayed and used to START the TAC. The other is used to STOP the TAC. For details on how a TAC works see Appendix 1. At first

this order appears to be counter intuitive. This is explained by Fig. 3 and by the fact that only when the TAC receives a good *START-STOP* combination will it produce an output pulse. To delay the signal to the TAC *START*, use the delay box supplied with the experiment. How much delay should be introduced?

Thus all the events that have a *START* but no *STOP* within the TAC time window will result in no TAC output. For events with a good *START-STOP* combination the TAC output pulse has an amplitude proportional to the difference in time between the *START* and *STOP*. The TAC output signal is analyzed in the MCA. This is the good news. The bad news is that if a second muon passes through the scintillator close in time to first, then the second muon is indistinguishable from a decay electron. This results in a random accidental signal that should be uniform in time and thus produce a flat background. Start to think how you will analyze the data to accommodate this background!

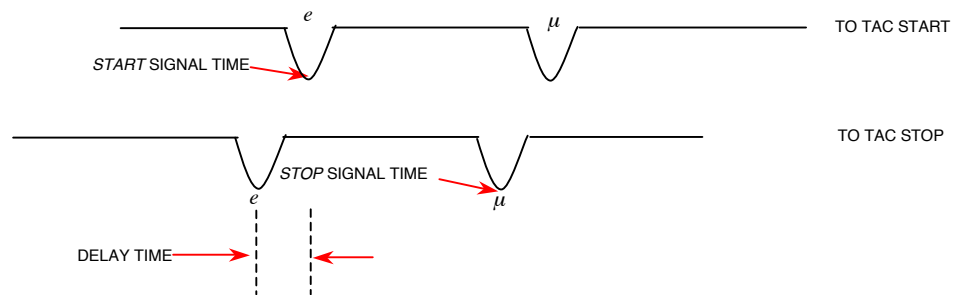


FIG. 3. Sketch of the signals entering the TAC versus time (not to scale in time). The effect of the delay is to cut off the first part of the histogram stored in the MCA. It does not change the exponential nature of the histogram.

Set the time window on the TAC to $\sim 5-10$ muon lifetimes. Thus the data at large times will be essentially all accidentals. Don't set the time window too long or you will only be studying accidentals. If you have time you should accumulate and analyze data taken with different TAC time windows.

To obtain adequate statistics you will need to run for at least 24 hours. Remember to leave a big **DANGER HIGH VOLTAGE** sign on your apparatus.

The raw data from the MCA is a histogram of counts versus channel number. You need to calibrate the system. That is, you supply a well defined time signal into the TAC/MCA combination to obtain the conversion from channel number to time. This is shown schematically in Fig. 4. Use a pulse generator followed by a discriminator (or simple splitter) to create two *in-time* signals. Put one through a precision delay. Calibrate the full scale of the TAC/MCA. If you take data sets with different TAC time windows you will need to calibrate for each TAC setting. Remember to calibrate the TAC/MCA immediately before or after your data run, i.e. before you inadvertently change something.

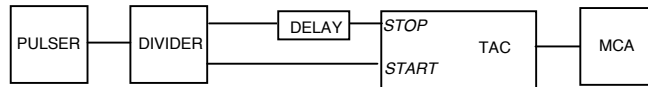


FIG. 4. Arrangement for time calibration of the TAC-MCA.

The recommended technique to analyze the data is to extract a spread sheet file from the MCA to manipulate and fit the data. You will need to correct for background counts. Remember if your time bins become too wide then the simple 1-exponential form is no longer correct. How does your measurement compare with the world average of $\tau_\nu = 2.197 \mu\text{s}$?¹⁵ If you agree within 5-10 % you are measuring the Fermi coupling constant to that same precision!

2. Dedicated Board Based Measurement

The QuarkNet card was designed and built by engineers at Fermilab in Batavia, Illinois to replace traditional NIM. A single circuit board amplifies PMT signals by 10x and uses voltage comparators for discrimination with adjustable threshold. On-board timing is implemented with CPLD (Complex Programmable Logic Device) via software installed at Fermilab. Photon events are time-resolved with an accuracy of 1.25 ns using a time-digital-converter. A micro-controller interfaces with the control PC using a custom LabVIEW program.

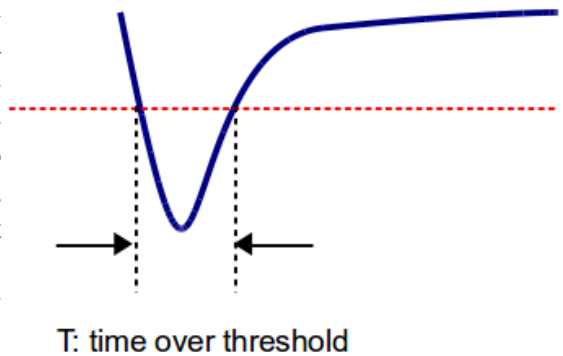
Connect the PMT outputs to two detector input channels on the QuarkNet card. Each channel preamplifier has 50Ω input impedance, so if the PMT signals are also being monitored on a parallel oscilloscope the channel input impedance should be set to 1 M Ω . Apply 5 VDC power to the QuarkNet card by plugging the AC adapter into a wall socket. A blinking LED associated with each channel indicates the occurrence of a local trigger. The LEDs can give a rough visual guide to assist in configuration (Note: the digital counter is of little value). Open the LabVIEW program Setup.vi.

Card Timing: Triggering can be initiated by either: 1) one pulse from a single PMT or 2) coincident pulses from 2, 3, or 4 PMTs. Coincident triggering is more reliable because it is less susceptible to false signals produced by random background noise. This experiment has two PMTs available to monitor photons in the scintillator tank.

If coincident triggering is used, the time overlap window (coincidence time) must be set. The default value is 40 ns. At the default setting, two PMTs must produce individual pulses that exceed their specified threshold voltage AND occur within 40 ns of each other to create a trigger. If the coincidence time is too short, relatively few card triggers will occur. If it is too long, there is increased probability of false triggers. The oscilloscope display of the pulses can guide this setting. The coincidence time has no meaning in the single trigger configuration.

Once the card triggers, all the detector input channels will record above-threshold photon signals during a specified time (gate width). The proper gate width will depend on the type of experiment being performed. If only the triggering pulse or pulses are to be recorded, the gate width can be relatively short. If muon decay events are of interest, the gate width must exceed the expected muon lifetime by 4 to 5x. Longer than this will introduce noise; a significantly shorter gate will make determination of the decay time difficult.

Threshold: Each channel of the QuarkNet card will locally trigger when the amplified PMT pulse exceeds a specified threshold voltage. This is illustrated by the dotted red line in the adjacent figure. Recall that the threshold voltage must be adjusted by 10x compared to the PMT output to account for amplification on the card. Also note that individual channel triggers do not guarantee the gate will open if coincidence triggering has been selected. Simultaneous PMT events as defined by the coincidence time window are required.



The time-over-threshold of an individual pulse can be recorded with a precision of 1.25 ns. This time gives an approximate measure of the integrated power and hence the relative energy in the PMT pulses.

Setup: The LabVIEW program Setup.vi helps configure the QuarkNet card. The goal is to set the PMT bias voltage along with the channel thresholds to acquire reliable data counts. The negative-going voltage of the PMT output pulses must be sufficiently above the background noise and at a level where they can be readily discriminated.

Initial setup should be performed with single detection, a gate width of 100 ns, and 100 mV threshold. Negative voltage for all PMT signals is assumed, so the threshold is entered as a positive number. These settings are not critical, but should be a good starting point. The sampling period should be long enough that the count does not vary widely between display updates. Start the program, wait three seconds for the card to initialize, and press the RUN button. Detector counts will be displayed. To change an operating parameter, press PAUSE, make the desired change, then press RUN. The PAUSE button allows parameters to be modified without a complete card reset. As the threshold voltage increases, the count rate should drop. When higher thresholds do not noticeably reduce the count rate, a good operating threshold voltage is identified. Keep the PMT voltage constant and configure the second channel using the same criteria. If adequate thresholds can't be established on both channels, the PMT voltage must be changed.

Select the coincidence tab to enable single counting from both PMTs and display their coincidence counts. Both detectors should be counting at a higher rate than the coincidence events; you can also determine which of the two detectors is limiting the coincidence trigger rate. Proper behavior verifies the threshold settings and the width of the coincidence time window. Record the working parameters and do not adjust the PMT voltage.

Open the LabVIEW program Muon.vi. With appropriate timing settings and threshold parameters determined above, this program records photon events collected by the PMTs. Two measurements can be performed: photon energy distribution and muon decay lifetime.

Energy distribution: Select the measurement 'Energy' and open the Coincidence tab. The experiment can be done with a single PMT, but more reliable data is obtained with simultaneous

signals from two PMTs to verify the presence of a valid photon in the scintillator. The goal of this measurement is to determine the approximate energy of each photon event by recording its time above threshold, shown as T in the above figure. The gate width can be set with the aid of the oscilloscope. It should be long enough to capture the photon signal; too long will introduce unnecessary noise. Since the width of the triggering photon is of interest, the gate minimum should be set to zero. Only data from one of the PMTs (decay detector) will be recorded.

Start the program and wait 3 seconds for the card to initialize. When the card is ready, press the RUN button. You will be prompted to specify the name and location of a data file where the collected values of T (in ns) will be written. Since data can be collected for an arbitrarily long time, this file will auto-save at a user-specified interval. Real-time data is displayed on an updating histogram. The distribution should approach an ideal Gaussian depending on the number of data points and histogram bins.

When sufficient data has been collected, stop the program. Repeat the measurement but stop it when the number of data points is about half of the first run. Change the decay detector to the other PMT and do the same pair of measurements (4 total). For the analysis, produce a histogram with a Gaussian fit for all the data sets to determine the mean pulse width and variance; express the latter as a percentage of the mean. How does the analysis depend on the number of histogram bins? Comment on the differences and calculate the experimental uncertainty for each data set.

Muon decay: Select the measurement 'Decay' and open the Coincidence tab. In this experiment, the decay detector waits for a second photon that follows the coincidence trigger, which should correspond to a muon decay. The program must be configured to ignore trigger events, which will radically skew the data toward time zero. The gate minimum setting must be set longer than duration of any possible trigger pulse, accounting for fluctuations introduced by the coincidence time window. (Tip: The gate minimum should be longer than the gate width used in the preceding experiment) To observe the expected exponential decay, the gate should remain open for several muon decay lifetimes (order of microseconds). If the gate width is set longer than 5 muon lifetimes, data accumulated at long times will represent the noise background. The background data introduces a constant offset on the statistics that can be subtracted. The desired decay events are statistically rare, so an hour or more may be needed to accumulate a useful data set. When sufficient data is collected, stop the program. The time events are all written to the specified data file. For the analysis, setup an appropriate histogram on a semi-log plot. The slope of the linear fit is the measured muon decay lifetime. Calculate the experimental uncertainty and compare the lifetime to the accepted value.

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APPENDIX 1: Time-to-Amplitude Converters

Bill Miller and Paul Schwoebel

A Time-to-Amplitude Converter (TAC) is a device that accepts a start pulse and waits for a stop pulse. Circuitry inside the TAC determines how much time has elapsed between the two pulses. The TAC produces a voltage pulse with an amplitude that is proportional to the elapsed time.

To use the TAC:

1. Check if there are any special power requirements like ± 6 V. This can usually be found on the front panel. Some units have a rear panel switch that allows for either ± 12 V or ± 6 V. Make sure that your NIM bin has correct voltages available.
- 2) Check to see what logic family the unit uses, NIM logic (a "V" looking character) or TTL (a representation of a positive going pulse). Some units can be switched between the logics.
- 3) Set up the TAC for the proper time scale. If you set it up for a 1 μ s scale and give it a signal with 2 μ s between start and stop you will not get an output from the TAC. Similarly, If you select 1 μ s and deliver only 1 ns the TAC will provide no output.
- 4) There can be a number of extra functions on the front panel. For *COINC* and *ANTICOINC* select *ANTICOINC*. *GATE* should be *OPEN*. The *SCA* is not important for this experiment. Leave the *ULD* at 10 and the *LLD* at 0. Buttons or switches associated with the *SCA* should be set to *OFF* or *OUT*. Anything that says *DELAY* is not important. This adjusts the time between the accepted *STOP* signal and the TAC output pulse. For slow count rates, 10 μ s is nothing to worry about.