The determination of muon rate and fluorescene life-time using MPPC Array

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Hardware Camp for Fast and Low-light detection

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Introduction

- In our modern world, we can detect "fast" and "low-light," with "fast" referring to nanoseconds and "low-light" referring to a few to hundreds of photoelectrons. This provides us with a massive amount of information and knowledge for future scientific studies.
- In this Hardware camp for Fast and Low-light detection, our group learned and practiced some experiments related to MPPC, Wavelength shifting fibers, and Fluorescences.

Introduction

- To begin, I will quickly describe the concept of muon decay. Muons are elementary particles having a charge of -1e and a spin of 1/2.
- Muons are heavier than electrons and neutrinos but lighter than all other matter particles.
- They decay due to the weak interaction. Since leptonic family numbers are maintained in the absence of a highly rare instant neutrino oscillation, one of the muon decay product neutrinos must be a muon-type neutrino and the other an electron-type antineutrino (antimuon decay yields the corresponding antiparticles). As a result, all muons decay into at least one electron and two neutrinos.

In formulaic words, these two decays are as follows:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Introduction

In this course, we use MPPC to detect signals for collecting data. Specifically, we will explain the following experiments:

- Collecting dark count rate
- Muon count rate.
- Fluorescence decay time.

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MPPC

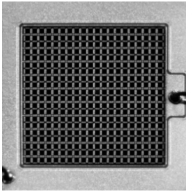

Figure: Single MPPC

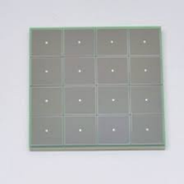

Figure: Multi-channels MPPC

- MPPC stands for multi-pixel photon counter, also known as Silicon Photomultiplier (SiPM)
- A solid state photodetector.
- Made up of a matrix of avalanche photodiodes (APD).
- Operated in Geiger mode.
- Detect low-intensity light signal

MPPC Array

4	8	12	16
3	7	11	15
2	6	10	14
1	5	9	13

- MPPC array 4x4, model Hamamatsu S13361-3050AE-04.
- Our MPPC Array contains 16 pixels which can connect to 16 channels, but we only use 4 pixels: 6, 7, 10, 11.

MPPC Array Specifications

Parameter	Value
Number of channels	16 (4x4)
Number of pixels	3584
Operating temperature	-20 to +60 ($^\circ C$)
Spectral response range	320 to 900 (nm)
Peak sensitivity wavelength	450 (nm)
Photon detection efficiency	40%
Gain	1.7×10^6
Breakdown voltage	53 $\pm 5(V)$
Operating voltage	$V_{breakdown} + 3(V)$

Table: S13361-3050AE-04 specifications

PBA116 Amplifier

- Our MPPC array is provided along with a dedicated Printed Circuit Board.

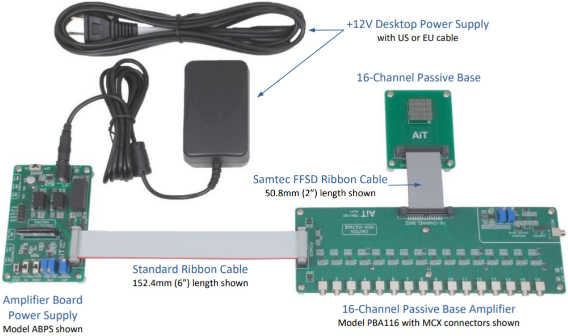

Figure: 16-Channel 1-Stage Passive Base Amplifer

PBA116 Amplifier

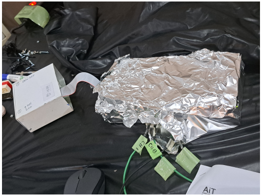

Figure: Amplifier wrapped by tin foil

- The amplifer board and power supply board are wrapped in tin foil
  $\rightarrow$ Faraday cage.
- Faraday cage: external electrical field causes the electric charges within the cage's conducting material to be distributed so that they cancel the field's effect in the cage's interior.
  $\rightarrow$ Protect sensitive electronic equipments' electromagnetic pickups from interference.

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Plastic scintillators and Wavelength shifting fibers

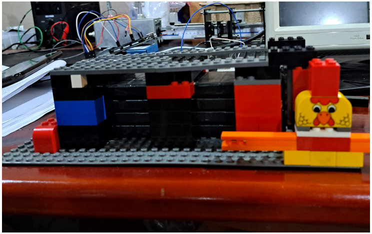

Figure: Preparation of scintillators

- Scintillators:
  - Size: 2.5cm width x 1.3cm thick x 25cm long
  - Area: 17cm x 5cm
  - The facets of the scintillators are covered by Titanium Dioxide which absorbs the recoil protons.
  - 4 bars of scintillators.
  - Arrangement: The scintillators are layered on top of one another.
  - Light tightening: make sure the two-ends are light-proof (photon-proof) by wrapping them with tin foil.
  - Use black tape to reinforce the wraps and prevent external light from entering the set-up.

Plastic scintillators and Wavelength shifting fibers

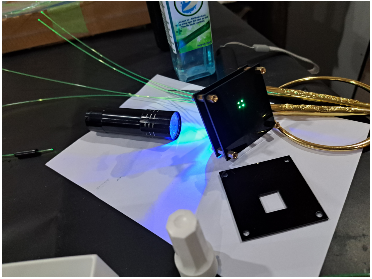

Figure: Preparation of WSF

- Wavelength shifting fibers:
  - Widely used for light collection from scintillation counters.
  - Cut the WLSF into equal lengths for implementing the set-up.
  - The fibers are then polished.
  - Light tightening of the fibers: using black plastic covers.
  - UV-glued to customized plate.
  - Channel mapping of MPPC array

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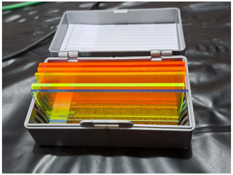
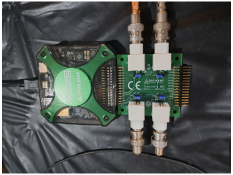
Fluorescenes

- Analog Discovery 2 and Digilent WaveForms software is used to generate waveform for UV led (385 nm).
- 5 Thorlab's fluorescenes panels: red, orange, yellow, green, blue.
- We examine the voltage of the Analog Discovery from 4V to 5V, the voltages from 4 to 4.4 are weak, the symmetry over 7% cause the shutdown on the system. The speed of pulse is limited because of the system.

Amplitude	4.6 V
Frequency	1MHz
Symmetry	5%





Oscilloscope SDS1104X-E

Figure: Oscilloscope front

Bandwidth	100MHz
Channels EXT (two channel series)	4 (four channel series) 2
Trigger Type Interval, Dropout, Pattern, Video	Edge, Slope, Pulse Width, Window, Runt,
I/O Pass/Fail, Trigger Out, Sbus (Siglent MSO)	USB Host, USB Device, LAN,
Display	7 inch TFT -LCD (800x480)

Table: Oscilloscope specifications

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Dark current and muon counter set-up

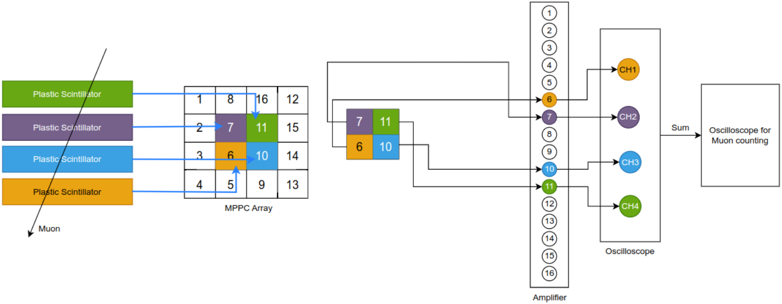


Figure: Muon counter set-up

- The stacked scintillators are fixed using LEGO frame.
- The WSF glued plate is connected to the MPPC array. The arrangement and order of connection between scintillators, MPPC array and channels are noted above carefully.

Width of the window's measurement using cursor of the oscilloscope set-up

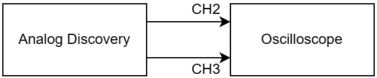


Figure: Width

- Analog Discovery 2, which is connected to the oscilloscope, generates 2 pulses but have different initial phases.
- The pattern measurement is set for two signals on the oscilloscope.
- Increasing the different initial phases of two signals by 5 degrees till there is no coincidence
- Using cursors to measure the time difference of two signals. Mark the time when there is no coincidence.

Fluorescences decay time real set-up

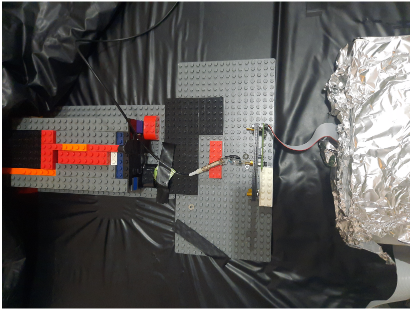


Figure: A complete set-up includes the led coupling with the MPPC, and the MPPC is connected to the amplifier circuit

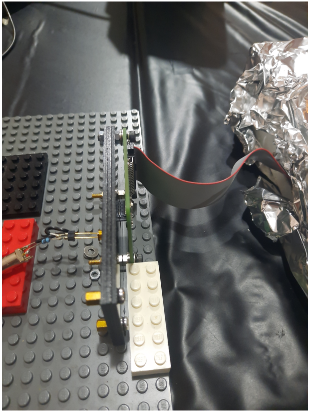
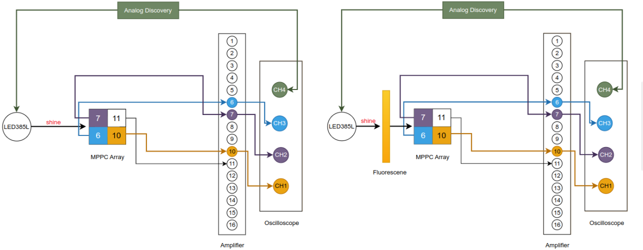


Figure: A zoom-in to the LED coupling with the MPPC array

Fluorescenes decay time set-up



- LED controlled by the Analog Discovery 2 shines to the fluorescence. The fluorescence plate is coupled to the MPPC array.
- Channel 6, 7, 10 through the amplifier are connected to channels 1st, 2nd and 3rd of the oscilloscope.
- The decay time which is the time duration indicated by 2 points which are 90% and 10% of the peak.This value is extracted by using the cursor and by processing the .csv file from the oscilloscope.

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Dark count (1)

To better detect the muon's signal, the values which are proportional to a value of one a pe, (1pe, 2pe, 3pe, etc.) are measured corresponding to each channel when the system has no light shine on it. By doing this, we can identify some threshold values to remove background noise from the dark current.

Channel	1 pe	2 pe	3 pe	4 pe	5 pe
1	5,2	10,4	15,8	21,3	26,6
2	4,2	9,9	14,8	20	25,4
square height3	4,2	8,7	12,3	16,5	20,5
4	5,6	11	16,6	21,5	28

Table: Dark current of individual channels

The default "window" time interval is measured to verify the given equation to calculate the coincidence frequency.

degree different	0	0,5	1	1,5	2	2,5	3	3,5	4
time(ns)	0	30	45	54	67	76	85	109	DNE

Table: Measurement to determine the default coincidence's "window" width

Dark count (2)

The equation to calculate the coincidence frequency of two sources:

$$f_{coin} = 2 \times f_1 \times f_2 \times W$$

Parameters:

- f_{coin}: coincidence frequency of source 1 and source 2
- f_1, f_2: frequency of source 1 and source 2
- W: time value of the interval "window"

Pe	$f_1(kHz)$	$std_1(kHz)$	$f_2(kHz)$	$std_2(kHz)$	$f_{coin}(kHz)$	$std_{coin}(Hz)$	$f_{theo}(kHz)$
1	145,98	14,36	571,41	4,97	2,38	147,84	17,93
2	80,76	2,81	77,27	2,68	1,81	150,08	1,34
3	13,16	0,36	11,35	0,37	0,15	801,89	0,03
4	2,16	0,18	2,022	0,25	0,000022	-	0,00094

Table: Coincidence of dark current of channel 1 and 2

For 2 channels' coincidence:

- the frequency of coincident of 4 pe. of 3 channels is approximately 0.
- For 2 pe, the frequency of coincident measured by the oscilloscope is approximately equal to the calculated one by the equation.

Dark count (3)

The equation to calculate the coincidence frequency of three sources:

$$f_{coin} = 3 \times f_1 \times f_2 \times f_3 \times W^2$$

1. f_{coin}: coincidence frequency of source 1 and source 2
2. f_1, f_2, f_3: frequency of source 1 and source 2
3. W: time value of the interval "window"

Pe	$f_1(kHz)$	stdev $f_1(Hz)$	$f_2(kHz)$	stdev $f_2(Hz)$	$f_3(kHz)$	stdev $f_3(Hz)$
1	81,09	8, 75	601, 46	4, 97	133	328,86
2	85,09	2,55	82,76	3,29	84,31	3,14
3	13,30	394,73	11,78	344,03	15,64	553,94

Table: Coincidence of dark current of channel 1, 2, and 3

Pe	$f_{coin}(Hz)$	stdev f_{coin}	f_{coin} *theoretical*
1	465,78	155,58	224,90
2	0,02	NA	20,58
3	0	NA	0,08

Table: Coincidence of dark current of channels 1,2, and 3 (continue)

For 3 channels' coincidence:

- The frequency of coincident of 2 and 3 pe. of 3 channels is approximately 0.
- The frequency generated by the oscilloscope is far larger than the frequency calculated by the given equation.

Pe	$f_{coin}(Hz)$	stdev f_{coin}
1	0,0167	NA
2	0	NA

Table: Coincidence of dark current of channels 1, 2, 3, and 4 (manually measured)

Notice here, the frequency of coincident of 2 pe of 4 channels is approximately 0. Therefore, the coincidence of 4 channels at the threshold above 2 pe is chosen to detect the appearance of muon passing the detectors.

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Predicted muon flux

Figure: Scintillator used in experiment

- Area of plastic scintillator: 17cm x 5cm
- Muon rate can be estimated as **slightly less** than one muon per square centimeter, per minute:

$$17(cm) \times 5(cm) \times 1\mu/cm^2/60s \approx 1Hz$$

- This is the expected muon count rate that we want to find from the experiment.

Practical set-up and results

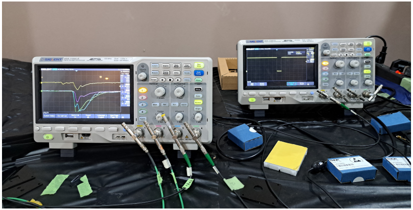

Figure: Muon count rate practical set-up

Time (s)	Number of hits	Frequency (Hz)
3840	1796	0.5
9132	8326	0.91

Table: Results of mount rate over a period of time

With a long period of time, the muon arrival rate comes closer to the theoretical value which is 1.

Expected muon lifetime

- Mean time for a muon at rest to decay: $(2.1969811 \pm 0.22e-5\mu s)$
- However, these muons travel near the speed of light
  $\rightarrow$ Consider special relativity
  $\rightarrow$ Muon lifetime while in motion will be longer than at rest.

$$t = \gamma\tau$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$N = N_0 e^{\lambda t}$$

$$f(t) = \lambda e^{\lambda t}$$

$\rightarrow$ PDF of the muon decay time can be modelled to estimate the value of muon decay constant λ.

Muon decay time measurements

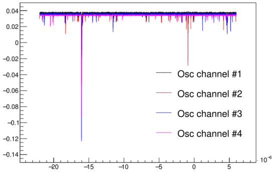

Figure: Event 56

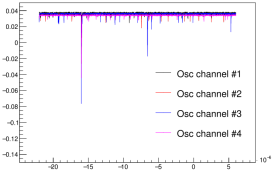

Figure: Event 398

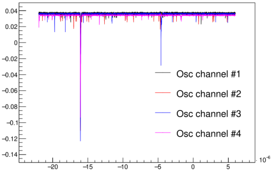

Figure: Event 609

- Coincidence: Channel 1, 2 and 3
- Thresholds: 2.5 pe
- Total events: 8000 events.
- Total time: approximately 14 hours (6 pm to 8 am)
- Number of candidates: 65 candidates
- Frequency: 1.3e-3 Hz

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Average of acquired signals

Figure: Amplitude 4.6V (Blue fluorescence)

Figure: Amplitude 4.8V (Blue fluorescence)

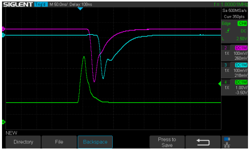


Figure: Amplitude 5V (Blue fluorescence)

Average over 1024 signals observed in the set-up of the blue fluorescence, with 4.6V, 4.8V and 5V applied.

Fluorescence decay time using Oscilloscope cursors

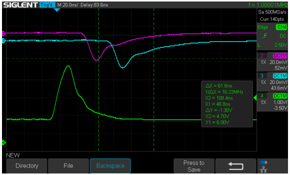


Figure: Lifetime measurement on CH2

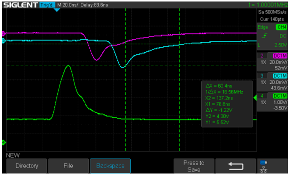


Figure: Lifetime measurement on CH3

The decay time is measure by from the 90% of the peak to the 10% from the baseline.

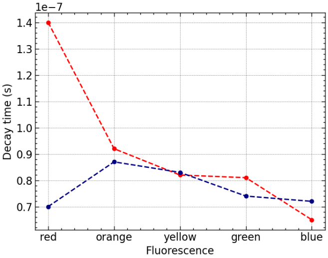
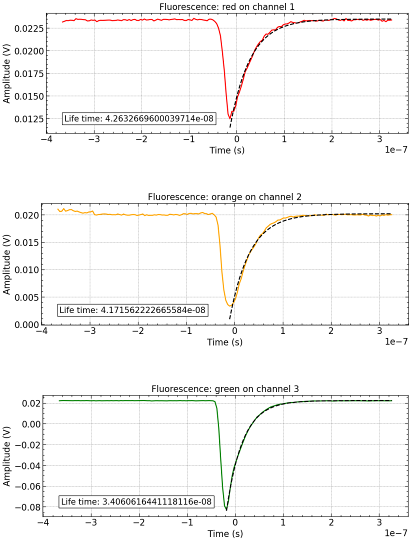


Figure: Decay time estimation using cursor

Fluorescence life time using Jupyter Notebook



- Fluorescence lifetime (FLT): is the time a fluorophore spends in the excited state before emitting a photon and returning to the ground state.
- The decay determines by the expression: $I = I_0 \times e^{-\frac{t}{\tau}}$.
- Data acquisition from telescope of 100 events using Root, then takes the average and convert to .csv file.
- We fit emission data to the decay equation using Python to find to best fit of I_0 and τ.

Fluorescence life time

- The life time measured by fitting the equation is more consistent than the decay time measured by the cursor.
- The life time decreases propotional to the wavelength.

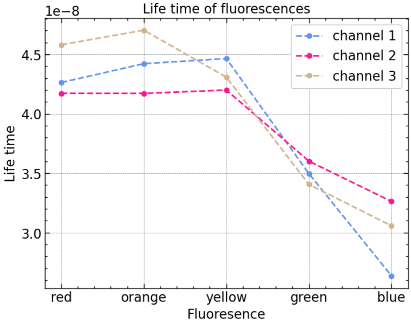


Figure: Life time of fluorescences using Jupyter Notebook

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Dissussion

- The dark count coincidence frequency measured from experiment is not consistent with the calculation from the formular.
- The coincidence from three or four channels can be set to a specific threshold to eliminate the dark current
- The muon rate from experiment is close to the value from the expectation value.
- The decay time of fluorescene decrease proportionally with the wavelengths. The reason is because as the wavelength of the excitation light becomes shorter, its energy increases. This can result in a greater likelihood that the excited fluorescent molecule will lose energy through non-radiative processes, such as collisional deactivation or energy transfer, before it has a chance to emit a photon and return to its ground state.

Future Work

- Change the set up the fluorescene with the better waveform generators to achieve the faster pulse, so that we can get the better values of lifetime.
- Find a better equation for the coincidence frequency.

Thank You For Your Attention