Evaluation of a Charge Readout Pad Scheme for nEXO

by

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Abstract

The neutrinos are fundamental particles. They are amongst the most difficult particle to detect due to their properties. The existence of the neutrinos has been known for the last several decades, yet their masses still have not been measured by experiments. The Enriched Xenon Observatory, EXO, is one of the experiment attempting to probe the masses of the neutrinos by observing the ultra rare neutrinoless double beta decay of ^{136}Xe . The EXO-200 detector uses a liquid xenon filled time projection chamber (TPC) to achieve high sensitivity measurements. The work presented here focuses on the development of a new charge readout scheme.

A small gas TPC was built to test a series of charge readout pad structure. This detector measures the ionization signals (direct and induction) produced from the gas ionization by an alpha source emitter. The signals are read out with a commercial data acquisition system and a model is fitted to the data. The data analysis will demonstrate some of the challenges faced in the operation and modelling of this readout pad system. Even with the difficulties encountered, energy resolution and angular distribution results provide guidance for the collaboration for the future of this type of charge readout scheme.

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Chapter 1

Introduction

Experimental sciences are always on the lookout to obtain new measurable quantities to help prove or disprove the different theories that govern the universe. Unlike theoretical results, experimental results are often limited by precision of the experiment. As technology improves to be more efficient, so does the precision and accuracy of those results. The neutrino experiments are one of the best example of the required improvement of technology. The neutrino only interacts weakly due to its neutral charge and it does not interact via the strong force making them difficult to measure. Neutrinos were proposed to solve the beta decay puzzle seen in the experimental results, as is described in the next chapter. At that time, they were even considered massless. Since the 1950's, diverse neutrino experiments have helped to understand this particle. Then came the neutrino oscillations experiments. The oscillation of the different flavour eigenstates of the neutrinos can only occur if they possess different masses. Again, these experiments were not sensitive to the absolute mass nor are they able to distinguish between neutrinos and anti-neutrinos leaving the possibility that neutrinos and anti-neutrinos are in fact the same particle. Many experiments continue to pursue measurement of the neutrino mass.

The Enriched Xenon Observatory, EXO, is one of those experiment that is

currently looking at the double beta decay of ^{136}Xe . As is discussed in Chapter 2, the discovery of the ultra rare process known as the neutrinoless double beta decay would provide a measurement of the neutrino mass and new insights into the neutrino properties. The current detector contains 200 kg of liquid xenon enriched to 80% in the ^{136}Xe isotope inside a large time projection chamber, TPC, operating underground at the Waste Isolation Pilot Plant, WIPP, near Carlsbad, New Mexico. This detector detects both the scintillation light and ionization charge signals produced through interactions in xenon. Different quantities can be measured with the combination of those two signals. The most recent results reported a lower limit on the neutrinoless double beta half-life of $1.1 \times 10^{25}\text{yr}$ at the 90% confidence level [1]. This corresponds to a neutrino mass of 190-450 meV. This mass value depends on the nuclear matrix elements used.

The EXO-200 detector is a small prototype. A next generation detector called nEXO is currently in its research and development phase. Knowledge and experience acquired with EXO-200 gives the path to follow for this next detector. The nEXO detector will also use the ^{136}Xe isotope.

This thesis will elaborate on a new charge readout scheme. A new way to collect the ionization signal will be described and tested out in an isobutane filled chamber. Ionization will be produced by an alpha decay inside the gas filled chamber. These charges will be drifted down by an electric field onto the collection pads. These pads made of conductive elements will be sensible to the induction produced by the charges drifting down and will collect the charge once it reaches the pads. The signal is then sent to a data acquisition system which gives an output waveform of the voltage over time. The output voltage signal is also modelled with simulations. A model is made using the physical aspect of the detector and the Ramo-Shockley theorem for

the induction signal. Fitting the model to the data, can give the energy resolution and initial and final event parameters for the reconstruction. The energy resolution will be determined with two different estimators. The first one used is found with the pulse height distribution of events. The pulse height is proportional to the integral of the signal which is proportional to the energy. The second estimator is a scaling energy factor from the model and the fitting of the events. Different configurations of read-out pads are used to see the maximum pads size that should be required for the nEXO detector. Event topology is very important in double beta decay experiment do discriminate between events and backgrounds. A good energy resolution and spatial reconstruction are required to find the right energy of the event and to reject background that will deposit energy in more than one location inside the detector.

Before discussing the new charge readout system further, this thesis will provide some background information. The second chapter will give a historical background to the neutrinos. Some general theory will be explained alongside with important results from different experiments. Many aspects, such as: neutrino oscillations, massive neutrinos, distinction between Dirac and Majorana particles, and double beta decay, will be presented.

The third chapter will give a general description of the EXO-200 detector. Then, the possible future for the EXO collaboration will be explained by giving current specification of the nEXO detector and its current state.

The fourth chapter will cover the isobutane test chamber to measure the ionization signals. It will elaborate on the physical detector and on the theory behind it. Special attention will be given to the creation of the ion-electron pair inside the gas and on how they can be measured by the data acquisition system.

The fifth chapter will go over the characterization of the model and its implications. It will also go over the characterization of the data acquisition system transfer function and general signal processing theory.

The sixth chapter will go over the results and the analysis done. Signals produced under different conditions will be shown, explained, and modelled. The fits of the model are all done with ROOT's implementation of MINUIT [2] and are all Chi-Square minimization fits. It will also cover the different aspect of the different readout pads configurations.

The seventh and final chapter will cover the conclusions and implications provided by the analysis and will go over future works and modifications that could be done to the detector.

1.1 Author's Contribution

The author of this thesis worked in designing and assembled the major components of the isobutane chamber with the help of the group's technicians. The readout pad structure inside the chamber were tested and commissioned by the author. Many changes were made during the testing phase to different components. Many improvements were implemented to reduce the backgrounds noise picked up by the electronics. A lot of effort and time were concentrated to the reduction of the noise. The data acquisition system electronics were modelled by taking a known pulse and fitting the appropriate transfer function. This model can be used for any experiment using the electronics. A model for the output signal from the readout pads was implemented. This model includes the geometry of the detector, the Ramo-Shockley

theorem and the appropriate physical aspect of the detector. Several set of data were taken for different readout pads configuration and external parameters to understand how the output signals varies under those changeable parameters. The model was then fitted to the data to obtain the relevant physical quantities.

The author also went to the EXO-200 detector at WIPP to be trained for monitoring shifts. These shifts consist on slow controls monitoring of the detector in case a problem shows up. Shifts were done both on site at WIPP and remotely at Carleton University.

Chapter 2

The Neutrino

Over the years, numerous subatomic particles have been discovered through experimental measurements. Scientists have been attempting to classify all experimentally observed fundamental particles into one model. Each time a new particle was discovered, it was added to the model. This theoretical model is called the Standard Model of particle physics. The fundamental particles in the Standard Model includes 6 quarks, 6 leptons, 4 gauge bosons, and finally the recently found Higgs boson. Each of the quarks and leptons has a corresponding anti-particle partner. Inside the lepton family, which are spin 1/2, 3 different flavours exist: electron e , muon μ , and tau τ and their respective neutrino partners ν_e , ν_μ , and ν_τ . These neutrinos were assumed to be massless in the Standard Model. But measurements at the end of the 20th century by the SuperKamiokande and SNO experiments showed that neutrinos do in fact have mass. Their masses are extremely small compared to the other fundamental particles. Although these measurements show that neutrinos do have mass, they were only sensitive to the mass differences and were unable to measure the neutrino mass scale as it will be elaborated later in this chapter. Experimental limits on the neutrino mass scale indicate that the neutrinos are lighter than the other fundamental particles by orders of magnitude. This large difference is not easily accommodated within the Standard Model and measurement of the neutrino mass

and its properties could lead to an understanding of physics beyond the Standard Model. The double beta decay with and without neutrinos, as it will be described in details in this chapter, are two decays that could lead to two things: the mass scale of the neutrinos and their nature. This second one will determine if they are Dirac or Majorana particles. Neutrinos only interact weakly due to their neutral charge and colourless state. This can make them harder to be observed experimentally.

During the course of this chapter, a brief history of the neutrino will be presented along with a summary of some experimental results that demonstrated that neutrinos have mass, found with what is called the neutrino oscillation, and an introduction to the neutrinoless double beta decay theory.

2.1 The Neutrino Postulate

In 1930, physicists observed a problem with nuclear beta decay. This decay would, in principle, involve 3 particles: a nucleus that decays into a lighter nucleus with the emission of an electron. By looking at a basic center of mass kinematics problem with fixed mass for the particles [3], the energy of the emitted electron is:

$$E = \left(\frac{m_1^2 - m_2^2 + m_e^2}{2m_1} \right) c^2, \quad (2.1)$$

where E is the electron energy, m_1 the mass of the decaying particle, m_2 the mass of the daughter of the decay, and c the speed of light. This two-body decay model predicts that the electrons should always be emitted with the same amount of energy since everything remains constant. After examining results from different experiments, it was found that the energy of the electron was not a fix value but instead a spectrum of values. This characteristic clearly violates the conservation

of energy. Some physicists started to question this conservation law. Wolfgang Pauli proposed that the emitted electron had a partner. This new partner would need to be neutral to conserve charge and would carry the missing energy of the decay.

A few years later, Enrico Fermi incorporated the new particle in his theory of beta decay and named it the neutrino, ν . The beta decay then became:

$$n \rightarrow p + e + \nu. \quad (2.2)$$

A neutron, n , discovered by Chadwick [4] in 1932, would decay into a proton, p , an electron, e , and a neutrino, ν .

In fact, the neutrino produced in a typical beta decay is an anti-neutrino, $\bar{\nu}$, which conserves the lepton number. This conservation law consist on assigning a number to a leptonic particle. This was conceptualized by E.J.Konopinski and H.M. Mahmoud in 1953 [5]. They stated that for a reaction to be allowed the lepton number needs to be conserved in the initial and final state. To this end all leptons are given a lepton number $L = +1$ and their anti-partners are given $L = -1$. By looking at the beta decay, the left hand side would have $L = 0$ since there is no leptons, which means that L needs to also be 0 on the right side. The electron is $+1$, therefore the neutrino, in this case the anti-neutrino, needs to be -1 to allow this reaction.

Many experimentalists doubted its existence since it was extremely difficult to detect. Moving on to the 1950s, Davis and Harmer [6], alongside the results of Cowan and Reines [7] on neutrino interaction in inverse beta decay, wanted to

see if neutrinos and anti-neutrinos could be differentiated. They used a flux of anti-neutrinos produced in a nuclear reactor. They became the first reactor-neutrino experiment and observed anti-electron neutrino, $\bar{\nu}_e$, scattering. Cowan and Reines observed the following reaction:

$$\bar{\nu} + p^+ \rightarrow n + e^+, \quad (2.3)$$

which was compelling confirmation of the existence of the neutrinos as a particle. This result also shows that this cross reaction also exists:

$$\nu + n \rightarrow p^+ + e^-. \quad (2.4)$$

Davis and Harmer looked at the anti-neutrino version of this last reaction:

$$\bar{\nu} + n \rightarrow p^+ + e^-, \quad (2.5)$$

which is forbidden by the lepton number conservation law. They were unable to observe the reaction and they concluded that neutrinos and anti-neutrinos are in fact distinct particles.

2.2 Neutrino Flavours

The lepton number conservation law was introduced in the previous section. This law can help on determining if a reaction involving leptons is forbidden or not. By

looking at the following muonic decay with a photon, γ ,

$$\mu^- \rightarrow e^- + \gamma, \quad (2.6)$$

one could assume that this decay is allowed since the lepton number is conserved on both sides of the reaction. But in fact, this decay was never observed experimentally. Powell managed to observed the muon decay with two neutrinos and an electron,

$$\mu^- \rightarrow e^- + \nu + \bar{\nu}, \quad (2.7)$$

but not with the photon. By using the lepton number conservation law, the left hand side gives $L = +1$ while the right hand side gives $L = +3$. This observed reaction seems to violate the accepted and working conservation law except if one of the neutrino is in fact an anti-neutrino. To forbid the muonic decay to an electron and a photon but not the channel with an electron and two neutrinos, the lepton number law had to be extended. To counter this problem, a proposal was made to assign a different lepton number between the electron and the muon which, by extension, makes the supposition of two different type of neutrinos, one associated with the electron and another one with the muon. This gives a flavour to the neutrinos depending on which lepton they are associated with. This lead to another modification of the beta decay. It was modified to:

$$n \rightarrow p + e + \bar{\nu}_e. \quad (2.8)$$

This also modified the muon decay to:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu. \quad (2.9)$$

These two decays are both energetically and lepton number allowed. Prior to 1975, only two types of lepton, what we call flavour, were known to exist. M. Perl [8] discovered a third and final lepton; called the tau, τ . A third member of the lepton family would mean the possibility of a third neutrino which was confirmed by the DONUT [9] experiment in 2000. The experiment was performed at Fermilab using the Tevatron by looking at the decay of charm quark. Some of the charm quark decay produce ν_τ , which were then observed interacting with the DONUT detector.

Figure 2.1: The fundamental particles of the Standard Model of particle physics.

These new leptons were added to the lepton family and the Standard Model shown in Figure 2.1 with the 6 quarks, 4 force carriers and the Higgs boson. Table 2.1 [10]

gives a small summary of the current lepton family members with a few properties. Leptons are fermions with spin $1/2$. Although it is now known that the neutrinos have mass, so far attempts to measure the masses have only yielded upper limits as shown in the table.

Leptons			
Particle	Symbol	Mass [MeV/c ²]	Electric Charge [e]
Electron	e	0.511	-1
Electron Neutrino	ν_e	$< 2 \times 10^{-6}$	0
Muon	μ	105.66	-1
Muon Neutrino	ν_μ	< 0.19	0
Tau	τ	1776.82	-1
Tau Neutrino	ν_τ	< 18.2	0

Table 2.1: The lepton family according to the Standard Model along with some of their properties. For the anti-particle case, the charge is the opposite sign. The masses for the neutrinos are the best known limits [10].

2.3 Neutrino Oscillations

Several experiments exist today which observe the neutrino flux coming from the Sun. This flux comes from the pp chain alongside alpha particles, electrons, positrons, photons, etc. The pp chain is a fusion process of hydrogen into helium that occurs in the Sun and emits ν_e at different stages. The relevant neutrino production modes are shown just below. In 1938, Hans Bethe [11] explained this chain of reaction happening inside the Sun. The energy and the flux of neutrinos depends in which step of the chain they are produced. Figure 2.2, from N. Bahcall [12], shows the energy spectrum of those neutrinos. The major supply of neutrinos comes from the pp chain but with lower energies. The 8B produces a lower flux but a larger energy range.

Figure 2.2: Energy spectrum of the neutrino coming from the different production modes occurring inside the Sun. The pp chain offers the highest flux but at lower energies only[17].

$$p + p \rightarrow d + e^+ + \nu_e \quad (2.10)$$

$$p + p + e^- \rightarrow d + \nu_e \quad (2.11)$$

$${}^3\text{He} + p \rightarrow \alpha + e^+ + \nu_e \quad (2.12)$$

$${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e \quad (2.13)$$

$${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e \quad (2.14)$$

The pp solar neutrinos were measured by Ray Davis in the late 1960s with the Homestake experiment [13]. This experiment consisted of a tank of chlorine deep underground to observe the following reaction:

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-. \quad (2.15)$$

Davis's experiment observed only one third of the neutrino flux predicted by Bahcall's model [12]. Many physicists questioned the validity of the experiment but also the theory, especially since other experiments ended with similar results of the missing neutrinos.

This is when Bruno Pontecorvo proposed that neutrinos produced in the Sun might be able to go through a flavour changing process [14]. His supposition was principally made for electron neutrinos since they are the ones coming from the Sun. He based his idea from the K -meson [15] mixing observed by Gell-Mann and Pais [16] in 1955. They stated that the K^0 could turn into its anti-partner the $\bar{K}^0$ through a second order weak interaction. In the end, none of those two particles were observed but a linear combination was. Pontecorvo applied this to the neutrino problem and it became the neutrino oscillation theory.

2.3.1 Two Neutrinos Oscillation Example

Just like for the K -mesons sector, by taking an orthogonal linear combination of the two neutrino flavour eigenstates in vacuum [17], the two neutrino mass eigenstates can be expressed as:

$$\nu_1 = \cos\theta\nu_\mu - \sin\theta\nu_e \quad (2.16)$$

and

$$\nu_2 = \sin\theta\nu_\mu + \cos\theta\nu_e, \quad (2.17)$$

with θ the mixing angle from 0 to 2π . Choosing the *sin* and *cos* function is to have a simple normalization. This linear combination means that the flavour states of the neutrinos come from the mass states and they are not mass eigenstates.

Neutrinos propagate through space-time as mass states but are produced and detected as flavour states. During the propagation, the flavour content can oscillate to make a initial ν_e beam turn into a ν_μ beam with a non-zero probability of observation. This probability of converting a ν_e to ν_μ is expressed with Equation (2.18) [17], using $L = ct$ for the distance travelled and setting $\hbar = c = 1$.

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2(2\theta) \sin^2 \left[\frac{\Delta m^2 L}{4E} \right], \quad (2.18)$$

with the energy $E = E_2 - E_1$, and with the squared mass difference shown as:

$$\Delta m^2 = m_2^2 - m_1^2. \quad (2.19)$$

From 2.18, one can find the probability of the ν_e to not transform. In other words, the survival probability is express as:

$$P_{\nu_e \rightarrow \nu_e} = 1 - P_{\nu_e \rightarrow \nu_\mu} = 1 - \sin^2(2\theta) \sin^2 \left[\frac{\Delta m^2 L}{4E} \right]. \quad (2.20)$$

For the oscillation to be possible, both of the masses cannot be 0. Thus contradicting the massless neutrino property within the Standard Model.

2.3.2 Three Neutrinos Mixing Matrix

When the two neutrino example is applied to the three flavours that exist, they can be related with the PMNS matrix [18]. This is shown in Equation (2.21) with l for the e , μ , and τ . Again, ν_e , ν_μ , ν_τ are weak eigenstates and not mass eigenstates.

$$\nu_l = \sum_{i=1}^3 U_{il} \nu_i \quad (2.21)$$

The previous equation says that a linear combination of the three flavour eigenstate for the neutrinos is taken. The PMNS, for Pontecorvo-Maki-Nakagawa-Sakata, matrix is represented by the following equation:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{\frac{i\alpha_{31}}{2}} \end{pmatrix}, \quad (2.22)$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ with relevant mixing angle θ_{ij} from 0 to 2π . δ , α_{21} , and α_{31} are the CP violation phase. CP is the Charge conjugation Parity. The C converts the particle to its anti partner, while the P creates a spatial mirror image

of the particle. This means that under CP conservation, the anti-particle has the opposite charge and direction of its particle partner.

2.3.3 Experiments Confirming Oscillation

Many experiments confirmed the oscillating nature of the neutrino. In the early 2000's, the SNO experiment, sensitive to both the ν_e and total ν_T flux unlike Davis's experiment, reported that the ratio of the $\frac{\phi_{\nu_e}}{\phi_{\nu_T}}$, flux of the ν_e flux to the rest of all the other ν , from the 8B beta decay in the sun was $0.306 \pm 0.026(stat) \pm 0.024(syst)$ [19]. The SNO detector consisted of a spherical shape chamber filled with 1000 tonnes of heavy water. This shell was surrounded by 3000 tonnes normal water acting as a shield. Finally the outside layer is surrounded by nearly 9456 PMTs to capture the light events produced inside the detector. This provided significant support to the statement that neutrinos did indeed change flavours from when they are being produced in the Sun to when they are detected on Earth. Table 2.2 gives examples of the fitted parameter [18] for the solar neutrino problem.

Parameter	Best-fit ($\pm 1\sigma$)
Δm_{21}^2 [$10^{-5}eV^2$]	$7.58^{+0.22}_{-0.26}$
$ \Delta m_{31}^2 $ [$10^{-3}eV^2$]	$2.06^{+0.12}_{-0.09}$
$\sin^2\theta_{12}$	$0.306^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$	$0.021^{+0.007}_{-0.008}$
$\sin^2\theta_{13}$	0.0251 ± 0.0034

Table 2.2: Best fitted parameters range from global fit of current neutrino oscillation data from T2K and MINOS results. Values were taken from [18].

2.4 Neutrino mass

As mentioned, for oscillation to occur, the neutrinos cannot be massless. By keeping the three neutrinos model, the three mass splitting are defined as [17]:

$$\Delta m_{21}^2 = m_2^2 - m_1^2, \quad (2.23)$$

$$\Delta m_{32}^2 = m_3^2 - m_2^2, \quad (2.24)$$

and

$$\Delta m_{31}^2 = m_3^2 - m_1^2. \quad (2.25)$$

The oscillation measurement from different experiments show that one of the three splittings is much smaller than the others, specifically, the Δm_{21}^2 . This means that ν_1 and ν_2 are more likely to have similar mass compared to ν_3 . This is similar to the charged leptons, the τ having a much bigger mass than the e or μ . Or it could be that ν_3 is the smallest compared to the two others. All this means that ν_e and ν_μ might have a similar mass value. Oscillations experiments have a limitation on the information they can give out. These experiments are only sensitive to the difference of the square of the masses and not the absolute mass of the neutrinos.

Knowing all this, three different scenarios for the mass spectrum hierarchy are possible [18](if only one eigenstate is considered heavy(> 0.1 eV) and considering $m_1 < m_2$ thus keeping Δm_{21}^2 positive);

1. Normal Hierarchy

$$m_1 < m_2 < m_3. \quad (2.26)$$

2. Inverted Hierarchy

$$m_3 < m_1 < m_2. \quad (2.27)$$

(In the case that all are > 0.1 eV)

3. Quasi-Degenerate

$$m_1 \cong m_2 \cong m_3. \quad (2.28)$$

As of right now, experiments can only set upper limits on the mass of the neutrinos. For example, the mass limit set on the ν_e comes from looking at the electron energy spectrum from the beta decay of tritium. This process is as follows:

$${}^3_1T \rightarrow {}^3_2He^+ + e^- + \bar{\nu}_e. \quad (2.29)$$

A tritium, T , atom decays into an helium daughter alongside with an electron and anti-electron neutrino. This is a beta decay. For the mass limit on ν_τ and ν_μ , decays of the τ and π^+ into a ν_τ and ν_μ , respectively, were studied by looking at the energy spectrum of the products in the τ decay [20] and the momentum of the muons produced [21].

There is viable alternative way to probe the neutrino mass. It can be done by observing the neutrinoless double beta decay inside even-even nuclei. The functionality of this decay will be developed in the next sections.

2.4.1 Dirac or Majorana?

The neutrinos are fermions with spin $1/2$. This important property makes them obey the Dirac equation. All Dirac particles possess a distinct anti-particle. As stated in the beginning of this chapter, there are two possible possibilities for the nature of neutrinos; either being a Dirac or a Majorana particle. Being a Dirac particle involves having an anti-partner with different properties just like for the rest of the fermions, but being Majorana makes them the same particle. If the neutrino is Majorana, two additional CP violation phases, α_1 and α_2 , are added to the PMNS matrix. Being Majorana also, and more importantly, makes the neutrino its own anti-particle. It is similar to the idea of the photon. There is no, observable, anti-photon. This would mean that there is only one neutrino per flavour. Majorana proposed to modify the model, for the neutrinos, such that it must be invariant under charge conjugation due to the neutral charge of the neutrinos and make them both the same particle.

2.5 Double Beta Decay

Only a limited set of unstable isotope exist in nature can decay into a ultra rare process knows as the double beta decay instead of the normal beta decay. Experimentalists are designing experiments to probe for this decay which produces 2 neutrinos alongside a pair of electrons by the conversion of two neutrons into protons. This decay follows the Standard Model and has been measured in several isotopes. This decay had been proposed by M. Goeppert-Mayer in 1935 [22] and four years later W. H. Furry [23] incorporated Goeppert-Mayer's idea with Majoranas condition. The addition of this condition makes it possible for an even rarer decay to occur in those isotopes. It is called the neutrinoless double beta decay. The neutrinoless mode requires a high energy resolution to be able to distinguish it from the 2 neutrinos mode. As it will be explained, the discovery of this decay would establish that the neutrinos are in fact

Majorana particles and would provide the first measurement of the neutrino mass scale.

Figure 2.3: The fundamental processes of double beta decay modes described by Feynman diagrams. (Left) Shows the regular double beta decay with 2 neutrons and 2 electrons and (right) shows the forbidden and theoretical neutrinoless double beta decay either exchanging a massive neutrino or going through a neutrino annihilation.

Figure 2.3 shows the respective Feynman diagram for the two possibilities. There are several suppositions on what is happening in the neutrinoless case: do the 2 neutrons annihilate? Is it an exchange of a massive particle? Future results from experiments will answer this question.

2.5.1 2 Neutrino Double Beta Decay

As just stated, the double beta decay is very similar to the typical beta decay described earlier, but instead of having one neutron decaying it is a pair decaying at the same time in the same nucleus:

$$(Z, A) \rightarrow (Z + 2, A) + e^- + e^- + \bar{\nu} + \bar{\nu}. \quad (2.30)$$

This decay can only happen in even–even nucleus. Some of these isotopes with the

average 2 neutrino double beta decay half-life value are shown in Table 2.3 [24].

Isotope	$T_{1/2}^{2\nu}$ (years)
^{48}Ca	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$
^{76}Ge	$1.6^{+0.13}_{-0.10} \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
^{116}Cd	$(2.85 \pm 0.15) \cdot 10^{19}$
^{128}Te	$(2.0 \pm 0.3) \cdot 10^{24}$
^{136}Xe	$(2.20 \pm 0.06) \cdot 10^{21}$

Table 2.3: Examples of isotopes for which double beta decay has been observed and the corresponding half life [24]

Equation (2.31) represents the decay rate of this reaction with the corresponding phase space factor $G^{2\nu}$ and the nuclear matrix element $M^{2\nu}$, which is model dependent. This decay does not differentiate between Dirac and Majorana neutrinos, nor does it directly depend on the masses. It does not violate the lepton number conservation either

$$(T_{1/2}^{2\nu})^{-1} = G^{2\nu} |M^{2\nu}|^2. \quad (2.31)$$

2.5.2 0 Neutrino Double Beta Decay

The first thing to mention about this decay is that its observation has not been observed by any group and is strictly forbidden by the lepton number conversation law. Even with these important constraints, experimentalists keep working forward the observation of this decay. Instead of emitting two electrons with two anti-neutrinos, decay only two electrons are emitted in this ecy. This reaction looks like:

$$(Z, A) \rightarrow (Z + 2, A) + e^- + e^-. \quad (2.32)$$

The ultra rare decay, again, only occurs inside even-even nuclei just like for the regular double beta decay. Therefore, the isotopes shown in Table 2.3 are also prone to the neutrinoless double decay.

Figure 2.3 shows that the two W^- emitted could exchange a virtual massive neutrino. Only two electrons are emitted sharing the full measurable decay energy.

The relation between the decay rate $(T_{1/2}^{0\nu})^{-1}$, phase space factor $G^{0\nu}$, nuclear matrix element $M^{0\nu}$, and the square of the effective Majorana mass $\langle m_{\beta\beta} \rangle$ of ν_e is:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2, \quad (2.33)$$

where

$$|\langle m_{\beta\beta} \rangle| = \left| \sum_{i=1}^3 U_i^2 m_{\nu_i} \right|. \quad (2.34)$$

The decay rate is the experimental quantity to be measured. The phase space factor can be calculated with Feynman diagrams and the nuclear matrix element can be computed with a certain uncertainty with different models. The effective ν_e mass is, here also, a linear combination of the mass eigenstate and the PMNS matrix as shown with the last equation. Having a long half-life, reduces the effective mass.

2.5.3 Experimental Results

To detect the double beta decay processes, the detectors need a set of specific requirements. The total energy released is called the Q value. It is described as

the difference in energy of parent and daughter nuclei. When neutrinos are present in the process, the Q value is shared between them and the two electrons since the nuclear recoil of the daughter is negligible due to its heavy mass. For the neutrinoless process, all the decay energy is taken by the electrons and therefore produce peak at the Q value unlike a spectrum with the neutrino process. This is shown in Figure 2.4. The measured Q value should be different enough from any event produced by the backgrounds. This permits to see an excess over a possible low background.

Both of these process have extreme low rate and could easily hide in the background noise. Having a large mass helps to observe more decays thus giving better statistics. The backgrounds can be reduced by developping an ultra-low radioactivity detector and being underground. Excellent energy resolution is also required. Having a narrow resolution can help to distinguish between events and especially between the two processes.

Figure 2.4: Spectrum of the sum of the emitted electron kinetic energies, K_e , normalized at endpoint Q. The dotted curve is for the 2 neutrinos double beta decay normalized to 1 compared to the solid line for the 0 neutrino double beta decay normalized to 10^{-6} [25].

Table 2.4 gives a range of the mass calculated by different experiments using different isotopes. It also gives the possible mass obtained with their half-life value. The sensitivity is crucial for these kind of experiments. It is given by following equation [26].

$$T_{1/2}^{0\nu\beta\beta} \propto a\varepsilon\sqrt{\frac{Mt}{B\Delta E}} \quad (2.35)$$

with a , the isotope enrichment used in the detector, ε , the detector efficiency, M , the

total mass of the isotope used, t , the exposure time, B , the background rate, and ΔE , the energy resolution at the Q value of interest.

Isotope	Experiment	$T_{1/2}^{2\nu\beta\beta}$ [yr] $\times 10^{21}$	$T_{1/2}^{0\nu\beta\beta}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]
^{136}Xe	EXO-200	$2.165^{+0.016(stat)}_{\pm 0.059(syst)}$	$>1.6 \times 10^{25}$	$<140\text{-}380$
^{136}Xe	KamLAND-Zen	$2.38^{+0.02(stat)}_{\pm 0.4(syst)}$	$>1.6 \times 10^{25}$	$<120\text{-}250$
^{130}Te	CUORICINO	-	$>2.8 \times 10^{24}$	$<300\text{-}700$
^{76}Ge	GERDA phase I	$1.84^{+0.09}_{-0.08}(fit)^{+0.11}_{-0.06}$	$>2.1 \times 10^{25}$	$<200\text{-}400$

Table 2.4: Half-life values of the two double beta decay with the according effective mass of the neutrino for various isotope. Values were taken from [27], [28] and [29].

Table 2.4 only shows a small sample of the running experiments for the neutrinoless double beta decay. Looking at [24] through [29] gives an idea of the leading experiments currently operating or in development.

It was previously stated that no observation of the neutrinoless double beta decay has been confirmed. One previous experiment, not shown in the table, claims an obversation of this decay. The experiment was by Klapdor-Kleingrothaus et al. They used ^{76}Ge and reported a value of 1.2×10^{25} yrs for half-life for the neutrinoless double beta decay [30]. This result has not yet been confirmed by any other experiments.

EXO-200 uses ^{136}Xe and will be explained in the next chapter. KamLAND-Zen is EXO's closest competitor using the same isotope to probe the double beta decays.

Their [31] 3 metre diameter balloon-shaped detector is filled with 13 tonnes of liquid scintillator to detect signals coming from their 330 kg of Xe gas enriched to 91% for ^{136}Xe . This balloon is contained within an outer balloon of 13 metres diameter filled with over 1kton of liquid scintillator. Over 1000 PMT's are located on the outside stainless-steel layer to detect scintillation light. Finally, the whole outside layer is surrounded by over 3 ktonnes of water-Cherenkov detector for possible veto-ing of cosmic ray muons that could come by.

CUORICINO, the small prototype of CUORE, is located at the Grand Sasso laboratories in Italy. It uses ^{130}Te as a medium. Over 200 kg tellurium dioxide crystal enriched at 27% to the ^{130}Te is located inside a bolometer at a temperature of 10 mK [27].

GERDA [29] is another detector at Gran Sasso, but unlike CUORE it uses high purity germanium detectors enriched to 86% for the ^{76}Ge isotope. The detectors are submerged in liquid argon that acts like a cooling fluid and a shield from backgrounds from the surroundings. The second phase of GERDA is expecting to lower the background by a factor of 10, from the first phase, while improving results and sensitivity.

All of the previously named experiments are working on their next phase to probe the next region of the neutrino mass. Most experiments will become bigger which brings the exposure time up and will try to bring down the background to an all time low to be able to be the most sensitive neutrino experiment.

Chapter 3

EXO Collaboration

The Enriched Xenon Observatory, EXO, Collaboration is an international collaboration utilizing xenon to search for the neutrinoless double beta decay. The collaboration is utilizing a time projection chamber, TPC, filled with liquid xenon to carry out this search.

There are many past, current, and future experiments racing to find and observe the neutrinoless double beta decay using different isotopes. EXO uses the ^{136}Xe isotope due to its natural abundance of 9%, enriched by centrifugation techniques and easily purified and re-purified as needed.

The first section for this chapter will go over general requirements for experiments, especially EXO, to observe the two different double beta decay modes. This will be followed by two sections: one for the operational liquid phase detector and another on specifications for the next generation detector prototype. Emphasis will be placed on the charge readout to do a comparison with the work of this thesis.

3.1 Generalities

To be able to measure the absolute mass of the neutrino, experiment requires an excellent energy resolution and sensitivity due to the rareness and long half-life of the decay. Experiments also require a multi-kilogram, if not multi-tonnes, scale to have the possibility of measuring the neutrinoless double beta decay with a sensitivity on the double beta decay effective neutrino mass of 50 meV. Having more mass increases the event statistics and the exposure time. The goal is to measure the effective mass with a sensitivity below the inverted mass hierarchy. The different hierarchy were presented in Chapter 2.

A low Background environment is also a great asset to possess. Noise coming from the electronics or the environment can greatly affect and alter measurements. It can also give false positives in some cases. In cases where the noise is superior to the low event statistics, the noise can hide the signal. Having a detector deep underground helps to reduce some possible induced backgrounds coming from cosmic-rays by using the rocks as a shield. Another asset is to ensure the decay observed has an energy higher than the one from the possible backgrounds. For example, the Xe-136 Q -value is at 2457.83 ± 0.37 keV [29], which is a region free of naturally occurring uranium gamma lines. The usual background coming from underground rocks and materials is due to the Uranium-238 and Thorium-232 chains which produce Bismuth-214 and Thallium-208. The Thallium emits a 2614.5 keV photon, and a beta particle. The Bismuth comes with two beta decays with endpoints at 2663 keV and 3272 keV, and a photon of 2447.8 keV. These are close to the Q value for xenon, which is why a reduced background environment is required and also being able to distinguish between real and gamma events.

An observable physical event, which corresponds to an energy deposition inside the detector, will produce ionization and scintillation signals. In xenon, it is essential to measure both signals since there is a large anti-correlation, on an event to event basis, in the amount of energy going to each of these channels. The scintillation will be collected almost instantaneously compared to the ionization, which takes time due to the drifting of the charge. The choice of the isotope is important to ensure a significant amount of signal creation. In Chapter 2, Table 2.3 showed some isotopes currently being used to look for the double beta decays.

3.2 Liquid Xenon Detector

Many experiments use a liquid phase detector since, in some cases, like for the ^{136}Xe in EXO, the liquid will act like both the source and active medium. This leads to a smaller and more compact system to minimize backgrounds and energy loss especially for xenon since 200 kg occupies only 0.07 m³ of space. Using liquid can also reduce the possibility of electron diffusion. A few main disadvantages are the limited track reconstruction, and the requirement of a constant cryostat cooling.

3.2.1 EXO-200

EXO is currently operating a detector called EXO-200 [32]. ^{136}Xe is chosen due to all the advantages stated earlier. From the total xenon mass, 110 kg of it is in the active region of the detector. It is located at the Waste Isolation Power Plant (WIPP) in Carlsbad, New Mexico, inside a class 100 clean room. Having it underground gives a depth of 1585 metres water equivalent shield. The detector consists of a double cylindrical time projection chamber (TPC) vessel with a length of 44 cm and a diameter of 40 cm sitting inside a double-walled vacuum insulated copper cryostat. Figure 3.1 shows a schematic of one side of the TPC. The enriched

gaseous xenon, $(80.6 \pm 0.1)\%$, is liquefied after passing through two heated zirconium getters (part of the purifying process). The HFE-7000 coolant around the TPC keeps the environment at liquid xenon temperature and also serves as shielding. The TPC operates at 167 K and 147 kPa to ensure the liquid state of the xenon. The TPC components are mainly made of copper, bronze for conductors and acrylic for dielectrics. For more details, refer to [32].

Figure 3.1: Cutaway view of the EXO-200 TPC [32].

An event will consist of an ionization and a scintillation signal. By measuring them both, alongside the TPC configuration, a topological three-dimensional reconstruction of each energy deposition event will be achievable. This will, in the end, give an energy spectrum of the reconstructed events inside the detector, and the energy resolution. This is essential to differentiate between real double beta events and possible backgrounds generated by gammas.

The 178 nm scintillation light generated by the excitation of the xenon is collected by 468 large area avalanche photodiodes (LAAPDs). These offer a lower radioactivity content, work at low temperatures, and possess a high quantum efficiency for the scintillation collected. The side of the field cage is made of Teflon tiles to increase the scintillation collection by reflecting the VUV scintillation.

Figure 3.2: Schematic of the wire planes with the vector U representing the angle at which the wires are placed, similarly with the vector V for the second set of wires. Also shows the difference in size of the fiducial and active volume of xenon inside the detector. The circle represents the field cage ring area, thus the necessity of a fiducial volume to eliminate events beyond that limit [32].

The ionization requires a more complex configuration. The ionization signal is measured with two wire planes. The first one is the shielding wire plane (V), located in front of the charge collection wire plane (U). The shielding, or induction, plane

acts like a Frish grid to measure only the induction caused by the drifting of the charges. The two planes are at 60 degrees to each other. To be able to drift the charge down to the planes, an uniform electric field is generated inside the detector by a series of field shaping rings around the TPC. Ten rings are connected with 900 M Ω resistors to achieve the voltage gradient. The positive charges will drift away from the wire planes while the negatives will drift towards the wire planes to be collected. When a charge is created and starts drifting it will induce a signal on the induction plane. These induced signals of the positive ions and electrons are read out by the V wires while the U wires only sees the direct signal from the electrons once they reach them. Reading out the induction and the direct signal is essential to give spatial coordinates of the ionization cloud alongside the scintillation light. Making the two planes at an angle from each other allows a two-dimensional reconstruction. Figure 3.2 shows a top view of the U and V wire planes. The U wires will also give the energy of the charge. Figure 3.3 shows the schematic and geometry of the wire planes. It also shows that the planes are separated by 6 mm, and the wires in each planes by 3 mm which is called the pitch. These dimensions were chosen to maximize the fiducial volume and high voltage on the V wires. Figure 3.3 also shows the trajectories of the charges. The ionization converges to the U wires because there is a much higher drift field between the U and V planes. This ensures that every charge is collected. There is no amplification or avalanche created by the electrons near the U wires because this would alter the energy resolution measurement by not having a precise measurement of the initial energy deposition of the event. The wires are also grouped in triplets, which gives a readout spacing of 9 mm for a more convenient mounting. Each wire is attached at each end with springs to give tensions less than 8.8 N.

The two planes of wires are very sensitive and give a planar reconstruction coming

Figure 3.3: Schematic of the wire planes with dimensions and ionization drift trajectories due to the electric field produced by the field cage rings and the more powerful field between the two wire planes. The avalanche photo-diodes, APD, are located after the two wires planes. [32].

from the ionization. The last coordinate is obtained by the drift velocity and time since the charge should drift straight down. Figure 3.4 shows a picture of the rings containing the two wire planes.

After measuring and collecting a signal, with preamplifiers located outside the TPC, it is important to understand what their response means. A way to do this is to do a calibration. EXO-200 inserts a gamma rays source, like ^{137}Cs , ^{60}Co , and ^{228}Th , inside a copper guide tube which is around the outside of the TPC vessel. By knowing the energy and the position of the sources, calibration can therefore be done.

Latest results from the EXO-200 can be found in a recent article published in Nature [1] and gives a range of the upper limit of 190-450 meV for the Majorana neutrino mass with a half-life of 1.1×10^{25} yr for the 90% confidence level lower

Figure 3.4: Picture of the wire planes during the construction phase. The circular support is made of copper. The wires are at 60deg and attached at the end to create the appropriate tension [32].

limit of the neutrinoless double beta decay. Figure 3.5 shows the effective Majorana mass from the double beta decay measurement with the total mass. It compares the latest EXO-200 results and the final expected region of sensitivity. Having the final projected measurement brings the mass hierarchy into the reverse hierarchy region as elaborated in Chapter 2.

Figure 3.5: Sensitivity plot for the effective Majorana mass of the neutrino shows that the projected nEXO detector sensitivity would cover the inverted hierarchy and some normal hierarchy. [33]

3.3 nEXO

The EXO-200 detector was built as a prototype for a large scale detector. With its successful results, the next generation detector, named nEXO, is currently undergoing research and development. The nEXO detector is being designed to contain approximately 5 tonnes of liquid xenon with similar design to EXO-200. This new detector will include, as well as the multitonne capability, new scintillation and ionization collection scheme and other new technologies. Having a new large scale detector will improve the chance to observe the neutrinoless double beta decay and will use state of the art technologies that are currently in development.

Just like EXO-200, nEXO will be a liquid xenon filled TPC but this time the xenon will be enriched at 90% for the ^{136}Xe isotope compared to 80% for EXO-200.

NEXO's will be very similar to EXO-200 [34] but between 3 and 4 times larger and again with a TPC made out of copper. Having one longer TPC, instead of two back to back, will result in lower background in the middle of the detector. A 2.5 MeV gamma attenuation length is about 8.5 cm which is well contained inside a 5 tonnes detector.

The detector is expected to be located in the Cryopit at SNOLab near Sudbury, Ontario. The detector will be situated inside of a water shield tank to reduce backgrounds arising from the Cryopit environment [35]. Figure 3.6 shows a design concept of the Cryopit and the detector located in the center. Water will be located on the exterior and will act like a background shield, and HFE will again serve as a coolant for the TPC inside the cryostat in which it will be placed.

Figure 3.6: nEXO proposed design inside the Cryopit. The vessel located in the center will be suspended in water with supporting cable on top [36].

The scintillation and ionization signals will need to be measured. Figure 3.7

shows the light sensor and the charge readout. Unlike EXO-200, nEXO will use silicon photomultipliers, SiPM. These will offer a better signal over noise ratio, higher gain, can be of any shape, and do not require any high voltage bias. The SiPM will be placed around the lateral surface to give a much higher collection efficiency. Each SiPM pixel are designed to be 1.34 cm by 1.34 cm with 1.2 cm by 1.2 cm of active area. The detector will require up to 4 m² of photo-detectors. Having a full lateral surface of light detector will remove the necessity of Teflon reflectors inside the vessel. The SiPM, which are not usually sensitive to the VUV scintillation light produced, will need to be modified and are currently in development and testing.

Figure 3.7: View of the inside of the TPC for nEXO. Charge readout at the end will collect the electron drifting along the field created by the rings. Scintillation light will be collected around the vessel [34].

The charge readout pitch with EXO-200 was 9 mm due to the triplet of wire. NEXO is projected to operate at a smaller pitch. This will, in principle, give a higher granularity and better spatial resolution for the charge collected and will also give a better discrimination between electron-gamma events and multi-site events. Another change is that wire planes will most likely not be used. Strips or arrays are currently

proposed and being prototyped as charge readouts. The work of this thesis is to test one of those proposed arrays structured. A series of conductive pads will be lying down at the end of a TPC to measure the induction and collection signals coming from the ionization channel produce inside the chamber. Different configurations are used to evaluate the energy resolution and the event reconstruction capability. Also, having a larger readout plane should help optimizing the granularity and reject background more efficiently. The charges will drift down the vessel following the electric field produced by the field shaping rings surrounding the vessel.

Incorporating all the mentioned changes and ameliorations, and others like cold electronics, noise and background reduction, nEXO is projected to be the next state of the art detector for neutrino physics. The first phase of nEXO is expected to be sensitive to half-life as long as $T_{1/2} > 6.6 \times 10^{27}$ years at the 90% confidence interval, which translate to a neutrino mass of 7-18 meV [36]. In the end, nEXO is expected to achieve a 1% or better energy resolution and reach Majorana mass sensitivities of 4-10 meV [37]. As shown earlier, Figure 3.5 shows the sensitivity of the Majorana mass for nEXO compared to the EXO-200 results. nEXO gives the possibility of covering the full inverted hierarchy and possibly even access the normal hierarchy depending on the success of many factors.

Chapter 4

Isobutane Filled Chamber

New generation detectors searching for the neutrinoless double beta decay will require lower backgrounds and better energy resolution to be able to determine precisely the masses of the neutrinos as elaborated in the previous chapters. EXO-200 and nEXO both require measurement of the scintillation and ionization produced in liquid xenon to observe a possible neutrinoless double beta decay event. A small chamber was designed to test a new charge readout schemes to be implemented into the nEXO detector. The goal is to detect the ionization signals produced inside the chamber to calculate the energy resolution and reconstruct the event. Both the charge induction created by the motion of a charge particle and the collected charge signal are measured by the readout pads and sent to a data acquisition system. An ^{241}Am alpha source will ionize the gas. The produced charges will drift, with the help of an electric field. The negative charges will drift down to a series of conductive square pads while the ions will drift away from them. These pads lie inside a vacuum chamber acting like a time projection chamber. A series of copper rings which creates the electric drift field for the charges. The chamber acts like an ionization chamber without any electron avalanches to create amplification of the signals as they reach the pads, unlike for proportional ionization chamber such as wire proportional counter. The no amplification regime is preferred for energy

resolution calculations and event reconstruction. Figure 4.1 shows a simple schematic of the entire detector system. Important components are shown in the Figure and will be elaborated on during the course of this chapter.

Figure 4.1: Schematics of the detector with important components labelled.

It is important to note that all inside components were properly cleaned and baked afterwards. They were then handled only while wearing proper equipment, kept away from open air and swiped with isopropanol and methanol before being assembled in the detector. This process reduces the contamination of the vacuum seal components and reduces the loss of produced charge inside the chamber due to possible contaminants.

The goal of this chapter is to present the new charge readout prototype and the vessel used to test it. This new configuration of charge readout scheme has for a

goal to simplify the induction and collection process without losing any resolution. The wire pitch in EXO-200, as stated in the previous chapter, is about 9 mm. It is hoped that reducing this pitch would help to reject backgrounds. With nEXO being much larger than the current EXO-200, making uniform tensioned wires over a larger surface can be a non-trivial task. The current wire planes in EXO-200 separates the induction and collection signals. Having the induction plane on top of the collection plane, this first plane measures the induction from both the ions and the electrons drifting inside the vessel. The second plane is only sensitive to the electrons coming down towards it due to the fact that the first plane acts like a shield by observing the ions signals. By considering the induction and collection signal on a different readout scheme, it is hoped that good spatial resolution will come out and then lead to a better energy resolution for the produced signals. Achieving lower than 1% energy resolution, identify background events, and determine the ideal pad size would give support to the implementation of this readout scheme to the nEXO detector.

4.1 The Vessel Characteristics

The vessel, as seen in Figure 4.2, is mounted on a solid table and bolted to reduce any movements and vibrations. It consist of a 8 inch opening 5-way cross made of stainless steel from *KURT-LESKER*. The back and right hand-side flange are closed with a simple blank flange and could be used for other outputs if required. The left hand-side flange is the electronics output. It consist of a 8 inch flange with a 6 inch hole which is mounted by a 6 inch multi-pin sub D push-on Feedthrough CF, conflat, Flanged. This feedthrough, as seen in Figure 4.3, will link each pad to the data acquisition system while keeping the vessel vacuum tight.

Figure 4.2: Picture of the 5-way cross showing the five 8 inches flanges.

Figure 4.3: Picture of the side view flange with the multi-pin connector that will connect the detector to the data acquisition system

Figure 4.4: Picture of the top flange serving as a multi-feedthroughs connector. Only 4 of the feedthroughs are currently in used.

The top flange is another 8 inch flange with six 1 and 1/3 inch and one 2 and 3/4 inch CF flanges shown in Figure 4.4. Three of the feedthroughs are used for this experiment. The first one is for the gas-line which will be elaborated in the next section. The second one is connected to a Ionivac high vacuum pressure gauge (Sensor ITR 90, No: 12103). It has a range of pressure of 5×10^{-10} mbar up to 1 bar. The third one is the high-voltage input to create an electric field inside the chamber which will also be explained later in this chapter. Finally, the larger middle flange is occupied by a micrometer source positioner. This will give the freedom of moving the source and cathode along the z -axis of the chamber without having the need to open the system.

The bottom flange is attached to a vacuum pump. The Varian pump is a duo scroll and turbo pump that can bring the chamber's pressure down to low 10^{-6}

mbar. A gauge was installed on the scroll side to be able to monitor the backing pressure between the two pumps. This pump is connected to the vessel by a 3 inches pipe with an 8 inches connector. This pipe can be closed from the pump with a bellows sealed valve. This pump will empty out the vessel once its properly sealed to be able to fill it up with the proper gas.

All of these flanges are torqued to 25 Nm with a size appropriate 1/4 inch, high purity and oxygen-free copper gasket¹.

4.2 Gas-line

To be able to observe any particle production, a vacuum must first be made inside the chamber. The emptied out chamber can then be filled up with a purified gas. By eliminating any impurities, i.e. air particles, signals produced will not be diminished. A simple line from a gas bottle passing through a purifier was implemented as seen in Figure 4.5. If the gas does not require purification, it can skip the purifier and go to the vessel by opening up the adjacent knob.

The purifier used is a MC50 with a 905 media that can remove H_2O , CO , CO_2 , O_2 , and H_2 to lower than 1 part per billion.

The gas chosen for this experiment is isobutane. Table 4.1 shows some important gaseous isobutane properties [38], while comparing it to gaseous argon and xenon. The gas can then move towards the purifier and finally fill up the chamber with the correct pressure; between 1 and 2 bars for this work. At the 4-way cross fitting there is: a release valve set to 2 bars absolute assures a pressure below 2 bars,

¹Information on CF flanges and their gasket can be found at www.lesker.com

Figure 4.5: Schematic of the full gas-line from the gas bottle up to the vessel.

a vent to bring back the chamber to atmospheric pressure, and a way straight inside the chamber.

To assure a good purity, the flow to the purifier needs to be kept at a maximum 10 standard litres per minute. For the time being, only isobutane gas was used but the gas line could easily support argon or even xenon both in gaseous state with simple modification of the gas line. Isobutane was chosen due to its similar characteristics to xenon as seen in Table 4.1. Also, the event size of the electron cloud from the ionization process is contained within the detector and should be fully observed without any electron avalanche amplification.

Gas	$\langle Z \rangle$	$\langle A \rangle$	ρ	E_i	E_i	$-dE/dx$	n_p	n_t
		u	$[\text{g}/\text{cm}^3] \times 10^{-3}$	[eV]	[eV]	[keV/cm]	$[\text{cm}^{-1}]$	$[\text{cm}^{-1}]$
Ar	18	39.9	1.66	15.8	27	2.44	29.4	94
Xe	54	131.3	5.89	12.1	22	6.76	44	307
C_4H_{10}	18	58	2.42	10.6	23	4.50	46	195

Table 4.1: Argon, xenon and isobutane gases properties at Standard Pressure and Temperature for a minimum ionizing particle. E_i and E_i are the first ionization and the mean ionization potentials, respectively, while n_p and n_t are the number of ion-electron pairs per cm for the primary ionization and the total (primary and secondary), respectively. The energy loss is described by the $-dE/dx$ and varies for the type of radiation and their initial energy.

4.3 Gas Ionization and Charge Production

Like stated previously, ion-electron will be produced inside the chamber. This ionization is done when an electron is stripped from the neutral state of the atom. This will be done by the energy deposition of an alpha particle. The alpha decay is represented by:

$${}^A_Z X \rightarrow {}^{A-4}_{Z-2} Y + {}^4_2 \text{He}. \quad (4.1)$$

The nuclei X emits a helium atom, known as an alpha particle, and the nuclei Y is the new formed atom by X 's alpha decay. The energy available from this decay is called the decay energy [39] or the Q-value, just like for the double beta decay shown in Chapter 2. It is simply found by looking at the initial and final masses of the interacting particle. For the alpha decay the Q-value is determined with:

$$Q = M(A, Z) - M(A - 4, Z - 2) - M(4, 2). \quad (4.2)$$

This will give the available decay energy of the ionizing alpha particle.

An Americium-241 source is chosen as the alpha emitter for this experiment. The source possess a half life of 433 years. This emitter is a thin 2.5 cm diameter disk. It will emit alpha particles with energy at 5.5 MeV with an activity of 0.15 μCi . The alphas will ionize, i.e. deposit their energy, to the isobutane gas inside the chamber. This energy deposition will produce around 2.4×10^5 ion-electron pairs per alpha. This high number of pairs does not require gas amplification to be fully detected. This can be calculated with:

$$N_{pairs} = \frac{\text{Total Energy}}{\text{Mean energy to produce one pair}} = \frac{E_{tot}}{W}. \quad (4.3)$$

The W value can be found in Table 4.1. It is the mean energy to produce one pair of ion–electron. The number of pairs produced follows a Poisson distribution, and therefore the statistical fluctuation in this mean number is characterized by the square root of the total number of produced pairs [40]. For the case of the 2.4×10^5 ion-electrons pair per alpha, the fluctuation lays between ± 490 pairs.

The total energy is the Q-value from the Americium-241 decay into Neptunium-237 as seen with the following reaction:

An alpha particle can be considered as moderately relativistic charged heavy particles. Its rate of energy loss can be described by the Bethe-Bloch equation by [41]

$$-\left\langle \frac{dE}{dx} \right\rangle = D_e \frac{Z^2}{\beta^2} n_e \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2}{W_{mean}} - \beta^2 - \frac{\delta(\gamma)}{2} \right], \quad (4.5)$$

with $D_e = 5.0989 \times 10^{-25}$ MeV-cm², β and γ the relativistic factors depending on the energy of the alpha, n_e the electron density of the gas, m_e the mass of the electron, and $\delta(\gamma)$ a correction for the density effect developed by Sternheimer [42]. Figure 4.6 shows the projected range of a 5.5 MeV alpha particle inside 1 bar of isobutane gas. These values are calculated from a SRIM-2013, Stopping and Range of Ions in Matter [43], simulation. Figure 4.6 also shows the energy loss of the same alpha. Again these values are calculated from SRIM-2013.

Figure 4.6: The energy loss (diamonds) and the range (squares) of alpha particles, from SRIM 2013, up to 5.5 MeV at 1 bar. A typical 5.5 MeV alpha will travel about 14.71 mm and will travel shorter distances for lower energies. The energy loss has a Bragg peak profile.

The range simply describes how far the particle will travel into a medium before

coming to a full stop. It varies on the medium chosen to travel in, and its density. By having more gas particles (higher pressure), the track of the alpha will be much smaller due to its ionization interaction. This range can be calculated with the stopping power of a specific case. Equation (4.6) [41] gives the mean range, which is when half of the initial energy still remains.

$$R_{mean}(E) = \int_E^0 \frac{1}{-\langle dE'/dx \rangle} dE'. \quad (4.6)$$

For a charged ionizing particle like an alpha, the ionizing peak, which is related to the range, generally occurs near the end of the ionizing track, nearly at rest, due to the increase in the interaction cross section between the particle and the gas. At this point, the velocity of the ionizing particle is also decreased while depositing its energy in the gas. This peak is called the Bragg peak [41] and follows the Bragg curve. Figure 4.6 showed this Bragg curve for alpha in isobutane.

Figure 4.7: The SRIM-2013 range calculation for an alpha particle inside isobutane. The vertical axis is the distance in mm an 5.5 MeV alpha needs to travel before coming to a full stop and the horizontal is the gas pressure in bar.

Figure 4.7 shows the distance travelled at different pressure calculated with SRIM-2013 simulations for a 5.5 MeV alpha. As expected, the range of the alpha goes down as the pressure rises. This simply means there are more gas particles for the alpha to ionize versus distance as a function of pressure.

The ions and the electrons that are produced need to be separated, otherwise they will recombine. An electric field will separate them and thus reduced the recombination probability due to the Coulomb attraction between them. The number of ionization follows a Poisson distribution [44]. The mean distance between two ionization points, λ , is described by:

$$\lambda = \frac{1}{n_e \sigma_{Ion}}, \quad (4.7)$$

with n_e the electron density of the gas and σ_{Ion} , the ionization cross section between the ionization particle and the gas. With this, and the fact that it acts like a Poisson distribution with mean (and variance) L/λ , L is the length, the distribution is:

$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} e^{-L/\lambda}. \quad (4.8)$$

As Figure 4.6 shows, alphas have a low penetration depth. This can be associated to their charge and mass. The pressures were chosen in such that the alpha would be contained within the limits of the detector.

During the drifting phase of the electrons, impurities could capture them thus reduce the number collected at the readout. As stated before, the majority of the impurities will come from the many electron-hungry air particles still present in

the chamber. Their electronegativity properties will capture the drifting electrons. This effect needs to be accounted for even with the usage of a purifier. Impurities can come from many sources. They could come from not having a perfect vacuum, could have not been filtered by the purifier, or could come from the outgassing of components inside the chamber. The number of electrons, N_e , drifting to the detector during the drift time, t_d , can be describe as:

$$dN_e(t_d) = -kN_e(t_d), \quad (4.9)$$

with k the sum of all the attenuations coefficients due to the impurities. This simple differential equation gives a solution for $N_e(t_d)$ as:

$$N_e(t_d) = N_e(t=0)e^{-kt_d}. \quad (4.10)$$

The last equation can directly be changed to consider the charge attenuation, $Q(t_d)$ by including the electron lifetime, τ_e , and Q_0 the total initial charge:

$$Q(t_d) = Q_0 e^{-\frac{t_d}{\tau_e}}. \quad (4.11)$$

The drift time is simply the distance travelled divided by the velocity. These are determined by the position of the source, the electric field, and the gas pressure. This purity factor will be used in the description of the model in Chapter 5.

4.4 Ionization Drift Chamber

Similar to EXO-200, this vessel is used as an ionization drift chamber. This means that charged particles will be produced and drift inside the vessel without any amplification.

The alpha source located at the top of the detector near the cathode will emit alpha particles which will produce an ionization track as shown in Figure 4.8. This track is usually straight [45]. The positively charges will go along the electric field, while the negatives ones will drift in the complete opposite direction. Figure 4.9 shows a simple schematic of the trajectories of the newly produced charged particles. The electric field will be produced by a series of copper rings of inner radius of and outer radius 7.52 cm and 9.0 cm, respectively, spaced by 1 cm. These 16 rings are connected in series with 10 M Ω resistors. The high resistance (low current) is to prevent the creation of a too intense magnetic field that would change the trajectories of the charged particles. Figure 4.10 shows the copper rings with the resistors that are vacuum grade. These ring go directly into the chamber with all the events contained inside their dimensions.

Figure 4.8: Track of ionization of an alpha particle moving through a gas. In this case, the red dots represents the ionized isobutane molecule and the blue dots the electrons of these ionization. The alpha deposits its energy and creates the ionization along its track with a high concentration at the tail.

Figure 4.9: On the left: After the alpha particle deposits its energy inside the gas, ions, large dots (blue) and electrons, small dot (black) will be created in the vicinity of the deposit. Without any electric field the charges will most likely recombine. On the right: With the electric field, the ions and electrons are separated. The electrons drifts down to the anode, where the pads are located, and the ions drift up to the cathode.

This configuration of rings assures an uniform electric field along the z -axis of the drift volume. In other words, by neglecting lateral diffusion inside a gas, the charged particles will drift in a straight line along the electric field.

The voltage will be set through the high voltage feedthrough located on the top flange with a Bertan 10 kV high voltage supply. The voltage leaving the power supply will be lead to the feedthrough by an SHV or MHV cable. This applied voltage will stay between 800 V to 8 kV. With the 16 rings, the electric field is set between 45 and 450 V/cm.

Typical ionization chambers, such as wire proportional counters, rely on charge

Figure 4.10: The copper rings are mounted in a cylindrical shape to 3 insulators pillars to create the electric field. The rings are joined by a series of vacuum proofed resistors. The three first rings are at the same potential and are joined by two conductive wires instead of resistors.

avalanche production due to the secondary ionization from the electrons. These avalanches occur when the electrons acquire enough kinetic energy to ionize the gas through collisions [46], especially at high electric field. This creates a gas amplification. The charge readout observes more charges than is initially produced. For a wire chamber, under certain condition of applied voltage and gas type and pressure, the amplification happens as the electrons move closer to the anode wire, since the electric field in those chambers is proportional to $1/r$ [39]. The advantage of having gas amplification is that the output signal is amplified and can help to achieve a better signal to noise ratio. Amplification is important for weakly ionizing

particles since the output signals might be small, and also if the noise level is high enough to deteriorate the signals. Since the detector presented in this work has for goal to measure the energy resolution and possibly do some preliminary event reconstruction, having amplification would alter the output signal and the precision of the measurement of the initial energy deposition. Therefore, the electric field values used are set to not produce any amplification inside the detector. Isobutane is also often used as a quencher to limit any type of secondary ionization.

The typical electron drift velocity, v , varies with the pressure and the magnitude of the applied electric field. Without any electric field, the electrons motion is characterized by a Maxwellian distribution [47] at value kT . Figure 4.11 shows a linear relation between the velocity and the applied field. This linearity is only valid at this range of pressure and field strength. These values are taken from [48] and [49]. As seen, there is different values for the drift velocities at the same conditions. The variation can come from the method of measurement and the uncertainties associated with them. An average was taken to be used as the nominal values for the electron drift velocities.

Figure 4.11: Drift velocity of electrons inside isobutane in the range of the electric field that will be applied at different pressure. Two set of literature data, blue [48] and red [49], were used to show the possible range of the velocities.

The ion drift velocity is much smaller than their electron partners. In the case of an isobutane molecule, the ion mobility, μ , is $0.614 \text{ cm}^2/\text{V sec}$ [50]. This mobility gives a drift velocity of roughly 270 cm/s at a 450 V/cm . This is over 7400 times slower than the electron drift velocity value. By the time the electrons reaches the bottom of the vessel, the ions will have barely moved upwards.

As the electrons drift, their trajectory could be altered due to diffusion. This diffusion depends on the characteristics of the gas the electron travels in and the external electric field [48]. The diffusion of the electrons in a direction follows a Gaussian distribution with a standard deviation shown with Equation (4.12) with D the diffusion coefficient, x the distance, and w the drift velocity. Figure 4.12, taken from [51], shows typical values for the longitudinal, σ_l , and transverse, σ_t , diffusion at different electric fields over pressure values. For a pressure of 760 Torr (roughly 1 bar), the transverse diffusion will be around 0.11 mm for 1 cm , which gives around 1 mm diffusion for a 10 cm total drift distance. This will give less than 1% variation and will be neglected but not forgotten for this experiment. Also, this diffusion is

smaller than the actual event range of 1 to 2 cm, depending on the pressure.

$$\sigma = \sqrt{\frac{2Dx}{w}} \quad (4.12)$$

Figure 4.12: Diffusion values of electrons for 1 cm drift in isobutane. The left scale shows values at 20 Torrs compared to 760 Torrs on the right side. To give an idea of the range for the diffusions, transverse, σ_t , and longitudinal, σ_l , 1 unit on the horizontal scale is about 750 V/(cm·bar) [51].

In the end, the drift distance of the produced charge will be determined by the height of the source. The micrometre, as seen in Figures 4.4 and 4.13, will move the source along the z -axis of the chamber from 2 cm to 17 cm from the anode. This will be useful to check different scenarios, e.g. verifying the purity of the chamber by having longer drift distance, and the effect of different drift distances.

Figure 4.13: The vertical black arrow shows the range of the possible positions with the use of the micrometer for the source and cathode.

4.5 Detector Package / The Readout Pads

When the charges are created inside the chamber, they will start to induce charge onto the pads. As they start to drift towards the pads, they will induce a current that is measured. Once the electrons reach the pads, this induction signal will then be a direct collection signal. The model, including the induction and collection for these pads configuration, will be elaborated in details in the next chapter.

Two readout pad scheme are used in this study. Figure 4.14 shows a top view of the single pad array on the left hand side while the right hand side shows the 16 pads array, both used in this detector. Both conductive area are made of solder plated copper of approximately the same size, but for the 16 pads case each pad is separated by 1 mm to get a segmentation. The electrodes or pads sit on a circular shape insulator made of PCB material (FR4G10). For the 16 pads configuration, the area between the different pads is also part of the insulator to limit the cross-talk between the pads. Connectors underneath will transport the signal to the electronics.

Figure 4.14: On the left: Schematics of the single pad with dimensions. On the right: Schematics of the 16 pads array with dimensions.

The single pad configuration is used to collect as much signal as possible to determine the energy resolution. This configuration does not allow the determination of the initial positions since only one pad will measure the signals. All the induced charge, as well as the direct charge, will be seen by the one pad and give one large signal. The 16 pads configuration is sensitive to the initial position thus giving some information on the spatial resolution as well as the energy resolution. The signals observed will vary from pad to pad depending on the initial parameters of the ionization process. Only a few pads will see some collection signal due to the fact that the track length of the alpha is in the same order of the pad size. These channels (the different pads) are all independent and the measured signals are collected through a data acquisition system (DAQ) independently of each other. Each pad has a signal and a ground wire which are then attached to the pin connectors to be sent to the DAQ outside the chamber.

This induction and collection scheme is different from the one currently in place in the EXO-200 detector. The pad or pads will both see the induced and collected signals due to the production and motion of the charges inside the chamber, instead of having two sets of wire planes which measures the two signals separately. The number of channels varies differently than in EXO-200. The wire planes offer a

$2n$ channels while the pads offer a n^2 number of channels. By adding more pads, the number of channels can significantly become very large which is never ideal. This number of pads/channels will vary depending on the geometry of the detector itself. The ideal size and number of pads should give the same, or better, spatial resolution than EXO-200.

By looking at signals in each pad for one specific event will give an idea of the size of the events and the possibility of reconstructing the event to study the spatial and energy resolution.

4.6 Readout Electronics

Every pad signal needs to be read by some readout electronics and modified into a useful form. To do this, a charge sensitive preamplifier data acquisition developed by CAEN with the collaboration of the LAr LEM-TPC group [52] is used. The charge sensitive preamplifier will produce an output voltage, V_{out} , with an amplitude proportional to the integral of the input current. This readout system is called the SY2791 TPC Readout System. One single crate can hold up to 256 different channels with 8 acquisition modules named A2792. These modules hold the preamplifiers inside each of the 16 boards. Figure 4.15 shows the crate with the 8 modules attached to a linear power supply on the far right.

A signal coming from a detector source, in this case from the readout pads, will be digitized by going through the preamplifier system of the boards. Figure 4.16 shows a simplistic diagram of the DAQ and its components. The wires connected to the boards are shielded with copper to reduce environmental noise as much as possible. Analogue signals will first be amplified, then will go through a RC-CR shaper to

Figure 4.15: The CAEN SY2791 TPC readout crate. The 8 different boards are labelled on the left handside and the power supply is on the right. The grey cable connects the detector to the module. It is shielded by copper.

finally be digitized at 12 bit 2.5 MSample/s ADC. One ADC count is equivalent to 0.805 mV. The digitized signals will then be processed by the field programmable gate array, FPGA, which can store the data in 1 MB circular memory buffer to then be sent to the PCI board A2818 connected to a PC via fire optical cables. Table 4.2 gives the nominal values of the preamplifiers components [53].

The DAQ sample number included in one acquisition window can be modified by adjusting the number of desirable buffers from 2 to 1024 per channel. It also offers two types of adjustable threshold to trigger on signals. When a signal surpasses the tunable high thresholds limit, of 75 ADC for this work, the system will trigger on that channel. To trigger on all other enabled channels, the low threshold is set to 0. This means that once a signal is observed, every enabled pad will trigger [54]. This is important to correctly map an event when using multiple channels. The trigger

Figure 4.16: Block representation of the conversion of an analogue signal going through a series of electronics to give an digitized output signal.

rates are about 10 events/s with the activity of the source and a mask with a small aperture used. This mask will be elaborated in Chapter 6.

Specification	Nominal Value
FET integrator decay time constant	470 μ s
Sensitivity	11.5 mV/fC
Shaper Integration time constant, τ_{int} (RC)	0.6 μ s
Shaper differentiation time constant, τ_{diff} (CR)	2 μ s
Signal to noise at 1fC (C = 200 pF)	10
ADC resolution	12 bit (FSR = 3.3 V, 1 LSB = 0.805 mV)
Output offset	0 to 5 V

Table 4.2: Nominal values of the different properties of component inside the A2792 boards.

4.7 Noise

When working with electronics such as a DAQ, any background electrical noise can be picked up and affect the output signals. Since electronics are very sensitive and information from signals could be lost in the noise, a lot of effort was put in place to reduce as much as possible environmental noise that the DAQ could pick up. The

first step was to reduce, as much as possible, the length of any wires, especially the ones carrying the signals to the DAQ. These wire going from the detector to the electronics input were copper shielded. A copper cage was placed around the open end of the connector to shield any possible noise that could interfere with the output connector. Figure 4.17 shows a picture of the copper cage. Another thing that was put in place was to use a low noise power supply to create the electrical field through the rings.

A major improvement was made by using a filter box. This filter box manages to cancel or avoid any ground loops that could exist with the different electronics used. All electronics; the DAQ, the power supply, etc., were plugged in it. This managed to reduce considerably some noise but in the end two main source of noise still remained. The power supply and the DAQ used were found to be producing noise that could not be eliminated.

Figure 4.17: Handmade copper cage with copper tape to block any possible environmental interfering noise that the connector could capture.

Chapter 5

Signal Modelling

To properly understand and analyse data, a model must be developed. The model for this thesis will depend on many physical aspects of the detector. The Ramo-Shockley theorem will govern the induced signals produced inside the chamber, alongside a charge distribution produced by the gas ionization of the alpha particle. The data is readout by a the commercial data acquisition system, DAQ, presented in the previous chapter. This DAQ possess a specific transfer function due to its different electronics components. This transfer function will be modelled using a known test input pulse. After developing the model, some expected waveform will be shown to understand how the different parameters affects the output signal.

5.1 Signal Processing

The components of an electronic system transform an input signal into an output signal with a series of electronics component such as amplifiers and shapers. This process is schematically shown in Figure 5.1, where the transfer function, $h(t)$ represents the total effect of the components to the input function giving an output signal.

Figure 5.1: Simple representation of an input signal going through some electronics to give an output signal.

The output signal is obtained through the convolution of the input signal and the transfer function as shown in Equation (5.1).

$$signal(t) = input(t) \otimes transferfunction(t) = \int_{-\infty}^{\infty} input(t - t') \cdot h(t') dt'. \quad (5.1)$$

The convolution integral can be simplified with the help of the Fourier transforms. The typical Fourier transformation from the time space to the frequency space is shown in Equation (5.2) where $f(t)$ is a time dependant function and $F(\omega)$ its frequency space representation [55].

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt. \quad (5.2)$$

From Equation (5.2), the output signal is the multiplication between the input and the transfer function in the frequency space as show in Equation (5.3).

$$\mathcal{F}\{signal(t)\} = Signal(i\omega) \cdot H(i\omega). \quad (5.3)$$

Using linear processing devices the input and output signals are related by a series of differential equations with time independent coefficients. By moving to the frequency space by using Laplace transform, the relation becomes algebraic with only the

different associated coefficient. These coefficient are the transfer function of the system and depends on the electronics components. The general transfer function is express as [56]

$$H(s) = \frac{(s - z_1)(s - z_2) \dots (s - z_m)}{(s - p_1)(s - p_2) \dots (s - p_n)}, \quad (5.4)$$

where s is a complex number, and z_m and p_n the zeros and poles of the function, respectively. These zeroes and poles are defined by the different components used to shape and amplify the signal.

As shown earlier, the CAEN readout electronics includes a preamplifier, a RC-CR shaper and an amplifier. The transfer function for this system can be obtained using the fact that a cascade of circuit components in series is simply the multiplication [57], in the frequency space, of every contribution from the components. The expected transfer function is shown in Equation (5.5).

$$H(i\omega) \propto \frac{1}{i\omega + a} \cdot \frac{i\omega + e}{i\omega + b} \cdot \frac{1}{i\omega + c} \cdot \frac{1}{i\omega + d}. \quad (5.5)$$

The first term is associated with the charge integrator feedback constant, $a = \tau_{preamp}$, the second to the CR differentiator, $b = \tau_{diff}$, the numerator on top of the second is for the suspected pole-zero cancellation, $e = \tau_{pz}$ installed in the electronics added to the CR differentiator factor. The third term is for the RC integrator, $c = \tau_{int}$. The last term is for the amplifier following the shaper, $d = \tau_{amp}$. The respective shaping time constants were verified experimentally since the full details of the CAEN SY2791 electronics were not known.

The verification can be done by sending a known input signal through the electronics and measuring the output signal. A Berkeley Nucleonics PB-4 Pulse generator was used to provide an impulse, which acted like an input signal, with rise, τ_{rise} , and fall, τ_{fall} , times that can vary from 0.05 to 10 μs and 0.5 to 1000 μs , respectively. The pulse from the generator goes through a capacitor and a resistor in series with values of 1 pF and 50 Ω , respectively, before reaching the CAEN electronics system. These components modifies the transfer function in Equation (5.5) by adding an extra $i\omega$ term on the numerator.

In order to describe accurately the input signal, two different functions were evaluated for this purpose. The two functions are shown in Figure 5.2. Both functions include a rise and fall time that are fixed by the generator itself. Finding the right input function can be done by sending a pulse straight onto an oscilloscope. After fitting both functions to the data, the second one was found to best represent the input signal with the appropriated rise and fall times. A simple fit of Equation (5.6) added to a linear noise, $p0 + p1 \cdot t$, can be seen in Figure 5.3. The fitting parameters are: $p0$ and $p1$ the coefficients of a linear noise applied to the signal, t_0 is the time bin, in nanoseconds, of the start of the event, while τ_{rise} and τ_{fall} are the rise and fall time, respectively, divided by 50 for the binning factor. The nominal values are 2 μs for τ_{rise} and 10 μs for τ_{fall} . The distributions of the fitted parameters for a few hundreds waveforms are shown in Figure 5.4. The distribution agreed with the nominal values of the input signal.

$$f(t) = \theta(t - t_0) \cdot (1 - e^{-\frac{(t-t_0)}{\tau_{rise}}}) \cdot e^{-\frac{(t-t_0)}{\tau_{fall}}} . \quad (5.6)$$

Figure 5.2: Comparing two possible choice for the input function. Both act similarly but the one on the right rises more abruptly and also contains a Heaviside function $\theta(t)$.

In the frequency space, the transfer function can now be determined with a division of the output signal, given by the DAQ, by the input signal. Since only the zeroes and poles need to be determined, this approach can be simplified by looking at the magnitude of these functions as shown in Equation (5.7) and more specifically with Equation (5.8) which is the magnitude of Equation (5.5).

$$|H(i\omega)| = \left| \frac{signal(i\omega)}{input(i\omega)} \right|. \quad (5.7)$$

$$|H(i\omega)| \propto \sqrt{\frac{\omega^2(\omega^2 + e^2)}{(\omega^2 + a^2)(\omega^2 + b^2)(\omega^2 + c^2)(\omega^2 + d^2)}}. \quad (5.8)$$

Figure 5.3: The fitted input function of Equation (5.6) with an added linear noise overlays the signal and thus is taken as the appropriate function. p_0 and p_1 represents a simple linear noise applied to the function while t_0 is the bin of the start of the event and τ_{rise} and τ_{fall} are the rise and fall time respectively using a binning factor of $1/50$.

Following the consideration of the LAr LEM TPC group in [52], which uses the same electronics, the pole zero component, the e parameter, is cancelled with the feedback decay time, the d parameter, and the amplifier time constant, the d parameter, being similar to the integrator time constant, the c parameter, simplifies Equation (5.8) to Equation (5.9). The cancellation of e with d corrects the baseline restoration by getting rid of the undershoot.

$$|H(i\omega)| \propto \sqrt{\frac{\omega^2}{(\omega^2 + b^2)(\omega^2 + c^2)^2}}. \quad (5.9)$$

Figure 5.4: Distribution of the input parameters over a few hundreds waveform. Performed a simple Gaussian fit to find the mean values of the distributions.

Equation (5.9) was verified to fit sensible parameters for the transfer function. The general form of Equation (5.8), with 5 free parameters, was also applied resulting in the best outcome when $c = d$. The pole-zero and feedback cancellation was verified only approximately, because their time constants were too large to be observed in the event time window. In the next chapter, it will be shown that the pole-zero suppression only reduces the magnitude of the undershoot caused by the feedback time, but not entirely. However, the full pole zero suppression used here is a good approximation for the noise level observed with the detector and the time window of the signal, which is smaller than the full decay time of the feedback capacitor.

The parameters b and c are related to the different time constants of the electronics system and are determined by the specific binning of the data collection which is chosen by the user and depends on the sampling clock frequency and the timing window. Equation (5.10) shows an example for a sampling frequency rate of 2.5 MHz and a time window of 512 bins.

$$\alpha = \frac{\text{binning}}{2\pi} = \frac{(\text{timewindow})}{2\pi(\text{frequency})} = \frac{512 \cdot 0.4}{2\pi}. \quad (5.10)$$

This factor can change depending on the user's choice, and the 2π is a normalization factor coming from the Fourier transforms.

The electronics transfer function in the time space is obtained by doing an inverse Fourier transform of the transfer function in the frequency space:

$$h(t) = \Theta(t) \frac{e^{-bt} + e^{-ct}[t(b-c) - 1]}{(b-c)^2}, \quad (5.11)$$

where $\Theta(t)$ is the Heaviside function and b and c relates to the time constant with Equations (5.12) and (5.13), respectively.

$$\tau_{diff} = \frac{\alpha}{b}, \quad (5.12)$$

$$\tau_{int} = \frac{\alpha}{c}. \quad (5.13)$$

5.1.1 Determination of the Electronics Time Constants

As just stated, the transfer function of the electronics can be found by looking at the output signal. Figure 5.5 shows the signal and its magnitude in the frequency space. The noise level associated with this event is less than 1% of the maximum pulse height. The big undershoot can be explained by the type of pulse sent and the capacitor before the CAEN system, which was stated to add an extra factor of $i\omega$ in the electronics transfer function. The binning of the magnitude is associated with the sampling clock frequency, 2.5 MHz, and the number of samples in the time space, 512.

Figure 5.5: On the left: output signal measured. On the right: magnitude, in ADC, of the output signal in the frequency space with the binning factors.

Before the transfer function was fitted to the collected data, the average of several waveform from the same input signal was taken. Taking the average reduces the random fluctuation noise. After that, the magnitude of the Discrete Fourier Transform on the average waveform is computed and then divided by the corresponding magnitude of the input signal. Figure 5.6 shows the fit results for a fall time and rise time of $10 \mu\text{s}$ and $0.05 \mu\text{s}$, respectively, of Equation (5.9) with a normalized constant,

A. The parameter A is an amplitude (scaling factor), b is the coefficient for the RC shaper time constant and c is the coefficient for the CR shaper time constant, while $p0$, $p1$, and $p2$ are the coefficient of a quadratic noise, $p0 + p1 \cdot \omega + p2 \cdot \omega^2$, added to the function. The contribution from the remaining noise was modelled by a second degree polynomial. The errors of the fitted parameters are obtained by assuming that all the points have the same errors since they are independent due to the fact that they are not known at priori, and adjusting them such that the reduced $\chi^2/NDF = 1$. NDF is the number of degree of freedom.

The weighted χ^2 , with weighted errors all equal to 1, is represented by:

$$\chi_{W_{errors}}^2 = \Sigma(data - model)^2. \quad (5.14)$$

Once this is calculated, the reduced χ^2 is set to 1 as shown with the following:

$$\frac{\chi^2}{NDF} = 1 = \frac{\chi_{W_{errors}}^2/\sigma^2}{NDF}, \quad (5.15)$$

Solving the previous for the approximated errors, σ_{approx} :

$$\sigma_{approx} = \sqrt{\frac{\chi_{W_{errors}}^2}{NDF}}. \quad (5.16)$$

This approximation is similar to say that all the errors are Gaussian distributed and that the model is a good description of the data.

Similar fits were performed for several different values of the falltime, between 0.5

Figure 5.6: Fit of the magnitude of the transfer function from Equation (5.9) with an amplitude A added to a quadratic noise to give out the integrator (RC) and differentiator (CR) time constant of the electronics, b and c respectively with the binning factor of Equation (5.9). The three last fitted parameters are a simple quadratic noise added to the model.

and $50 \mu\text{s}$, and risetime, between 0.05 and $0.1 \mu\text{s}$. Table 5.1 summarises the fitted values of the electronics time constants, and compares them to the nominal CAEN values. The values are compatible to the ones measured in [52], where a similar electronics system was used.

Component	Nominal (μs)	Fitted Value (μs)	Difference (%)
Integration time constant (τ_{int})	0.6	0.530 ± 0.008	12
Differentiation time constant (τ_{diff})	2	2.667 ± 0.027	25

Table 5.1: Comparison of nominal and fitted values for the integrator and differentiator time constant. The errors for the fitted value are the rms of several values.

5.2 Evaluation of Charge Collection and Induction

As mentioned in the previous Chapter, the readout pads will measure an induction and collection signal coming from the charge produced by the ionization of the gas by an alpha particle inside the detector. The model for the charge collection and induction will be elaborated. In this model, the induced signals done by the ions will be neglected because by the time the electrons have drift down to the pads, the ions will have barely moved due to their much slower speed, as seen in Section 4.4, thus not producing any induced current.

5.2.1 Charge Production

An alpha particle that exits the radioactive nucleus ionizes the isobutane region along its track. This ionization forms a cloud of electrons, that drifts to the readout pads because of the electric field between the cathode and anode. The electric charge of this cloud is approximated here by a linear charge density:

$$\rho(x) = \frac{dq}{dx}, \quad (5.17)$$

where dq is an element of charge. The charge density is proportional to the average energy loss of an alpha particle, $\frac{dE}{dx}$, evaluated with the SRIM-2013 values shown in Chapter 4. The energy loss of an ionizing particle along its track is usually known as the Bragg peak, and the relationship between the number of ionization electrons and the energy deposition is given by a constant usually referred to the W -value. In order to obtain an analytical solution to the charge measured by the detector, the Bragg peak for alpha particles in isobutane is approximated by the function shown in Equation (5.18). The function is composed of exponentials that represents a slow rise and then an abrupt fall for the charge density as a function of the track position

with the use of λ a parameter between 0 and 1 calculated by the distance normalised to the alpha track range.

$$\rho(\lambda) = A(B - e^{\lambda/C})(De^{\lambda/F} + e^{\lambda/G}). \quad (5.18)$$

Figure 5.7 shows the fit of the function in Equation (5.18) for the charge density. The plot on the right gives the residual defined as the relative difference between the fitted function and the values evaluated by SRIM 2013. The relative difference (residual) are under 10% for over 95% of the alpha range. Therefore Equation (5.18) was considered to be a good approximation of the Bragg peak for the alpha particles in isobutane. When the purity effects is involved, the charges are loss exponentially, therefore the charge density is transformed by Equation (5.19), with the electron lifetime τ_e and t is the time between when the charge density is evaluated and the start of the event.

$$\rho(\lambda) \rightarrow \rho(\lambda, t) = e^{-t/\tau_e} \cdot \rho(\lambda). \quad (5.19)$$

5.2.2 Charge Collection

There are two types of charge measured by the detector pads: the collected and induced charges. The collected charge are those electrons that drifts down to the readout pads and are collected. The collection signal is equal to the charge flux through the pad itself. The charges are electrons in this work since they are the ones being collected. The current for the collection is shown in Equation (5.20) with ρ the charge density, v_z the electron drift velocity in the z direction which is perpendicular

Figure 5.7: On the left: Bragg peak for alpha particles in isobutane at one bar evaluated by SRIM 2013 and fitted function. On the right: relative differences between the fitted function and values from SRIM 2013.

to the plane of the pads and $\lambda_p(t)$ is the parameter determined by the intersection between the charge density and the pad at time t . The intersection depends on the initial and final position of the alpha track, $\vec{x}_i$ and $\vec{x}_f$ respectively, and the drift velocity, v_z , of the charge density. If there is no intersection, the collected current is 0.

$$I_{col}(t) = \rho(\lambda_p(t))v_z. \quad (5.20)$$

To find the full charge collected, Q_{col} , Equation (5.20) can be integrated over the collection time, t_{col} . This integral is proportional to the number of electrons, N_e , as shown in Equation (5.21).

$$Q_{col} = \int_{t_0}^{t_{col}} I_{col}(t)dt \propto N_e. \quad (5.21)$$

5.2.3 Charge Induction

The induced charge on the electrodes by a point charge depends on the distance between the charge and the electrodes as well as on its drift velocity. S. Ramo [58] and W. Shockley [59] both independently came up with a similar theorem to calculate the induced current on the electrodes. The theorem says that by looking at the electric field produced by the electrode when it is held at 1 V, and all other electrodes at ground, i.e. zero potential, one can obtain the associated current on that specific electrode with Equation (5.22). The induced current is measured on the anode while the cathode is kept at ground with the field shaping rings.

$$I_{ind}^i = q\vec{v} \cdot \vec{E}_i. \quad (5.22)$$

$\vec{E}_i$ is the associated weighted field seen on the i th electrode done by a charge q moving at velocity v . The dot product implies that only the electric field along the same axis of the velocity contributes to the induced current. In the detector of this thesis, the charge will drift downwards in the z direction. Equation (5.22) is valid for one charge q and thus needs to be extended for a charge distribution as it will be shown.

The induced current on the i th electrode can be used to find the total induced charge that flows from that specific electrode, Q_{ind}^i , to the ground with Equation (5.23) [44].

$$Q_{ind}^i = \int_{t_0}^{t_1} I_{ind}^i(t) dt. \quad (5.23)$$

Therefore, the total induced charge seen on the i th electrode depends on the time the moving charge was produced, t_0 , and the time it reaches its specific electrode, t_1 . Since in the detector ions and electrons will be produced by the ionization of the gas due to the alpha particle, there are two possible contribution to the total induced current on the electrodes. The electrons drift towards the pads while the positive ions drift towards the cathode at a much slower speed. This means that the total charge that induce a current on the i th electrode will be equal to the total charge reaching that electrode, only once all the charges, positive and negative, arrive at their respective electrodes. Since the electrons travels much faster than the ions, the ions do not reach the cathode within the time that the electrons reach the anode. In fact, they will have barely moved, thus their contribution to the current induction is considered negligible here. This effect will be seen in Section 5.4.

Equation (5.22) can be rearranged to consider the potential, V , instead of the electric field, E by using the simple relation shown in Equation (5.24).

$$\vec{E} = -\vec{\nabla}V. \quad (5.24)$$

To find the induced current on a specific electrode, V needs to be calculated. This can be done by solving the Laplace equation with the proper boundary conditions. Since the box is square shaped with widths of w , and there's only a non-zero potential at the surface at a distance h from the charge, the Laplace equation is solved for a rectangular box shape [60]. The pads are located at the bottom and are kept at a non zero potential while the 5 other sides are at ground to satisfy the Ramo–Shockley theorem. The potential for a square pad of dimensions w at a distance h from the

source is fully described by [60]

$$V(x, y, z) = \sum_{n,m=1}^{\infty} A_{nm} \sin\left(\frac{n\pi x}{w}\right) \sin\left(\frac{n\pi y}{w}\right) \sinh\left(\frac{\sqrt{n^2 + m^2}\pi(h - z)}{w}\right). \quad (5.25)$$

The A_{nm} needs to be determined to find the complete solution of the potential. This can be done by integrating Equation (5.25) over x and y with the appropriate boundary conditions. Due the boundary conditions being for a square pads, the integral is separable such that $A_{nm} = A_n \cdot A_m$, where $A_n \leftrightarrow A_m$ with $n \leftrightarrow m$ and $x \leftrightarrow y$. Equation (5.26) shows the $A_n(x)$ solution of the integral. This solution is the same for $A_m(y)$ except with $n \rightarrow m$ and $x \rightarrow y$.

$$A_n(x) = \frac{2(-1)^n}{n\pi} \left[\delta_{nodd} C_{nlu} \sin\left(\frac{n\pi x}{w}\right) + \delta_{neven} S_{nlu} \cos\left(\frac{n\pi x}{w}\right) \right]. \quad (5.26)$$

The δ_{nodd} and δ_{neven} are the Kronecker delta-functions. The first one is 0 if n is an odd integer while the second one will be 1, and vice versa for the even integers. The C_{nlu} and S_{nlu} terms are shown in Equations (5.27) and (5.28), respectively, and serves only as a simplification of Equation (5.26).

$$C_{nlu} = \cos\left(\frac{n\pi x_l}{w}\right) - \cos\left(\frac{n\pi x_u}{w}\right), \quad (5.27)$$

$$S_{nlu} = \sin\left(\frac{n\pi x_l}{w}\right) - \sin\left(\frac{n\pi x_u}{w}\right). \quad (5.28)$$

The x_u and x_l , similarly for the y 's, represent the upper and lower positions of the pad, respectively, coming for the boundary conditions of the integral.

Since, as explained earlier in this chapter, the electron cloud is approximated by a linear charge density, the total induced current is then the integral of the specific charge density and the full voltage solution as just developed. Thus giving the result in Equation (5.29) for the total induced current, I_{ind} , on one electrode.

$$I_{ind}(t) = \int_0^{\lambda'} \rho(\lambda, t) E_z(\vec{x}(\lambda, t)) v_z d\lambda, \quad (5.29)$$

where E_z is determined by Equations (5.24) and (5.25), ρ is the charge distribution density given by 5.19, v_z is the velocity in the direction of E_z and is constant, $\vec{x}(\lambda, t)$ is the position of the charge density corresponding to λ at time t . This position depends on $\vec{x}_i$, $\vec{x}_f$, and v_z . The parameter λ' is either λ corresponding the position of the intersection between the charge density and the pad or 1, when the charge density has not reached the pad yet. Equation (5.29) is also valid for any number of square pads with appropriate boundary conditions, as long as they are at the same z position. Since the voltage varies depending on how far the pads are, the induced current should also vary accordingly. The further away they are from the charge, the smaller the induced current will be. Also, since the charge density function is approximated by a sum of exponentials, Equation (5.29) can be analytically solved.

5.2.4 Waveform Generation

The total current, I_{tot} measured by each pad can be described by:

$$I_{tot} = I_{col} + I_{ind}, \quad (5.30)$$

where I_{col} is given by Equation (5.20) and I_{ind} by Equation (5.29) to give

$$I_{tot} = \rho(\lambda_p(t))v_z + \int_0^{\lambda'} \rho(\lambda, t) E_z(\vec{x}(\lambda, t)) v_z d\lambda. \quad (5.31)$$

The recorded output voltage signal waveform after going through the DAQ will be given by $V_{out}(t)$ in ADC. The voltage is determined by the convolution of the total current and the electronics full transfer function as shown in Equation (5.32).

$$V_{out}(t) = \tilde{G} \cdot I_{tot}(t) \otimes h(t) = \tilde{G} \cdot \int_{t_0}^t I_{tot}(t') \cdot h(t - t') dt'. \quad (5.32)$$

where I_{tot} is given by Equation (5.30), $h(t)$, from Equation (5.11), is the transfer function, which includes the conversion from current to voltage with the electronics components, t_0 is the initial time of the event, and $\tilde{G}$ is the gain of the electronics, as it will be explained in the next section, considering that $h(t)$ is normalized. $V_{out}(t)$ is the charge store on the feedback capacitor divided by the value of this capacitor at time t .

5.3 Parametrisation of the Signal Modelling

The model proposed from Equation (5.32) depends on the following parameters:

- Configuration of the detector: number of pads and their size; distance between the anode and cathode, $z = h$, which is the same distance between the pads and the initial position of the alpha particle track; the size of the field shaping rings (square of widths of w); the pressure of the isobutane gas, P . These numbers are fixed and do not vary on an event by event basis.

- Alpha particle conditions: the full trajectory travelled by the alpha particle can be defined by six numbers that represent the initial, $\vec{x}_i = (x_i, y_i, h)$, and final, $\vec{x}_f = (l \sin \theta \cos \phi, l \sin \theta \sin \phi, l \cos \theta)$, with l the track length, positions of the alpha track. The initial distance to the pads is defined by the distance between the pads and the radioactive source, as stated above. The other two initial positions, located at the cathode, are the two direction angles, inclination, θ , and azimuthal, ϕ , as shown in Figure 5.8, of the alpha track depend on each event, thus are floating parameters on an event by event basis. Finally the last number is represented by the track length, which is chosen using the initial alpha energy with the corresponding Bragg peak for the appropriated pressure of the isobutane gas.
- Drifts conditions: two effects are considered here, the electron loss and the drift velocity. The charge loss is modelled by an exponential decay parameterized by the electron lifetime, τ_e , as explained in Chapter 4 with 4.11, also referred to the purity of the gas or purity factor. The drift velocity, v , depends on the drift field and gas pressure but is constant for fixed field and pressure conditions. The values were initially obtained from the literature [48], and are set according to the run conditions.
- Electronics: the generated waveform depends on the electronics time constants verified in the previous section as well as on the electronics gain and the selected baseline. The evaluation of the baseline is performed using data before the start of signal, and the time constants do not vary, therefore these parameters were made constant in the model. On the other hand, because the electronics gain, G , is not determined, it is used as part of the estimator for the energy measurement. The $\tilde{G}$ in Equation (5.32) is a combination of the electronics gain, W -value, the conversion between voltage and ADC units, as well as potential fluctuations of

the measured energy of the event by event basis. This is proportional to the measured energy and is allowed to float in the model. This scaling factor will be used to find the energy resolution due to its proportionality to the event energy.

Figure 5.8: Graphical representation of the inclination, θ , and azimuthal, ϕ , angles. The inclination is the angle between the z axis, drift axis, and the $x - y$ plane (plane of the pads), while the azimuthal gives the direction in the $x - y$ plane. The cathode is located on the $x - y$ plane at $z = 0$, while the anode is located higher at $z = h$. The apparatus is actually a 180 degree rotation making the z -axis pointing down.

5.4 Checks of the Waveform Expectations

With the full model it is possible to fix all the parameters and plot the expected output signal waveform and verify the signal shape dependence of those parameters. The observed signals will be the sum of the induction, that happens once the charge is created and drifts down, and the direct collection convoluted with the electronics transfer function.

5.4.1 Single Pad Configuration

The expected signals were calculated for different purities (i.e. electron lifetime), electron drift velocities and distances, and alpha emission inclination angle. The

single pad is not sensible to the azimuthal and to the initial (x, y) position since the pad is fully contained inside the field shaping rings, thus those parameters do not affect the waveforms.

The first case studied here is having an alpha source at 100 mm from the anode at an inclination angle of 0.2 rad with the produced electrons travelling at $10.5 \text{ mm}/\mu\text{s}$ for different purity values. As seen in Figure 5.9 the height of the waveform is greatly affected as the purity goes down. The pulse height is dropped by 200 ADC by reducing the electron lifetime to $5 \mu\text{s}$ from 10^9 . The shapes are not affected, just the heights since the number of electrons drifting the whole distance will go down.

Figure 5.9: Expected signal waveform for different purity factor. The signal is reduced shifted as the purity lowers. This is expected since there is more electron loss at low purities.

Figure 5.10 shows the expected waveform for different alpha inclination angles at a drift distance of 40 mm with velocity fixed at $10.5 \text{ mm}/\mu\text{s}$, and very high purity

($10^9 \mu s$). The three angles are chosen to help understand how this parameter affects the signal. At an inclination of 0 rad, the charge density is facing downwards, this means that the tail of the bragg peak distribution shown in Figure 5.7, will be closer to the pads. At an inclination of $\frac{\pi}{2}$ rad the charge density distribution will be at the horizontal, parallel to the pad, and all the charges will drift down from the same distance, unlike at smaller angles where the drift distance varies according to the track length. Figure 5.11 is computed under the same conditions as the previous one except for a longer drift distance. Comparing the vertical and horizontal cases shows that the time for the maximum is shifted to the right. This is due to the track length of the alpha particle. When the alpha is emitted straight down, the induction is larger at early drift times than when it is emitted at the horizontal. The difference in height in Figure 5.10 is about 3%, while going down to 2% for Figure 5.11.

Figure 5.10: Expected signal waveform at different inclination angle for the emission of the alpha particle at a drift distance of 40 mm. The signal is shifted to the right at horizontal emission due to the fact that the electrons must travel a longer drift distance before being collected.

Figure 5.11: Expected signal waveform at different inclination angle for the emission of the alpha particle at a drift distance of 100 mm. The signal is shifted to the right at horizontal emission due to the fact that the electrons must travel a longer drift distance before being collected.

Changing the velocity changes the signal width. At lower drift velocities, the waveform should be more stretched out on the time scale since they take more time to drift down. This affect can be seen in Figure 5.12 for three velocities with a very high purity ($10^9\mu\text{s}$) and inclination angle of 0 rad. The waveform for the slower speed rises much slower than for the faster speeds. The total signal should give out the same charge and energy as it will be seen shortly, if there is no loss.

Figure 5.12: Expected signal waveform for different drift velocities. For the same drift distance, slower electrons will produce a wider but smaller in height signal compared to faster electrons.

The drift distance affects when the signal starts and ends. By giving a lower purity ($10^2 \mu s$), the effect of the distance can be seen. Figure 5.13 shows the expected waveform at different drift distances for this purity factor at a drift velocity of $10.5 \text{ mm}/\mu s$.

Figure 5.13: Expected signal waveform for different drift distance at a lower purity value ($10^2 \mu s$) and at a drift velocity of $10.5 \text{ mm}/\mu s$ to see the effect of the height on the signals. The signals are translated to the right due difference in drift distance.

By calculating the integrals of the collection and induction signals, the total charge can be determined. The following tables will give the ratio of the calculated charge observed for the collection and induction with the total charge expected which is related to the initial energy of the alpha particle, for similar signal sample waveforms shown above.

$\frac{Q_{col}}{Q_{tot}}$	$\frac{Q_{ind}}{Q_{tot}}$	Purity Factor (μs)
1.000	1.000	10^9
1.000	1.000	10^6
0.991	0.993	10^3
0.417	0.492	10^1

Table 5.2: Comparison of the collected and induced expected signals at different purity values for a drift distance of 100 mm, drift velocity of 15 mm/ μs , and inclination angle of 0.2 rad.

For the lower purity case, the induced charge is larger than the collected, as seen in table 5.2. This can be explained by the fact that at this distance the induction is more significant at early times. The impurities will capture the electrons as they drift down even after they already contributed to some induction. The collected signal is smaller since less electrons will reach the electrodes.

As mentioned whilst showing the signal waveform for different velocities, the total charge, and thus energy of the event, should not change even if it takes longer for the electrons to all drift down. Table 5.3 shows this. The value for the energy of the collected and induced signals are equal to each other and the total initial energy of the alpha giving a ratio of 1. These two are not added together since

it is the same electrons that induce signals and being collected afterwards. This follows the Ramo-Shockley theorem elaborated earlier. At this height of 100 mm, the contribution of the ions is too small to be seen since it is smaller than the actual numerical precision of the model.

$\frac{Q_{col}}{Q_{tot}}$	$\frac{Q_{ind}}{Q_{tot}}$	Velocity (mm/ μ s)
1.000	1.000	5
1.000	1.000	10
1.000	1.000	15

Table 5.3: Comparison of the collected and induced expected signals at different drift velocities values for a drift distance of 100 mm, high purity ($10^9\mu$ s), and inclination angle of 0.2 rad.

Since the ions also contribute to the induction, one could expect to see their contribution in the total energy of the event. They produce field lines in the opposite direction of the electrons thus reducing the total induction signal. This can be observed in table 5.4 for a series of drift distance while keeping all the rest constant and no loss due to impurities. As the drift distance increases, the total induced charge gets closer to the collected due to the fact that the ions are much further from the pad and will barely move to induce a current. This difference is negligible and is much smaller than the model's precision.

$\frac{Q_{col}}{Q_{tot}}$	$\frac{Q_{ind}}{Q_{tot}}$	Drift Distance (mm)
1.000	0.911	40
1.000	0.975	60
1.000	0.992	80
1.000	0.998	100
1.000	0.998	120
1.000	0.999	140

Table 5.4: Comparison of the collected and induced expected signals at different drift distances, drift velocity of 15 mm/ μ s, and purity of $10^9\mu$ s.

5.4.2 16 Pads Signals

For the 16 pads configuration, the expected signals can be different from the ones in the single pad configuration. Some pads will only see induction since the charge will not be collected on those pads. This means that with a noise free background, some, maybe small, induction should be seen on every pad. The pads close to those where there is electrons collection from the alpha track will observe larger induction. The pad, or few pads, that will observe the collection will have the largest signals. In this case, the initial x and y position as well as both angles will influence the waveform. The waveforms can be calculated and plotted, as done for the following example. Keeping in mind that the center of the figure is the $(0, 0, z)$ origin.

The event presented in Figure 5.14 is for an alpha at $(-0.7, 0.6, 120)$ position in mm and with angles of $(1.3, 3.14)$ in radians. It is emitted on top of pad number 5 and going towards pad number 10. Since the alpha is emitted at a big angle and

has a long drift distance to drift down, the collection is practically all on pad 10. The signal on pad 5 contains both collection and induction. The collection is seen from the fact that the negative part of the waveform is not equal to the positive like on induction only pads. By looking at the height of the nearby waveform induction signal, it can be seen that the closest the pads are to the event, the larger is the induction. This is seen in pad 9 where the height is around 10 ADC while for pad 6 the height is lower at 6 ADC. Another example can be seen while looking at pad 0 since it is the furthest from the collection and it has the smallest signal height.

Figure 5.14: Expected signal waveform for an event starting on top of pad number 6 and going towards pad number 11 with a long drift distance. The pad with the most collection signal is shown with the small dashes and the pad with both collection and induction signal is shown with the large dashes. The scale is different on most pads to clearly show the behaviour of the induction signals.

Chapter 6

Signal Data and Analysis

Data was acquired while varying the source location (i.e. the drift distance), D , gas pressure, P , and difference of potential, V . Table 6.1 summarises the choice for these values for both pads configurations. The bold values indicate the single pad configuration, while the underlined values are for the 16 pads configuration. Taking data at different tunable conditions can help understand the physics involved as well as the readout electronics and signal modelling. During the signal modelling and fitting, the different parameters of the model elaborated in the previous chapter are either fitted or fixed depending on the pad configuration. The distinction between these parameters will be made in the respective following sections. The initial energy of the alpha is fixed at 5.5 MeV but the fitting includes an energy scaling factor to which the resolution will come from. The pulse height resolution will also be used as an energy resolution estimator. These two estimators will then be qualitatively compared to each other for the two configurations. The electronics transfer function model found in the previous chapter is fixed and does not vary for the analysis done in this work. A baseline is fitted for every event by looking at the bin values of the first 200 time bin where no signal is observed. The fitted baseline to a zero-order polynomial is then removed from every data point to give a better sense of the ADC values measured by the DAQ. The chosen DAQ settings are shown below:

- Sampling Clock Frequency : 2.5 MHz
- Number of Sample (bins) : 512
- Time for one Bin : $0.4 \mu\text{s}$
- Bins After Trigger : 256
- High Threshold : 75 ADC ($1 \text{ ADC} \approx 0.8 \text{ mV}$)
- Low Threshold : 0 (Triggers on all other enabled channels)
- Number of Events : > 1000 (1 pad) / ≈ 500 (16 pads)
- Event Rate: $\approx 10/\text{s}$.

P	V	D	P	V	D	P	V	D
(bar)	(V)	(mm)	(bar)	(V)	(mm)	(bar)	(V)	(mm)
<u>1</u>	<u>4000</u>	<u>40</u>	<u>1.5</u>	<u>4000</u>	<u>40</u>	<u>2</u>	<u>4000</u>	<u>40</u>
	<u>6000</u>	<u>60</u>		<u>6000</u>	<u>60</u>		<u>6000</u>	<u>60</u>
	<u>8000</u>	<u>80</u>		<u>8000</u>	<u>80</u>		<u>8000</u>	<u>80</u>
		<u>100</u>			<u>100</u>			<u>100</u>
		120						
		140						

Table 6.1: Summary of the external fixable parameters chosen: P is for the chamber gas pressure, V is the applied voltage between the anode and the cathode, and D is the source position from the pads, i.e. the total drift distance. Signals were taken at each pressure and their associated voltages and drift distances. The bold values indicates the single pad configuration and while the underlined values are for the 16 pads configuration.

Two different masks were used to restrict the alpha track initial positions and directions, as well as to reduce the event rate such that it could be handled by the DAQ. Schematics of the masks are shown in Figure 6.1. The mask with the single hole was used for the single pad measurements, while the one with two holes for the 16 pads measurements. These masks both offer an reduced event rate from the alpha source. The second mask offers a collimation of the inclination angle of the alpha particle, as represented in Figure 6.2. The one sided arrows represent the alpha particle. If the alpha is emitted in the middle of the hole, the maximum emission angle that can go through the mask is 0.245 rad, and for the extreme case on the right, the maximum angle is 0.464 rad. At higher angles, the alpha will be greatly attenuated. Some attenuated alphas could go through and will give out signals with lower pulse height.

Figure 6.1: Different masks used to cover the radioactive source to reduce the event rate and act like a collimator.

Figure 6.2: Geometry of the collimator mask.

The holes of the second mask number are aligned directly between the middle pads as shown in Figure 6.3. The middle dot represents the center of the reference system, i.e. $(x, y) = (0, 0)$, and the empty circles the position of the holes. The hypotenuse of the triangle of the distance from the pad to the center of the hole and from the center of reference can be used to find the minimum allowed inclination angle using the track length of the alpha, which depends on the pressure as explained in Chapter 4. This angle is defined in Equation (6.1) and as the angle to send the alpha towards the corners of the pads. For 1, 1.5, and 2 bars pressure the possible expected angles are 0.05, 0.08, and 0.10 rad, respectively. These are well within the physical limits of the collimator. Another angle of interest is that if the alpha particle is directed towards to the closest corner of the closest pad. In this case, the distance 0.5 mm is replaced with $\sqrt{0.5^2 + 2.0^2}$ in Equation (6.1), which results in the following angles at the pressure mentioned above: 0.15, 0.23 and 0.30 rad. The azimuthal angle does not have any constrain and can be anything between 0 and 2π . Additional constrains for the event selection will be elaborated later in this chapter.

$$\psi = \arcsin\left(\frac{0.5}{Tracklength(Pressure)}\right) \quad (6.1)$$

Figure 6.3: Geometry of the holes over the pads zoomed in the middle region. The pads limits extend with the dashed lines.

6.1 Single Pad Configuration

Waveform traces were measured with the single pad configuration and the first mask. Figures 6.4 to 6.8 will show typical traces of events for different settings of external parameters. Figure 6.4 shows a typical event at 1 bar pressure, 6000 V and 40 mm drift distance. The peak represents the signal voltage measured over time. The signal starts as the electrons begin to drifting down to the anode by producing an induced current and ends at the peak where all the electrons have reached the anode. The fall of the signal is due to the relaxation of the feedback capacitor on the pre-amplifier. The noise on the signal is very high and could potentially affect the shape of the output voltage. Figure 6.5 zooms on the noise. The magnitude of this noise is up to 20 ADC output amplitude. Also, this noise possesses two types of frequencies. Some modifications and possible noise reduction apparatus such as a ground loop cancellation box, low noise electronics, and shorter leads, were implemented. Some

other uncontrollable environmental noise was picked up by the DAQ. This noise was found to be coming from the power supply and, especially, the CAEN DAQ system. Unfortunately, the noise was not suppressed and affects greatly some signals. In addition, a noise of this level hides any possible small undershoots following the signal.

Figure 6.6 shows a sample event for the same pressure and voltage but at 140 mm drift distance. The difference from the previous figure is that the event has a longer rise time due to the longer drift distance. This was seen in Section 5.4.1 while looking at expected waveform from the model. Figure 6.7 is for a pressure of 1 bar, 8000V and 40 mm drift distance. Same as for the 6000 V case, the signal rises quicker with shorter drift distance. This is due to the fact that the closer the electrons are to the pads, the larger is their contribution.

Figure 6.8 shows an event at 2 bars pressure. As it will be seen while looking at the pulse height distribution, the signals have smaller height values than the 1 bar cases. This is likely explained by the increase level of impurities inside the chamber as the pressure increases. In the event shown in Figure 6.8, the noise is around 13% of the maximum pulse height compared to 7% for the event shown in Figure 6.4.

Figure 6.4: Sample event at 1 bar pressure, 6000 V, and 40 mm drift distance.

Figure 6.5: Noise of a sample event at 1 bar pressure, 6000 V, and 40 mm drift distance. The noise level goes up to 20 ADC.

Figure 6.6: Sample event at 1 bar pressure, 6000 V, and 140 mm drift distance. The events at longer drift distances rises slower than the ones at short drift distances.

Figure 6.7: Sample event at 1 bar pressure, 8000 V, and 40 mm drift distance.

Figure 6.8: Sample event at 2 bars pressure, 8000 V, and 100 mm drift distance.

6.1.1 Average Waveform

One interesting thing to do, since the noise of a single waveform basis is not negligible, is to take the average waveform of all events in each run. This procedure reduces any random noise that is uncorrelated between events. On the other hand, it assumes that each waveform is measuring the same event although in reality, there are physical differences between events like the inclination angle and energy. Figures 6.9 through 6.12 show the averaged waveforms for different voltages, pressures, and drift distance, with low noise level. As expected while looking at the model, especially with Figure 5.13, having different drift distances changes the time when the signal rises.

Figure 6.9: Averaged waveforms at 8000 V and 1 bar for different drift distance.

Figure 6.10: Averaged waveforms at 6000 V and 1.5 bars for different drift distance.

Figure 6.11: Averaged waveforms at 8000 V and 1.5 bars for different drift distance.

Figure 6.12: Averaged waveforms at 8000 V and 2 bars for different drift distance.

As the previous Figures show, the height of the waveform goes down as the pressure increases which can be partially associated with a change of the drift velocity as seen with Figure 5.12. At 1.5 and 2 bars, it also goes down as the drift distance is increased. This indicates that the purity is probably low at these pressures compared to the 1 bar pressure. The level of impurities is proportional to the amount of gas introduced in the chamber. Therefore, as the pressure increases the amount of impurities also increases. At 1 bar, the height seems to stay the same as it should be since the height

varies on the number of charge directly measured and this number of produced charge should stay the same with a small possible statistical fluctuation. Even though the purity is verified to be good enough at 1 bar, for 1.5 and 2 bars it becomes significantly poor.

The Drift Velocities of Electrons

Another important feature that was pointed from the averaged graphs is the difference on where the waveform starts to rise. Being further from the detection pads, the induction signals are longer, therefore starts earlier to induce signal compared to shorter drift distance. The relaxation time part of the feedback capacitor, after the maximum where all the charge have been directly collected, the behaviours are all very similar as expected since it comes from the same, fixed, DAQ. This feature of the average waveform, enhanced by the reduced noise, can be used to measure the drift velocity of the electrons. The measurements can then be compared to the literature values shown in Chapter 4 with Figure 4.11.

The drift speed is obtained by looking at the time it takes for the last electron produced to reach the collection pad. In the waveform, this time is approximately the difference between the last bin where it crosses the baseline, before the signal starts to rise, and the bin where the pulse height is seen, which is near the end of the charge collection. Figure 6.13 represents that. A cubic spline is evaluated to interpolate the waveform between data points, since the DAQ is only sensible to $0.4 \mu\text{s}$. The full drift time is determined by subtracting the time of the maximum of the averaged waveform, to the first zero. The first zero is determined by the second vertical line and would represent when the event initial occurred while the time of the maximum is represented by the third vertical line. Due to the high noise, the first zero is an approximation and needs an error. The error chosen is taken by

calculating the time difference between the first and second zeroes, as shown with the two first vertical lines. This is a systematic error on the time due to the fact that the signal could have risen earlier or later due to the uncertainty created by the noise.

Figure 6.13: Region of interest to make the time measurement to determine the drifting velocity. The averaged of signals in one run is taken. By looking at the time difference of the time of the maximum and the first zero, where the event initially starts, the drift time can be determined.

The drift distance, d , is evaluated from the distance between the pad and the cathode, along with a correction based on the alpha track length, l . This correction is shown in Equation (6.2). The $\cos(\pi/4)$ approximates the emitted alpha angle for the average waveforms. Hence the chosen total drift distance, $\tilde{d}$, is:

$$\tilde{d} = d - \frac{l \cos(\frac{\pi}{4})}{2}. \quad (6.2)$$

The error is then estimated by dividing $\tilde{d}$ by two.

Using the measured time and the corrected drift distance, the velocity can be determined by:

$$v_{drift} = \frac{\tilde{d}}{t_{drift}}. \quad (6.3)$$

Figures 6.14, 6.15, and 6.16 shows the measured velocities with errors and a fitted mean value for 1 bar, 1.5 bars, and 2 bars pressure respectively for the different applied voltages and drift distances. The results at the same voltage and gas pressure are contained within error bars resulting in good χ^2/NDF values for the zero-order polynomial fit.

Figure 6.14: Calculated velocities values from the averaged waveform for different voltages and drift distances at 1 bar pressure with a simple constant fit.

Figure 6.15: Calculated velocities values from the averaged waveform for different voltages and drift distances at 1.5 bars pressure with a simple constant fit.

Figure 6.16: Calculated velocities values from the averaged waveform for different voltages and drift distances at 2 bars pressure with a simple constant fit.

The previous velocities results obtained are combined in Figure 6.17 with the E/p dependence for a better comparison. A linear fit is done for the calculated values to be able to compare it to the literature values from Chapter 4 ([48] and [49]). The shaded area corresponds to the one sigma region of the linear fit. Errors are determined by the propagation of the error on distance and time as explained earlier. The errors

are proportional to the applied voltage as the uncertainty on the time increases with the voltage. This is likely attributed to the noise of the power supply going up as the applied voltage is increased. In the end, the measured velocities shown in Figure 6.17, with the fitted linear equation of $v = 0.03(\pm 0.03) + 0.00256(\pm 0.00013)\frac{E}{p}$ with a χ^2/NDF of 44.35/47, agree with the values found in [48] and [49] (the black dots) in Figure 6.17 by being contained within 1 of the linear fit.

Figure 6.17: Calculated drift velocities values for all 1 pad runs. The black dots are the averaged values taken from literature shown in Chapter 4 ([48] and [49]). The bold line is the fitted first order polynomial of the calculated values with the one sigma shaded region.

Signal Undershoot

Event waveform traces do not present any visible undershoot following the signal peak. This is an evidence of the pole zero suppression discussed in Chapter 5. However, the average waveform shows evidence that an undershoot happens with a magnitude smaller than the noise levels observed in each event. Figures 6.18 and 6.19 show that there is a clear undershoot in the time window of the event. They also show that the noise becomes more important at high pressure. After the relaxation time of the pre-amplifier, the waveform tail does not return to zero, but in fact stays

below that baseline of 0. Although, the undershoot is not visible on an event to event basis because of the noise level, Figures 6.18 and 6.19 show that this effect would appear in measurements of the average electronics gain if the time window is not long enough. This undershoot can be explained if the resistor introduced for the pole zero suppression does not match the decay time of the pre-amplifier, in other words, if $e \neq d$ in Equation (5.5).

Figure 6.18: Undershoot of averaged waveforms at 1 bar and 8000 V. After the decay of the feedback capacitor, the signal does not fully recover to 0 in the time window chosen for the event recording.

Figure 6.19: Undershoot of averaged waveforms at 2 bars and 8000 V. The noise level is increased compared to the previous example but the undershoot is still visible.

6.1.2 Pulse Height

By looking at each maximum ADC counts of each waveform, also referred to as the waveform height, the pulse height distribution can be made. This is done by looking at each waveform individually, therefore on an event to event basis, and taking the maximum pulse height of the signal. Since the pulse height is proportional to the total energy of the event, the resolution of the pulse height is chosen as the energy resolution estimator here. This resolution is defined as the standard deviation of a fitted Gaussian distribution over its fitted mean.

Figures 6.20 and 6.21 show the pulse height distribution for 6000 and 8000 V, with drift distances of 40 and 100 mm, at 1 and 2 bars of pressure, respectively. They show that at 1 bar, the resolution is better (3.8%) and the mean pulse height is

larger than those measured at 2 bars (6.9%). As the pressure rises, long tails starts to form around the mean value due to the more probable less energetic events due to a loss of charge during the drifting phase.

Figure 6.20: Maximum pulse height distribution of events measured at 6000V, 40 mm, and 1 bar giving a resolution of 3.8%.

Figure 6.21: Maximum pulse height distribution of events measured at 8000V, 100 mm, and 2 bars giving a resolution of 6.9%.

Figure 6.22 shows the fitted mean of the pulse height distribution for all the

single pad configuration. The error bars are the sigma of the fitted Gaussian to the pulse height distribution. It can be seen that as the pressure rises, and especially for lower voltages, the pulse height reduces considerably. This is due to the probable impurities present inside the detector more than just a difference in velocity effect.

Figure 6.22: Fitted mean of the pulse height distribution for the single pad configuration events.

The resolution is calculated with the values from Figure 6.22. Figures 6.23, 6.24, and 6.25 show this resolution for the data set at 1, 1.5 and 2 bars, respectively. Two things can be taken from the previous Figures; the resolution goes down as the voltage goes up, while it goes up as the pressure rises. This effect was also observed by looking at Figures 6.20 and 6.21. The resolution at 40 mm in Figure 6.23 is higher than at the other drift distances. This could be due to the bigger inclination angle dependency at small drift distance as observed in Section 5.4.1. The charge distribution is orientated at the vertical for small inclination angles while being at the horizontal (large inclination angle) which changes the drift distance. This seems to affect the pulse height distribution unlike at long drift distances or when

the inclination angle is larger making the charge distribution towards the horizontal. If the charge distribution is at the horizontal, the charges will reach the pad at approximately the same time, unlike when it is at the vertical where the tail will reach the pad earlier due to the fact that it is closer. This effect seems to be negligible at higher pressure where the noise becomes more important.

Figure 6.23: Pulse height resolution from the fitted mean and sigma at 1 bar for different voltages

Figure 6.24: Pulse height resolution from the fitted mean and sigma at 1.5 bars for different voltages

Figure 6.25: Pulse height resolution from the fitted mean and sigma at 2 bars for different voltages

6.1.3 Energy Measurement with Signal Model

The model elaborated in the previous chapter was used to fit all events in order to obtain an improved measurement of the event energy. In this case, all parameters of the model were fixed: initial energy to 5.5 MeV, initial position to $(0,0,h)$ in mm with h the distance from the cathode to the anode, azimuthal angle to 0 rad, inclination angle to $\frac{\pi}{4}$ rad, electron lifetime to $10^5 \mu\text{s}$, and drift speed depends on the pressure and voltage of the data run and were determined in the previous section. Only the energy scaling factor ($\tilde{G}$) and the baseline were allowed to float for the single pad configuration. This energy scaling factor is used as the energy resolution estimator in the case of the fittings.

All the fits were performed by the minimization of a chi-square function with help of the MINUIT package implemented in the ROOT TMinuit class [2]. In every plot, the red curve, on the left, is the induction signal, the middle green curve is the collection, and the highest and on the right blue curve is the sum of the contribution the two previous ones. The blue curve increases as the charges are directly collected at the pad. The errors assigned to the data points are the RMS of the baseline calculated with the initial 200 time bins. A typical RMS distribution from the data can be seen with Figure 6.26. In this case, the mean RMS is 4.8 ADC, much larger than the electronics precision of 1 ADC.

Figure 6.26: Sample run RMS distribution for the first 200 bins for each event.

Figure 6.27: Sample event at 1 bar pressure, 6000 V, and 40 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figure 6.28: Sample event at 1 bar pressure, 6000 V, and 140 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figure 6.29: Sample event at 1 bar pressure, 8000 V, and 40 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figure 6.30: Sample event at 1 bar pressure, 8000 V, and 100 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figure 6.31: Sample event at 1.5 bars pressure, 6000 V, and 100 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figure 6.32: Sample event at 2 bars pressure, 8000 V, and 100 mm drift distance. The red curve is the induction, the green is the collection, and the blue is the sum of the two contributions.

Figures 6.27 through 6.32 show the fitted model over the data. At 1 bar, and small drift distances, the expected waveform appears to describe the data better than at higher pressures. The collection contribution on the other hand seems well represented over all the waveforms. In the last sample shown, the noise starts to dominate the induction part of the signal. The relaxation time, or the decay time of the electronics, always seems to overlay nicely described by the model especially since it is fixed and does not float in the model. No noise was implemented in the model for these analyses.

For long drift distances, at early drift times where only the induction contributes to the measured waveform, the model seems to underestimate the induced current. In the current model, it was assumed, with the Ramo-Shockley theorem, that every wall of the rectangular box is an electrode at zero potential, except the pad itself. However, in Chapter 4, it is shown that the pads are actually surrounded by an insulator. This means that the area around the pad is not actually grounded.

This could make some induced electrical field lines go through the insulator towards the pad and contribute to the differences between the model's expectation and the data. Also, the side of the box used in the model are again assumed to be a full conductor, while in the detector it is a set of rings that do not cover the whole length due to the spacing of the rings. At small drift distances compared to the size of the field shaping rings, this effect is small, but it is increased if the drift distance becomes comparable or larger than the size of the rings. A numerical calculation of the weighted field from the Ramo-Shockley theorem, considering the best knowledge of the detector geometry, was performed for the 1 pad configuration with 100 mm drift distance using SIMION [61]. The SIMION correction did not improve significantly the agreement between the data and the model, thus stating that the model is indeed a good approximation for the system in the inner region of the pad for this study.

The minimization procedure should be driven by the collection region of the waveform, where the largest ADC counts are observed. The charge induction only contributes significantly to a few points of the waveform due to the DAQ limitation. Figures 6.33 and 6.34 show the reduced chi-square distribution, χ^2/NDF with $NDF = 510$, from the fits for two different cases. Even though there is an underestimation of the induced charge, the model generally works well for fits of single events, better for short than long drift distances as shown previously.

Figure 6.33: Chi-square over the number of degree of freedom distribution for the 1 bar, 6000V, and 40 mm run.

Figure 6.34: Chi-square over the number of degree of freedom distribution for the 2 bars, 8000V, and 100 mm run.

The measured energy resolution is obtained in a procedure similar to the one done with the pulse height distribution. Using the distribution of the fitted energy scaling factor, which is proportional to the energy, the energy resolution can be determined by the standard deviation over the mean of a fitted Gaussian distribution. One example is shown at Figure 6.35. This is done similarly for the rest of the data sets. The resulting fitted mean and error are shown in Figure 6.36. Figures 6.37 through 6.39 give the resolution for each runs at different pressures, voltages, and drift

distances. For the best scenarios, the one 1 bar where the signal is less attenuated by the probable impurities, the energy resolution is up to a factor of 2 better than looking at the pulse height from Figures 6.23 to 6.25. In the case of 1 bar, the pulse height estimator gave a resolution of 3% to 5%, while the scaling factor estimator gave between 2% and 4%. For the 1.5 bars case, the pulse height resolution was between 4% and 7% and went down between 3% to 4% for the fitted resolution. Finally, for the 2 bars case, the resolution for the pulse height was between 7% and 9%, while for the fitted resolution was 4% to 6%. Overall, the fitted scaling factor energy resolution estimator gave better resolutions values than the pulse height energy resolution estimator. Similarly for the pulse height, the resolution at 40 mm is worst than for the other drift distances. In this case, since the inclination angle is not being fitted, the difference is therefore included within the energy scaling factor thus giving a larger spread for the fitted values. Again, this effect is negligible at higher pressures.

Figure 6.35: Fitted Gaussian over the fitted energy scaling factor values measured for the events at 1 bar, 6000 V and 40 mm.

Figure 6.36: Fitted Gaussian mean and error of the energy scaling factor for the single pad configuration.

Figure 6.37: Energy resolution for 1 bar at different voltages and drift distances.

Figure 6.38: Energy resolution for 1.5 bars at different voltages and drift distances.

Figure 6.39: Energy resolution for 2 bars at different voltages and drift distances.

6.2 16 Pads Configuration

The data taken with the 16 pads configuration is summarized in table 6.1. Each event contains 16 traces for each individual pads. The mask with the two holes from Figure 6.1 was placed over the alpha source to restrict its initial and final positions. In particular, the charge collection of these events will be contained in one of the

4 inner pads due to the angular restriction. The other 12 outer pads should only measure the associated induction signals. Moreover, the distribution of pulse heights on Figure 6.40 shows that the two pads on the left of the 4 inner pads present more charge collection than the ones on the right. This indicates an uniformity of the radioactive source. An event selection was made for the previous figure and will be explained in the following section.

Figure 6.40: Typical event distribution by looking at the maximum pulse height for the collection. It shows that the left side observes nearly 86% of the events.

Figure 6.41 shows a typical sample event seen by the pads. With the comparable pulse height of an event in the 1 pad configuration, it is most probable that the event

was emitted on top of the 10th pad, channel 9, and went straight down because only induction can be seen on the neighbouring pads and the collection is contained within one pad. By looking at channel 3, on the top right corner, which is the furthest pad from the signal, some small induction can be seen. Comparing this number with a similar event shown in Section 5.4.2, this shows that this pad sees roughly 10 times more induction than what is predicted. Since small changes in the event topology cannot account for such discrepancy this supports the evidences of an underestimation of induced charge by the signal modelling, as pointed out in the data analysis of the single pad configuration.

The discrete Fourier Transform, DFT, is applied on the waveforms to show the distribution of the frequencies and help identify which noise could have been picked up by the electronics. Figure 6.42 shows the DFT signal of the previous event. There is a clear peak of noise around bin 90 for most pads which corresponds to a noise of around 440 kHz. This peak is clear especially on low signal pads and was observed on most events. By looking at the data, this peak could possibly correspond to the bigger oscillation that is seen in the outer edge pads. This noise is at least in the same order of magnitude of the charge induction signal.

6.2.1 Pulse Height

The energy resolution can be measured in a similar manner to that pursued for the single pad configuration with the pulse height distribution. In order to select events where the full, or nearly full, collection occurs at one pad, the following cuts are applied: the ratio between the pulse height of the pad and the maximum pulse height, among all 16 channels, is chosen to be greater than 99%, and the ratio

Figure 6.41: Sample event coming from the left side hole and going straight down to channel 9 at 1 bar, 8000V and 100 mm.

Figure 6.42: DFT signal of the previous event. Shows significant noise within the data.

between the second largest and largest pulse heights are chosen to be below 20%. The choice of the 20% is a trade off between having enough statistics and rejecting events with charges collection in multiple pads. Therefore, the events that will remain will have a big direct collection on one pad and small induction signals on the other pads.

A sample distribution of the pulse heights is shown in Figure 6.43. Because of the low statistics, the shape not is fully consistent with a Gaussian distribution, but for the sakes of being consistent with the single pad results, a Gaussian was fitted. As seen in that example, the RMS and Sigma values are close to each other. A summary of the measured energy resolutions, for the 16 pads configuration, using the pulse height distributions, is shown in Figure 6.44. There is a significant worsening of this resolution compared to those obtained in a similar manner with 1 pad readout. The resolution is between 7% and 13% for all the different runs. The pulse height means are shown in Figure 6.45, and similarly to the single pad configuration, as the pressure rises, the pulse height drops significantly.

Figure 6.43: Pulse height distribution on the maximum collection pad for the 16 pads configuration for run at 1.5 bars, 8000 V, and 100 mm, fitted to a Gaussian distribution.

Figure 6.44: Pulse height resolution on the maximum collection pad for the 16 pads configuration.

Figure 6.45: Pulse height fitted mean for the 16 pads configuration.

6.2.2 Energy and Angles Measurements with the Signal Model

In the 16 pads configuration, the alpha direction angles (θ, ϕ) and the initial (x, y) position impact on the shape of the waveform traces. Therefore, unlike for the single pad configuration where only the energy scaling factor and baseline were floating, the emission angles are also floating in this configuration. However, the fits are very sensitive to the initial parameters, and the possible presence of local minima makes the minimization convergences procedure more difficult. Moreover, the fit of 16 waveform traces is more CPU intense providing an additional complication of the measurements using the signal model. To minimize the effects of the mis-model on the outer pads, only the 4 inner pads are considered in this analysis.

The same event selection applied on the analysis of the pulse height distribution is considered here. The initial parameters are set such that the alpha particle begins at the closest hole to the collection pad, and the track is directed towards the closest corner of that pad. Fitting failures, such as non-convergence or poor chi-square, reduces the already small number of good events to analyse. Hence, only the most relevant results are shown in the next sections, considering that for different conditions the results obtained were similar.

Results for 1 bar, 6000 V, and 100 mm

The event presented in Figure 6.46 shows all the 16 pads waveform to give a sense of how the fit works. The following ones will only show the 4 fitted inner pads. In principle, this is less powerful to constrain the model parameters. However, as it was discussed, it is valid to discard the outer pads to avoid border effects that are not properly modelled in the calculations. For this event, chan anynel 9 possess the

signal with the charge collection while the other three only observe induced charge signals. Another example, in the same configuration, is shown in Figure 6.47. In this event, the charges are collected by the 6th pad, which corresponds to the top left, and, again, only induction is seen on the other ones. In general, the pad with the collection is well fitted while the 3 inductions pads are underestimated by the model.

Figure 6.47: Sample fitted event with the alpha is most likely directed straight to the corner of the top left pad.

Figure 6.48 shows the distribution of the reduced chi-square, χ^2/NDF with $NDF = 2044$ since 4 pads are being fitted, for this configuration of parameters. This distribution is between 1 and 3 indicating reasonably good results. The distribution of the scaling factor from the fitted results, proportional to the energy, is shown in Figure 6.49. In this case, the energy resolution estimator is 11%. This is consistent, although a little worse, with the results of the energy resolution obtained using the pulse height distributions. This suggests that the imperfections of the model, combined with increased information about the alpha track positions, can degrade slightly more the energy measurements than if a simple approach, like the pulse

Figure 6.46: Sample fitted event with all the 16 pads with the fit is only performed on the four middle pads.

height, is used.

On the other hand, the model also provides values for the alpha track direction. Based on the event selection, the alpha direction angles are constrained to go towards the pad. The azimuthal angle, ϕ , for hitting the top left would be between 0.245 and 3.08 rad and for the bottom left pad between 3.20 and 6.04 rad when looking at an emission from the left side hole. These constraints are due to the geometry of the pad and the holes presented earlier in this chapter. The inclination angle, θ , should be around 0.2 rad. The correlation between the two fitted angles is shown in Figure 6.50. This figure also indicates the allowed angular region for the track if it ends over the collection pad with the region on the left being for the top left pad and the one on the right for the bottom left pad. This is also seen by dividing the Figure 6.50 into four to represent the results coming from the different pads. Figure 6.51 shows the angles distributions for each pads. As expected, the left pads observe the majority of the events. The majority of the inclination angles happens near the 0.2 rad. This is expected if the model bias the track towards the neighbouring pads to increase its expectation for the induced charge on these pads to get a better agreement with the data. Most of the angles are contained within the two allowed regions for the left side pads since that is where most of the signal is expected to be seen from. The ones outside could correspond to non-physical events since the inclination angle is well over the constraint due to the mask. The spaces between the regions are due to the space between the pads themselves.

Figure 6.48: Chi-squared over the number of degree of freedom distribution from the fitted results.

Figure 6.49: Energy scaling factor distribution from the fitted results with a simple Gaussian fit to find the possible resolution.

Figure 6.50: Angles distributions from the fitted results. It also shows the expected region for the angles by looking only at the left side pads. The left side box represents the top left pad, while the right box represents the bottom left pad.

Figure 6.51: Angles distributions from the fitted results for the different pads. It shows that a majority of events were selected on the left side.

Results for 1 bar, 6000 V, and 40 mm

Following a similar procedure of that done with the previous configuration, Figures 6.52 and 6.53 show the reduced chi-square distribution and the energy scaling factor distribution, respectively. In this case, the number of events is reduced mainly because of fit failures. The reduced chi-square results are similar to the previous case, but the energy resolution is even worse. Its distribution, however, does not encourage the drawing of any particular conclusion. Looking at the correlation of the angles with Figure 6.54 pursues the same bias as for the other events. Except in this case, most events are located towards the bottom pads and are all contained in the allowed regions but with a lower statistics compared to the previous example. A sample event is shown in Figure 6.55, where there is good agreement for the charge collection, but some underestimation of the induction for the two top pads.

Figure 6.52: Chi-squared over the number of degree of freedom distribution from the fitted results.

Figure 6.53: Energy scaling factor distribution from the fitted results. No fitting in this case due to the low statistics and large spread.

Figure 6.54: Angles distributions from the fitted results. It also shows the expected region for the angles with the data contained within its limits.

Figure 6.55: Sample fitted event. The alpha is most likely directed straight to the corner of the bottom left pad due to the high amplitude.

Results for 1.5 bars, 8000 V, and 100 mm

The reduce chi-squared, and energy scaling factor distribution are shown in Figures 6.56, and 6.57, respectively. In this case, with nearly the same number of events as the 1 bar, 6000 V, and 40 mm data, the energy resolution is 5%. The correlation between the fitted track angles can be seen in Figure 6.58. The fitted track direction is similar to that in Figure 6.50, although the bias towards small azimuthal angles, to compensate the underestimated induction, is more accentuated. A sample event shown in Figure 6.59 shows a good collection agreement but an overall underestimation of the induction, especially visible on the bottom right pad.

Figure 6.56: Chi-squared over the number of degree of freedom distribution from the fitted results.

Figure 6.57: Energy scaling factor distribution from the fitted results with a simple Gaussian fit to find the possible resolution.

Figure 6.58: Angles distributions from the fitted results. It also shows the expected region for the angles.

Figure 6.59: Sample fitted event. The alpha is most likely directed straight to the corner of the bottom left pad.

Fitting Summary

A summary of the values of the fitted parameters for all the events shown is available at the end of the chapter on table 6.2. The errors shown with the parameters are the errors returned by Minuit. The values of the angles seems to agree with the track direction of the alpha observed in the data.

χ^2	θ (rad)	ϕ (rad)
1.154	0.21 ± 0.06	5.14 ± 0.06
1.184	0.438 ± 0.004	1.178 ± 0.009
1.053	0.2368 ± 0.0017	5.691 ± 0.007
1.405	0.171 ± 0.004	5.397 ± 0.017
0.9579	0.177 ± 0.006	2.580 ± 0.014

Table 6.2: Summary of the fitted parameters for the fits shown.

Similar to the single pad configuration, the energy resolution was calculated with the fitted values. The results for selected runs are shown in Figure 6.60. Just like stated earlier in this section, the resolution did get worst from the fitted values, from 8% to 17%, compared to the fitted pulse height resolution, from 7% to 13%.

Figure 6.60: Energy resolution for selected runs for the 16 pads configuration. This resolution is worst than the one calculated for the pulse height.

Chapter 7

Conclusion

A small gas chamber was built, as shown in Chapter 4, and tested to measure, with two different conductive pads configurations, the charge induction and charge collection signals produced by the ionization of a gas due to the propagation of an alpha particle. The two readout pad configurations that were tested were: a single pad, and 16 pads array. These readout pads are sensitive to both the induction and collection signals and to the initial parameters of the ionization. The 16 pads configuration has a finer sensitivity to the initial positions and all angles of the emitted alpha particle than the single pad configuration due to the fact that only a selected few pads can see both induction and collection. The induction and collection model developed in Chapter 5 includes the contribution of both type of signals. In Chapter 6, The data was collected under various conditions and the model was fitted to obtain information of the energy and positions. The fitting of the model to the data ended up being non-trivial and challenging due to the problems encountered.

Using the induction signals to reconstruct events and to obtain the different physical information from the events is, as stated, not an easy and trivial task to do. Many experiments use a Frisch grid to deal with the induction signals, while the collection is dealt with second set of electrodes, due to the complexity behind

the charge induction signals. In particular a system where the charge induction, and collection, signals are at the same level as the electronics noise it creates not an ideal situation to make small scale measurements. The noise, as seen for the single pad configuration, could reach several ADC counts (several % from the pulse height) which is not ideal and limits the information that can be taken out of the signals. Even though a significant amount of time and effort were concentrated to reduce the noise, the overall reduction did not suppress the noise to a decent low level. This was seen on the waveforms on an event to event basis, especially at high pressure where the pulse heights were low. Since no electron avalanches are produced, the signals pulse height are comparable to the noise level. Having more charge to measure would increase the signal while keeping the noise at the same level. This could greatly help the energy resolution but it would alter the precision of the total energy deposition. Since charges are produce by secondary processes, the energy measure would be significantly different from the initial energy deposition done by the alpha particle. This could also alter reconstruction since what is measured is different from what is produced initially. The commercial readout electronics used seemed to pick up any noise around or even produced noise on itself. Noise reduction could also be done using some filtering methods; the problem with these methods is that by filtering out some noise, one can lose important information coming from the signals. This information loss could affect more the smaller induction signals that are required to reconstruct the full event on a multiple pads readout scheme. It would be interesting to try to filter out the noise peak observed in the 16 pads configuration in Section 6.2.1.

Another significant amount of time was given to understand and model the electronics waveform shaping with very limited initial knowledge about the electronic components of the DAQ. The developed electronics model produced satisfying results for the transfer function and the value of its parameters and also to the fitted events

observed.

A purifier was used to try and filter out any possible contaminant in the gas. It was clear by looking at the pulse height at different pressures that there was in fact some possible contamination inside the detector. This contamination could have come from outgassing of components or from the gas not being properly filtered out with the purifier. An improved purification system with gas recirculation would be desirable to assure a good quality of the ionization gas. Usually, isobutane is used as a quencher especially for electron avalanches that can occur under the right conditions. The gas could have quenched some of the electrons as they drifted down thus acting like impurities. Using a different, non-quenching gas, could help seeing a more constant pulse height at different pressure conditions.

It was noticed that the tested model underestimates the induction coming from the pads. This could have partially been caused by the fact that the area around the electrodes is an insulator and not a conductor. For the single pad configuration, since the pad was the only electrode at the anode, it could have absorbed all types of border effects which makes the modelling harder to perform. A modification that should be done to the detector package is to have as little as possible insulator region on the detector package. This outside electrode could absorb the borders effect and not affect as much the pad readout. The underestimation was clearly seen in the single pads fitted events at long drift distance. The induction with the model starts later and rises more quickly than in the data. The combined effect of the noise affecting the data and the model underestimating the induction is seen in those fitted events. The underestimation and noise effect is also seen in the 16 pads configuration where the noise can be at the same order of magnitude of the induction.

The fit seemed to have been mainly driven by the collection of the direct charges, thus being less accurate for the induction. It is possible that the fitting function had some local minima which can be very difficult to get rid of, as noticed during the analysis. As seen with the angular fitted distribution, some non-physical events with the inclination angle being larger than the mask allowance were preferred from the fit.

Electron drift velocities in isobutane were calculated with the single pad configuration. These velocities from the linear fit applied to them ended up consistent with errors from the averaged values found in the literature from Chapter 4, most within 1σ difference. Systematic errors were taken for the study of the drift velocities.

Even with all the issues stated above, energy resolution calculations were done with the two different estimators. In the single pad case, which is not sensitive to the initial parameters of the alpha particle other than height (z position), using the maximum pulse height distributions produced energy resolutions between 3% and 9%, while the energy scaling factor from fitting the model to the data yielded resolutions between 1.8% and 5.5%. This model improves the energy resolution compared to the pulse height measurements. While comparing the resolution in the 16 pads configuration, the resolution for the pulse height (7% to 13%) were at a similar level as for the fitted model energy resolution (8% to 17%).

The choice of the thick mask to collimate the alpha could have degraded the energy resolution even though its main purpose was to localise the event and being able to differentiate events from both holes. As seen in Chapter 6 by looking at the pulse height resolution for the single and 16 pads configuration, the single pad with a thin mask offers better resolutions.

Some angle distributions were made and seemed to agreed with the physical constrains of the detector. The fitted angles, as shown in the previous chapter, were mostly contained within the allowed regions with some edging tendencies for the azimuthal angle that can be explained by the fit trying to compensate for the underestimation of the charge induction on the neighbouring pads. For the inclination angle, most events were contained with the mask restriction and kept around 0.2 rad, which was expected because of the event selection.

It would be useful for the collaboration to pursue the study of this style of readout scheme especially since the analysis, done in this thesis, can not rule out this readout scheme. The ultimate response was not achieved due to the different challenges and difficulties observed with this experimental setup. Modifications would allow the response to be greatly improved, but these are beyond the scope of this thesis. None-the-less, progress towards a model including charge induction and direct charge collection signals was achieved. The model did improve, for the single pad configuration, the energy resolution compared to the pulse height analysis. The model also showed the different sensitivities between the two configurations. Finally, for the 16 pads configuration, the model was able to reconstruct some angular information contained within the physical constrains of the detector.

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