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Photo-detector development for nEXO

Rapport de stage de Master
sous la direction de *Fabrice RETIERE*

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TRIUMF

Thanks

I would like to express my gratitude toward Mr. Fabrice RETIERE for giving me the opportunity to do an internship in one of the most important national Canadian laboratory called TRIUMF.

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Abstract

Founded in 1968 and located on the campus of UBC [1], TRIUMF [2] is one of the worlds leading subatomic physics laboratories.Different research topics whose the one about particles are conducted. On the microscopic scale TRIUMF and nEXO [3] work together to measure the neutrino-less double beta decay.
If the ^{136}Xe can produce such decay and then give light at 175 nm, my internship focus on the caracterisation of Silicum Photo-Multipliers. Such detectors will be used for the nEXO experiment to detect that light (photons). To caracterize them, efficiency dark noise and cross-talk were calculated at different over-voltage. Each SiPM has its own breakdown voltage upon which photons could be detected.
The electromagnetic noise let us caracterize only a MEG MPPC [4] at -100C. With an overvoltage of 3.5V (breakdown voltage of 57.2V at such temperature), the efficiency, the dark noise and the cross-talk were plotted.

Résumé

Fondée en 1968 et localisé sur le campus de l'UBC, TRIUMF -Laboratoire national Canadien pour la recherche en physique nucléaire et en physique des particules- est l'un des plus importants laboratoires de physique subatomique au monde. Différents thèmes de recherche dont celui des particles sont envisagé. A l'échelle nanométrique TRIUMF et nEXO travaillent ensemble à la recherche de la désintégration bta sans mission de neutrinos.
Si l'élément chimique ^{136}Xe est un candidat potentiel pour produire une telle désintégration avec émission de lumière 175 nm, le but de mon stage est de caractériser des détecteurs SiPM. De tels détecteurs seront ensuite utilisés lors de l'expérience nEXO pour détecter la lumière (photons) èmise. Ainsi il est possible de les caractériser en calculant l'efficacitè, le bruit noire et le crosstalk différentes tensions de polarisation. Chaque SiPM a sa propre tension partir de laquelle un photon est dètecté.
Le bruit electronique ne nous a permis de caractériser qu'un seul SiPM (MEG MPPC). L'efficacité, le bruit noire et le crosstalk ont été tracés.

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[1] University of British Columbia
[2] Canada's national laboratory for particle and nuclear physics
[3] next generation Enriched Xenon Observatory
[4] SiPMs produced by Hammamatsu

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Chapter 1

Introduction

This last internship of 3 months let student of the Master PSA from the University of Starsbourg to apply what they have learned 6 months before. The goal of this internship is to show that the student can conduct with responsability and authonomous a research experiment. In that way the student may be ready to continue by doing a Phd.

Founded in 1968 and located on the campus of the University of British Columbia,TRIUMF is one of the worlds leading subatomic physics laboratories and the first national laboratory in Canada. The main feature of this laboratory is a Cyclotron which was built in 1971 While maintaining ties to the research programs among the 19 different member unversities from across Canada, composed of international teams of scientists, post-doctoral fellow and students, this large community has expanded from nuclear physics to particle physics, molecular and materials science, and nuclear medicine.

In the particle research topic, TRIUMF hosts nEXO scientists who try to measure the possible neutrino-less double beta decay $0\nu\beta\beta$. If the standard model predict the ordinary double beta decay $2\nu\beta\beta$ the detection of $0\nu\beta\beta$ would validate "Physics beyond the standard model", show that the neutrino is a Majorana particle and measure the absolute neutrino mass.

Among the 35 natural isotopes, the ^{136}Xe is a potential candidat since the below equation conducts to the observation of $0\nu\beta\beta$:

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^- \tag{1.1}$$

So the two electrons, which are ejected with high kinetic energy, scatter in other electrons of ^{136}Xe atoms. If so, on of the hurted ^{136}Xe atoms is existed from the ground state and then de-energizes by releasing photons here is the scintillation. The wave lenght of the created light is 175 nm.

So nEXO is currently being designed to use 5 tons of enriched liquid Xenon contained in a barrel. The wall of this barrel are covered with SiPM detectors. [1]
The goal of my research internship is to indentify suitable SiPMs for nEXO, by testing devices

[1] Silicum Photo-Multiplier.

from several manufacturers.In 2014 a test setup was built : a box divided in two parts. The first part contains a Xenon flash lampwhich sends photons to the surface of two SiPM detectors. The signals are observed on the screen of an oscilloscope which is monitored by a computer to register and store waveforms. An algorithm (C++ and root) let us caracterize the SiPMs.

So the question is to know if the selected SiPM could fufill all the experiments requirements: achieve efficiency $\geq$15"%" at 175nm (the wavelength of Xenon scintillation), achieve dark noise rate less than 50Hz/mm^2 and limit the number of correlated pulses (cross-talk and after-pulse) to less than 0.02 per parent pulse.

If the first part will describe briefly the nEXO experiment and remind the reader how works a SiPM, the second part will give more details about the setup and the algorithm. That lets to understand the results on the third part.

Chapter 2

The neutrino, a Majorana particle?

2.1 nEXO Experiment.

If the introduction begins explaining what is the purpose of nEXO, I would like to sum up breifly the nEXO experiment. The reader could refer to the appendix A to obtain more information . nEXO is the little sister of the EXO experiment. They both try to observe the $0\nu\beta\beta$.

EXO-200.

EXO currently has a 200-kilogram Xenon liquid, containing in a copper cylindrical time projection chamber whose each extremity is covored by APD [1]. Xenon double beta decay $2\nu\beta\beta$ [2] was detected and energy limits have been set for $0\nu\beta\beta$. However the background radiation is a significant problem.
The neutrinoless decays would appear as narrow spike in the energy spectrum around the xenon Q-value (Q = 2457.8 keV).

Energy resolution is a key parameter to identifying $0\nu\beta\beta$ decays. Even if the gamma background can be rejected by selecting an energy region around 2.48 MeV, the EXO experiment is already limiting the energy resolution because of the low gain of APDs. EXO-200 must be improved by nEXO.

nEXO.

The nEXO experiment is just a bigger EXO experiment since the barral will be expanded to contain 5 tonnes of Xenon. Moreover since the gain of a SiPM is 10^4 than this of an APD (200), the APds will be subsituted by SiPMs which will cover the wall of that barrel.

[1] Avalanche photodiodes.
[2] In August 2011, EXO-200 was the first experiment to observe double beta decay of ^{136}Xe, with a half life of 2.11^1021years

2.2 SiPM.

Silicon photomultiplier (SiPM) is a photodetector with single-photon detection capability. This device consists in a monolithic array of multiple single avalanche photodiodes (APDs) pixel.
Each pixel produces a pulse of constant amplitude regardless of the number of impinging photons.
All pixels are connected to the same output channel The total output signal is equal to the sum of those from the indidividual pixels. SiPM offers good properties like high gain $10^6/7$ and sensitivity, a very good time (ns) and photon-counting (nm) resolutions.
One feature of the SiPM is that device operats in Geiger mode.

2.2.1 APD's operating.

This short section is to remind the reader APD's operating.
A reverse voltage is applied to the APD (which is a PN junction) : this is the Geiger mode. When the light enters a photodiode and if the light energy is higher than the band gap energy, electron-hole pairs are generated in the depletion layer (p-). Then because of an electric field created by the reverse voltage the electrons drift towards the n++ side and the hole towards to the p++ side of the PN junction : this is the avalanche phenomen.
With an higher electric field one avalanche can itself trigger a second avalanche at a different position. In Geiger mode this new situation is only due to the holes which can trigger other avalanches.
The avalanche is limited by the buildup of a limiting space charge in the depletion layer (p-) which decreases the field. Moreover, since the photodetector has a resistor (quenching resistor) in series, when the avalanche current flows through the resistor, the breakdown volatage applied to the junction drops below it. This quenches the avalanche; thus, the current decreases to zero, and the voltage across the p-n junction increases again above breakdown voltage. The pixel is then ready to detect the arrival of a new photon :

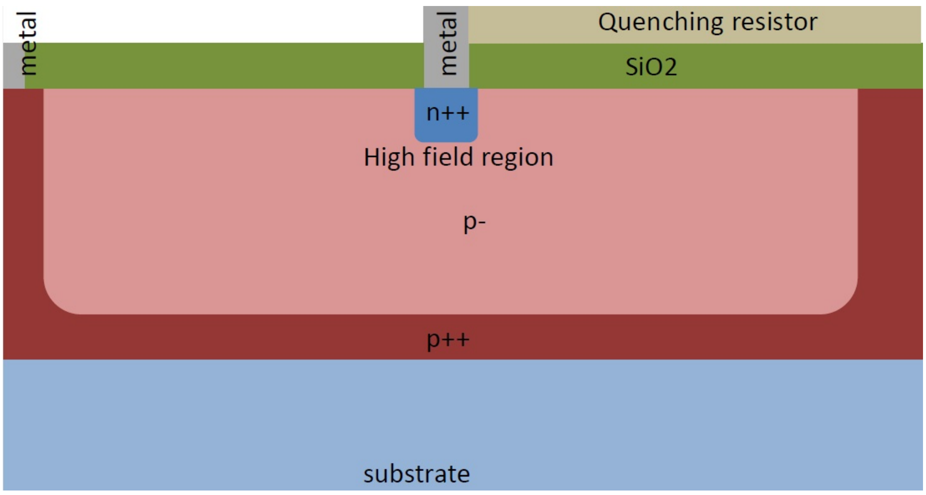

Figure 2.1: Details of a pixel of a SiPM.

Such ideal picture is strongly modified by the occurrence of phenomena leading to dark current, afterpulsing effects and crootalk.

2.2.2 The three issues of operating SiPM.

Dark Noise. The main source of noise limiting the SiPM performances is the dark noise rate, which mainly originates from the electron created thermally in the depletion layer (p-). Theses carriers trigger avalanches, exactly as if the pixel would have been fired. The probability that dark noise occurs decreases with the temperature.

Trapping phenomena : Afterpulsing. Traps may result from the damage caused by an implantation of some impurities in the fabrication process. In the depletion layer , deep levels trap some avalanche carriers and release them with a statistical delay. If the delay is greater than the dead time after the previous avalanche pulse, a released carrier can re-trigger an avalanche and cause a statistically correlated pulse. These carriers form the afterpulse.
The probability that an afterpulse occurs increases with increasing bias voltage.

Crosstalk. Hot carriers in avalanche p-n junction emit photons even in the visible range. Thus, during the avalanche breakdown, a photodiode operating in Geiger mode may emit a few photons. The photons emitted will be detected by neighboring pixels despite of a optical wall between two pixels **??**.
The picture below can resume these three main issues :

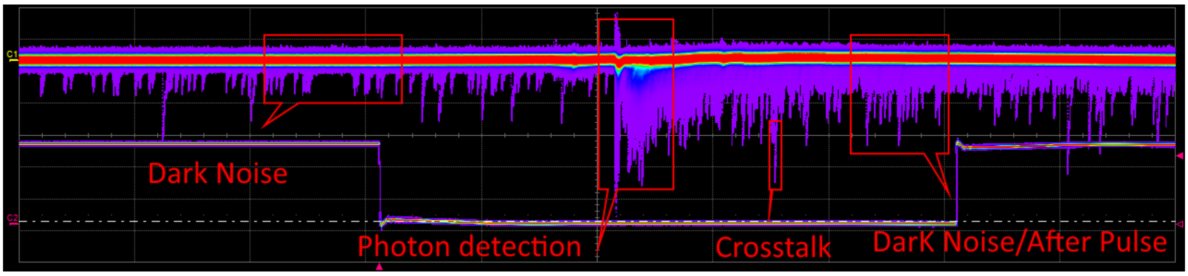

Figure 2.2: Dark noise, after-pulse and croos-talk

The reader could find more details about SiPM in the appendix **??**.

Chapter 3

The Setup.

For the setup we use an aluminium box divided in two parts. The picture above below can give a good idea what is our setup. In the first part stays a Xenon flash lamp and in the other one stays two photodetectors.

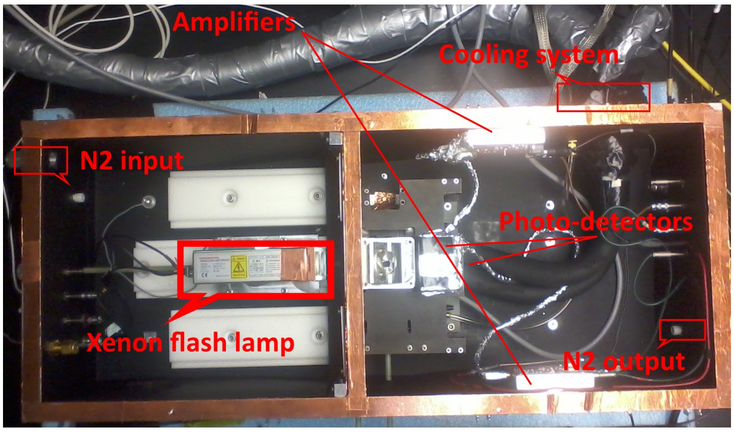

Figure 3.1: An aluminium box contains a Xenon flash lampand two photodetectors.

3.1 The Xenon flash lampand the MEG.

Xenon flash lamp A Hamamatsu L11035-03-21 Xenon flash lamp module is utilized as a light source in a nitrogen-filled, light-tight box to simulate the ultraviolet conditions of the future experiment. The amount of light hitting the photodetectors must be properly managed by a a square wave pulse generator overwise saturation of the signal from the photodetectors occurs.
To control light output and so the number of photons reaching the photodetectors, we can move out the lamp from the surface of the detector since intensity of light drops off as one over distance suqarred and set the voltage discharge on the lamp by adding an external voltage supply line.

For all our measurments, the position of the lamp and the external volatge are setted at

20 mm from the metal divider of the box and at 2.8 V. Then the light is collimated by 5 mm hole, filtered, and then either interacts with a beam splitter (BS). This last one separate the incoming beam in two equal beams which reach the surface of each photodetector -one on te top as reference and another one cooled on the bottom to be caracterised- on the same time.

As well, the Xenon flash lampemits a spectrum of light in visible-light wavelength regions. To select the three wavelengths around 180 nm, a filter select the UV region. This filter attenuate also the light of the Xenon flash lampby 20"%". Then two other same filters were added because the light reaching the photo-detectors was too intense.

At least as the photons propagate into the air on few mm, the box was filled with azote.

Othewise light leaks appear when the Xenon flash lampoperating. They can hinder and negate the results of data collection. Two kinds of light leaks has been observed :

- Visible light leaks can impact the surface of the photodetectors. So the efficiencies for the SiPMs and MPPCs being tested at 180 nm is being falsy. The solution has been to cover the Xenon flash lampwith a black box. Moreover the interior walls of the light-tight box were covered in matt black viny to absorbe these light leaks.
- Radiofrequency light leaks result in electromagnetic noise on the signals from the detectors.

Radiofrequency noise occurs when the Xenon flash lampis triggered by a square wave pulse generator and photon propagate through a series of collimators and filters until reaching the surface of the detectors : one on the top and another one on the bottom. The signal of these two detectors is increased by two amplifiers. The box must be nitrogen-filled to prevent the absorption of UV light and re-emission into the visible range [1]. As it is explained before, each SiPm has a certain rate of dark noise. The dark noise is a function of the temperature. So to reduce dark noise and to be in experimental conditions as close as those of the nEXO experiment, the bottom detector is cooled with liquid Nitrogen.
The two amplifiers are connected to the oscilloscope. My co-worker and I noticed that too much noise disturbed the signal from the amplifiers. It was not possible to identify pulses from photons because they had lost in that noise.

Two ways could help to reduce electromagnetic noise :

- Improve the code to take in account this issue. That would have taken lots of time before finding pulses
- Improve the setup. We have choosen that second solution.

Several source of noise were found.

3.2 Sources of electromagnetic noise

The noise we observed was only an electromagnetic sources. The temperature has no impact on the noise even if the detector on the bottom is cooled until -100C or when the Xenon flash lampwas working. We noticed that :

[1] See appendix 3

- There used to be no ground point and some devices were not grounded. The consequence is that we was able to observe some oscillations on the oscilloscope **??**.
- When the Xenon flash lampwas working it was creating some radio waves propagating through the air and were transmitted to any piece of conductive metal of the box. The consequences were :
  - The aluminium lid of the box conducted everywhere the electric field of these radio waves, which disturbed the amplifiers.
  - Each detector coudl feel these radio waves and the signal get worst.
  - The metal divider acted as a transmitter and the piece of metal of the signal wires connected to the amplifiers acted as antenna.

3.3 Three main solutions

The first solution was to create a ground point on which all devices -especially the square wave pulse generator- were connected with the same wire (to avoid ground loops). In that way, the oscillations of 3.4 have dispeared.

Isolate the lid from the box As it was described above the electric field from the radio waves propagates through the entire lid and when the box was closed it disturbed the working amplifiers. The solution has been to isolate the lid from the box by adding black tape and to guide the electric field with copper on the edge of the lid and so to the ground point.

Isolate the Xenon flash lamp As the Xenon flash lampcreates radio waves, we decided to isolate it by building a faraday cage around it. We have added a thick piece of metal to absorbe radio waves and we have covered this first part of the box with aluminium foil. In that way electric field propagates through the aluminium foil to the edge of the top box and so to the ground point.

Isolate the photodetectors and the amplifiers As the bottom and the top detector seems to capture radio waves, two faraday cages were created to protect them.

This picture below could resume our work (yellow signal is the bottom photodetector and the blue one is on the top):

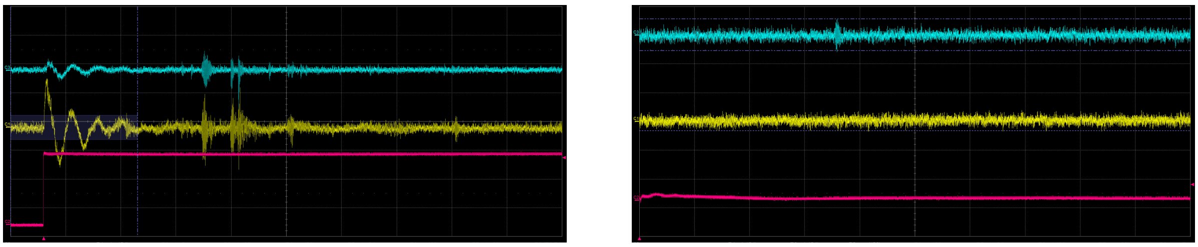

Figure 3.2: The noise level before (left) and after (right) solving the issues.

A SiPM, placed on the top, is used as a reference. He let us check if the light reminds constant when we caracterize different MEG MPPCs. These are layed on the bottom of the box and are cooled [2] at different temperature (-25C, -50C, -100C).

3.4 MEG

The appendix B explains the electronic circuit...

Like the SiPM [3] the MPPC is a type of photon counting device made up of multiple APD pixels operated in Geiger mode. The manufacturing of those pixels is shown in parts SiPM. And so the output current caused by Geiger discharge (due to the detection of photons) is a pulse waveform with a sharp rise time. The output current when Geiger discharge is halted by the quenching resistor is a pulse waveform with a relatively slow fall time.
The pictures below show a single photon pulse shape and also expand the rise time and the fall time.

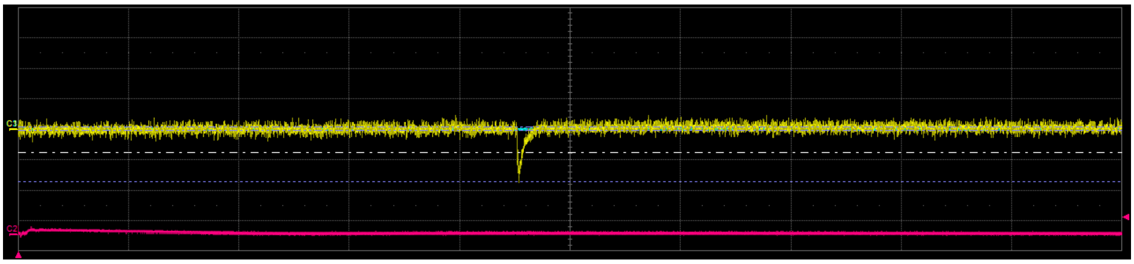

Figure 3.3: Pule shape @-100C.

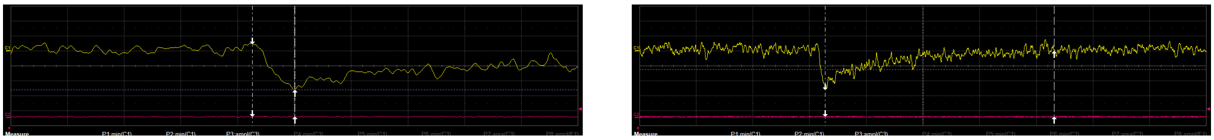

Figure 3.4: The rise time (left) is 7ns (10ns/div) than the fall time (right) is 200 ns (50ns/div).

[2] Appendix B explain how the dark noise decrease with temperature.
[3] See above section SiPM and appendix B.

Chapter 4

Results.

The observed waveform let us calculate the efficiency, the dark noise, the cross talk and the after-pulse. These 4 results caracterize the photodetectors.

4.1 The PDE.

A simple way to calculate the efficiency is to define two regions in the scope. On the left, the “dark region” do not let us to see pulse waveforms generated by the detection of photons and on the right, the “light region”, ie the region where the pulse waveforms will appear.
The both region has the same time range to be compared and pulses from dark noise can appear anywhere in these regions.
According to their definitions(see part 2.2.2), pulses from croos talk and after-pulse can only appear in the “light region”:

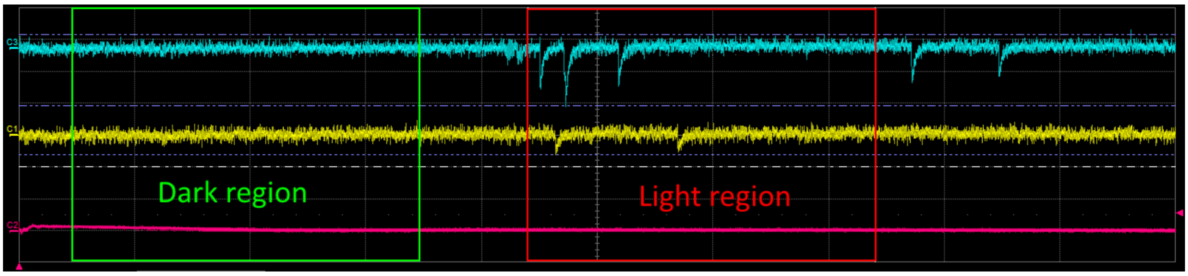

Figure 4.1: Dark and light regions.

So the efficiency -PE- of a detector is define with this relation below.

The probability of observing zero photon in the “light region“ is :

$$\frac{N_{L0}}{N_{tot}} = P_{L0} \ , \tag{4.1}$$

The probability of observing zero photon in the ”dark region“ is :

$$\frac{N_{D0}}{N_{tot}} = P_{D0} \ , \tag{4.2}$$

Moreover the Photo-Detection of Efficiency -PDE- follows a Poisson law :

$$P_{DE} = exp(- < PE >), \text{ with PE means the number of photo-electron in average} \tag{4.3}$$

$$\text{As the PDE is also : } P_{DE} = \frac{P_{L0}}{P_{D0}}, \text{ so here is the efficiency :} \tag{4.4}$$

$$< PE >= -ln(\frac{P_{L0}}{P_{D0}}). \tag{4.5}$$

To determinate the number of “zero” an algorithm was designed :
1. Smooth a waveform to reduce the Gaussian noise and therefore to increase the signal to noise ratio.
2. Set a threshold at 3.5 times the baseline σ.
3. Record all pulses above the threshold.
4. Record pulsewidth and charge for next step in analysing.

To have a good statistics we repeat this process for 15000 waveforms.
Then we plot the related histogram which determinate the number of “zero” PE (0PE), one PE (1PE which corresponds to te detection of one photon electron or one after-pulse since they have the same shape), two PEs (2PE which corresponds to the detection of two photo electrons or one cross-talk for the same reason) etc :
Here is one of our results for the MEG MPPC (for an over-voltage of):

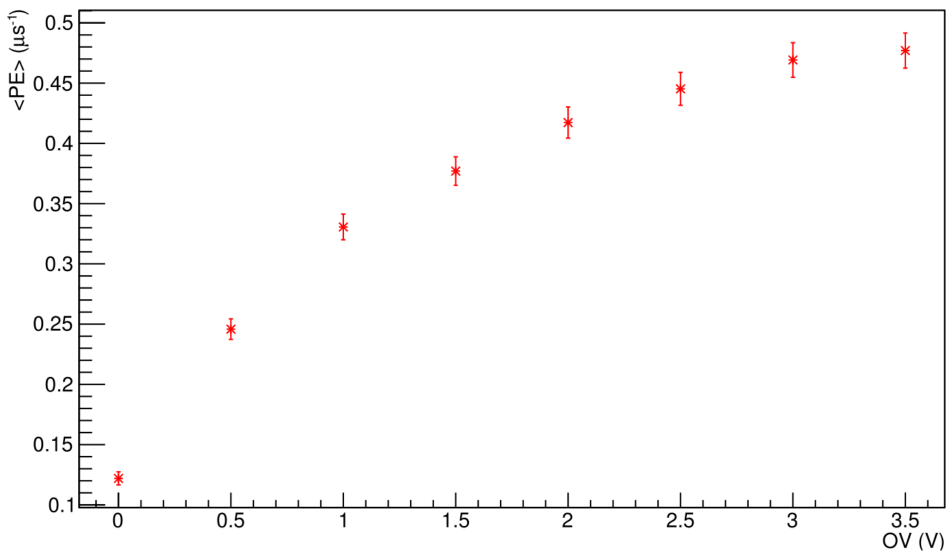

Figure 4.2: light region.

From all of the histograms it is now possible to plot the efficiency ($< PE >$). The efficiency is relative ($< PE >$) because we have not use the photo-detector on the top to check if the light is constant. According to some documentations [?] the shape of the curve is what we expected :

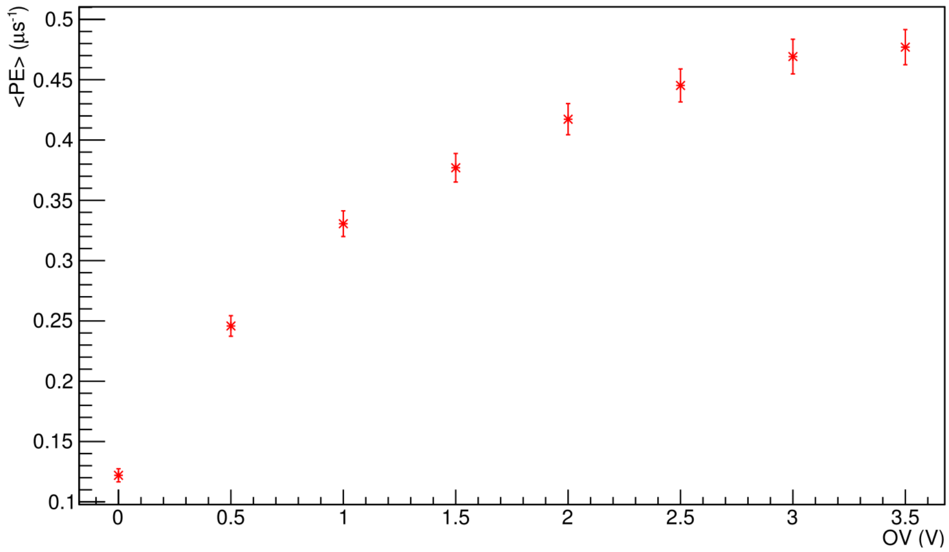

Figure 4.3: light region.

4.2 Dark Noise.

The dark noise -DN- follows also a Poisson law :

$$P_{D0} = exp(- < DN >) \iff < DN >= -ln(P_{D0}). \tag{4.6}$$

To plot the dark noise, all of the previous histograms are used :

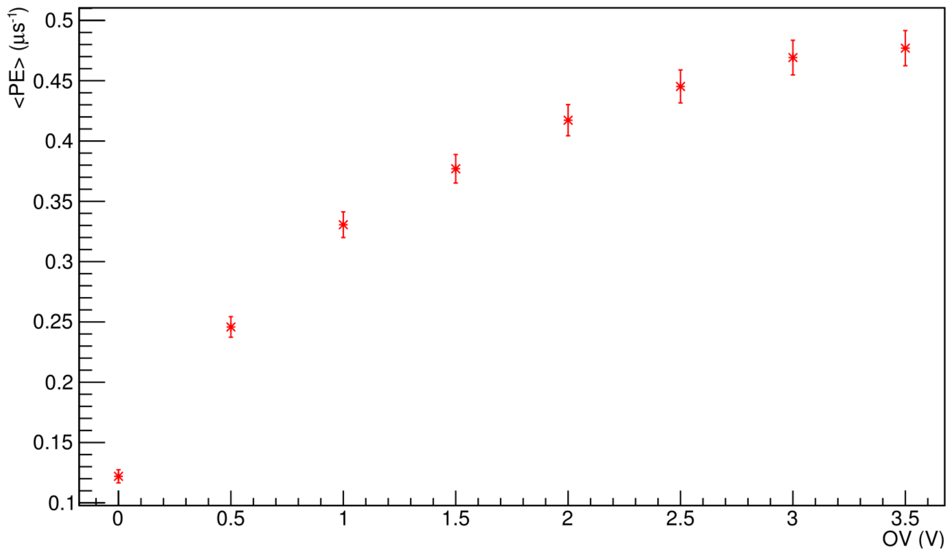

Figure 4.4: light region.

4.3 Cross-Talk.

To plot cross-talk, all the previous histograms are used : we integrate the 1PE peak divided by the sum of the rest of the histogram execpt 0PE :

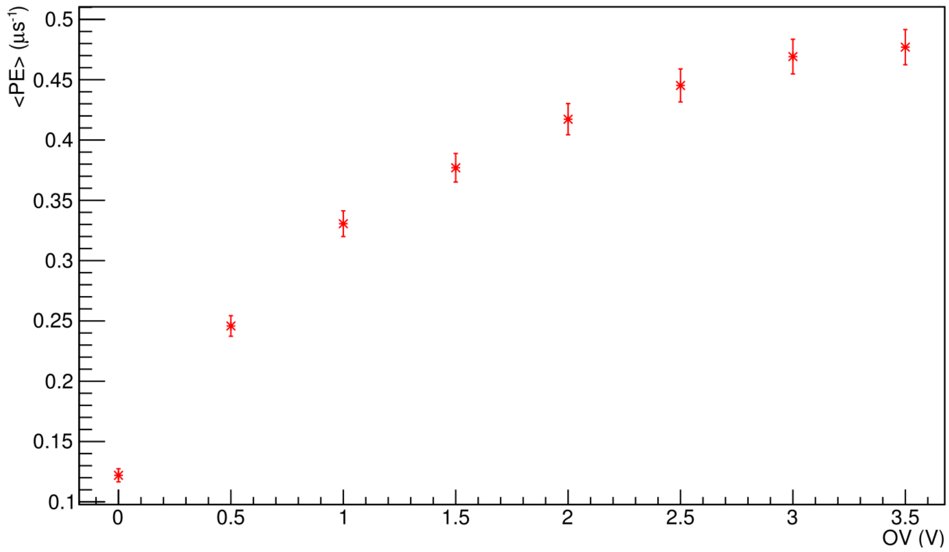

Figure 4.5: light region.

Chapter 5

Conclusion

The general curve of the PDE plot seems to be in concordance with other PDE calculation [6],[6].
The electromagnetic noise is a rea issue for taking data from the oscilloscope. My co worker and I spend three long days of the last week to take data from two different types of photodetectors : old generation of MPPC (an OV of 2V instead of 11V for the last) and labeled 1-9 (or 10?) VUV sensitive SiPM.
As there is one week left before my oral presentaion, that let us obtain more results and so it will be possible to discuss about them.

Bibliography

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[4] Double beta decay http://en.wikipedia.org/wiki/Double_beta_decay.

[5] Double beta decay http://en.wikipedia.org/wiki/Double_beta_decay.

[6] Double beta decay http://en.wikipedia.org/wiki/Double_beta_decay.

Appendix A

The nEXO experiement

A.1 the neutrinoless double beta decay : $0\nu\beta\beta$

History If this reference [6] could give more details about the $0\nu\beta\beta$, the double beta decay, which can proceed without emission of any neutrino, was discovered by W. H. Furry in 1939.

Majorana particle and leptonic number violation To explain the $0\nu\beta\beta$, lets start by reminding the double $2\nu\beta\beta$ according the Standard Model. As two neutrons become in two protons, the conservation of the charge imply the creation of two electrons. As 2 electrons appear, the conservation of the leptonic electronic number imply the creation of two anti-neutrino :

$$(A, Z) \rightarrow (A, Z + 2) + 2e^{-} + 2\overline{\nu} \tag{A.1}$$

$$leptonicelectronicconservation : \tag{A.2}$$

$$0 \rightarrow 0 + 2 * (+1) + 2 * (-1) \tag{A.3}$$

Now lets consider the case when neutrinos are Majorana particles [1] which means particles and anti-particles are identical except for their helicities. If so switching the helicity in this way allows a particle in one frame of reference to be an anti-particle in another.
That means that the emitted anti-neutrinos is neutrinos which conducts to the equation :

$$(A, Z) \rightarrow (A, Z + 2) + 2e^{-} + 2\nu \tag{A.4}$$

Here we can observe the lepton number violation which would be an observation of "Physics beyond the standard model" :

$$0 \rightarrow 0 + 2 * (+1) + 2 * (+1) \tag{A.5}$$

The Feyman diagrams related to $2\nu\beta\beta$ and $0\nu\beta\beta$ would be [2]:

[1] In opposition of Dirac particles where particles are distinct from anti-particles.

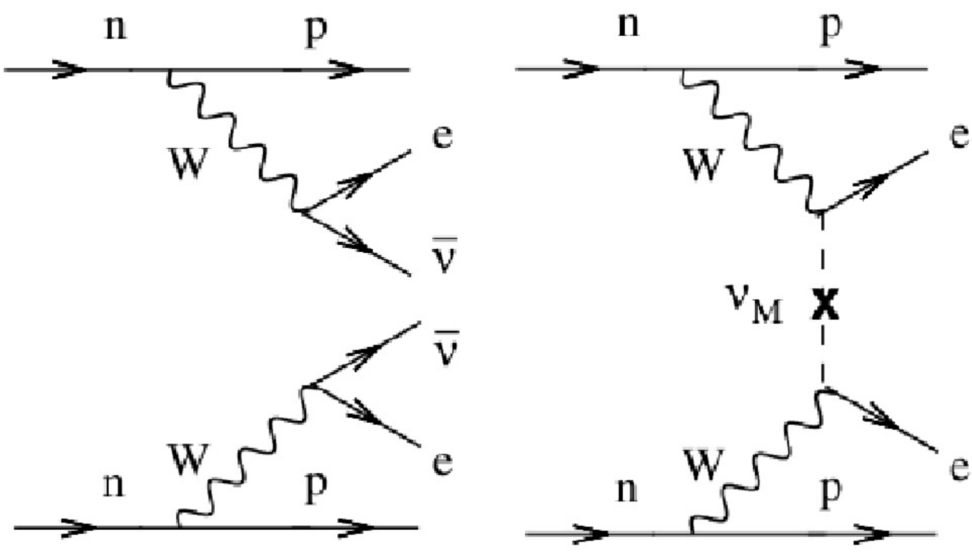

Figure A.1: The $2\nu\beta\beta$ (left) and the $0\nu\beta\beta$ (right) : a virtual ν instead of two $\overline{\nu}$.

The measurement of the neutrino mass If neutrinoless double beta decay were observed, it would also provide a measurement of the neutrino mass, since the rate of neutrinoless double beta decay is related to the square of the neutrino mass :

$$\Gamma = \quad G|M|^2|m_{\beta\beta}|^2, with m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2 . G : the two-body phase-space factor, M : the nuclear matrix elem \tag{A.6}$$

A.2 The nEXO experiment

The $2\nu\beta\beta$ or the $0\nu\beta\beta$ releases two electrons with a high energy (kinetic energy). The picture below details the scattering process of one these two electrons on an electron of an ^{136}Xe atom :

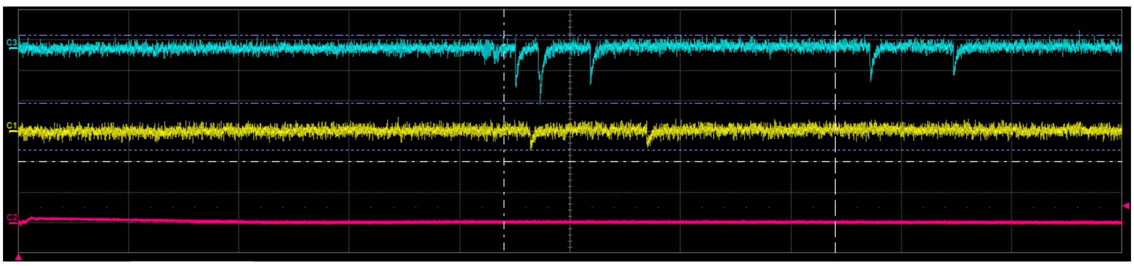

Figure A.2: light region.

The ^{136}Xe is then in an existed state. It relaxes by releasing a photon.

Then the relased photon enters inside a SiPM. The photoelectric effect happens and the avalanche process begins.

The nEXO experiment consist in a big barrel whose walls are covered by SiPMs. This barrel will be filled with 5 tonnes of Xe liquid :

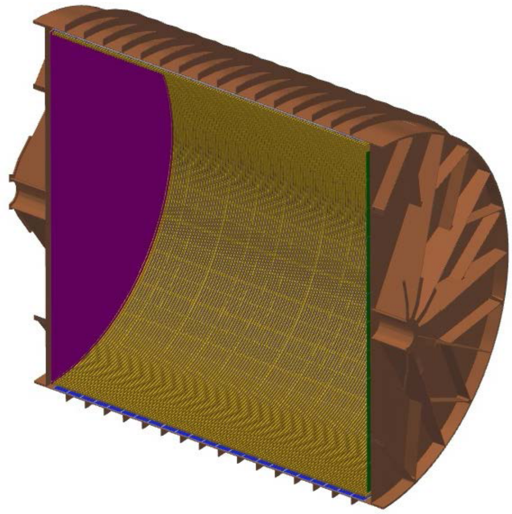

Figure A.3: The nEXO barrel.