RICE UNIVERSITY

Experimental Setup for the Operation of Gas Electron Multipliers in Liquid-Gas Xenon Detectors.

by

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ABSTRACT

Experimental Setup for the Operation of Gas Electron Multipliers in Liquid-Gas Xenon Detectors.

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A setup for the realization of dual-phase experiments using xenon as the active medium in a radiation detector has been built. The setup consists of a gas purification system capable of achieving a purity of the gas in the ppb level and a chamber system consisting of an ionization chamber containing the sensitive elements and a cooling component used to reach cryogenic temperatures inside the chamber in the range of liquid xenon temperature. The main goal of the dual-phase experiments is the operation of gas electron multipliers (GEM) in a cryogenic environment similar to the conditions found in experiments aimed to detect the most promising candidate for dark matter, i.e. the lightest supersymmetric particle known as neutralino or WIMPS.
Acknowledgments

I want to thank all the people that I met during these 3 years I’ve spent at Rice; people both here and at home who one way or the other helped me to find a better way in my life.

I must give a very special recognition to my family that has supported me throughout the many things that have happened during this period of my life.

Thank you everyone.
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Chapter 1

Introduction.

1.1.- Dark Matter.

One of the grand cosmic mysteries today is the nature of “dark matter”. This name is given to a form of nonluminous matter whose presence is detected only by means of its gravitational interaction with other massive bodies. The first evidence of its existence was discovered in 1933 by Zwicky [1] when he observed that the radial velocities of eight galaxies in the Coma cluster had an unexpectedly large velocity dispersion ($\sigma = 1019 \pm 360$ km/s). He concluded from these observations that the mean density of the Coma cluster would have to be 400 times greater than that derived from luminous matter (the actual value is $\sim$50 times greater considering a more accurate value for the Hubble constant). Later it was found that other clusters, e.g. Virgo cluster presented the same anomaly in the velocity dispersions of its galaxies, arising great interest on the nature and properties of this extra component found in the galaxy clusters. Six years after Zwicky’s observations Babcock (1939) obtained long-slit spectra of the Andromeda galaxy, which showed that the outer regions of M 31 were rotating with an unexpectedly high velocity. With the years these type of observations of spiral galaxies rotation curves would become the most widely known evidence of dark matter and it was these observations that finally convinced the majority of astronomers that missing mass existed in the universe. From these curves it is evident
that a clear discrepancy with respect to Kepler's law for the orbital motions in the outer
limits exists.

\[ v^2 = \frac{M(r)G}{r} \quad \text{(Kepler's Law)} \] (1.1)

\( v \) is the orbital velocity, \( M(r) \) is the mass inside radius \( r \), \( G = 6.672 \times 10^{-11} \text{ m}^3/\text{kg s}^2 \) is the
gravitational constant. This feature is considered indicative of an invisible
component in the galaxy that provides the necessary mass to explain the flat profile in
the rotation curves.

Figure 1.1. Rotation curve for the spiral galaxy NGC 6503. The points are the measured
circular rotation velocities as a function of distance from the center of the galaxy. The dashed
and dotted curve are the contribution to the rotational velocity due to the observed disk and gas,
respectively, and the dot-dash curve is the contribution from the dark halo. [2].
There is other evidence for the existence of dark matter in addition to galactic dynamics such as the anisotropies in the cosmic microwave background (CMB); if the luminous matter were all that there was, the duration of the epoch of structure formation after the Big Bang would be very short, requiring fluctuations in the CMB which would be larger than those observed. From these structure formation simulations it is clearly suggested the need of dark matter in order to reproduce the structures we see in the universe today. Also Big Bang Nucleosynthesis (BBN) calculations suggests that the baryon density is too small ($\Omega_b \leq 0.04$ [3], where $\Omega_b$ is defined as $\Omega_b = \rho_b/\rho_c$, with $\rho_c$ = critical density) to account for the total matter existing in the Universe, this limit on the density of baryons indicates that most matter in the universe is dark and of non-baryonic nature. Although a neutrino species with a mass of 30 eV could provide the right dark matter density considering only particles from the Standard Model, N-body simulations of structure formation in a neutrino-dominated Universe do a poor job of reproducing the observed structure [3] due to the relativistic velocities that characterize these particle (hot dark matter). Also some of the latest result find an upper limit for neutrino mass of $v_m < 2.2$ eV [4]. (Here and in the following paragraphs masses are given in energy units from the relativistic relation $E = mc^2$)

Although dark matter has never been detected in the laboratory, particle physics offers a concrete model for non-baryonic dark matter. One of the two leading candidates from particle theory is a weakly interacting massive particle (WIMP), which may arise in supersymmetric or other extensions of the Standard Model [3], the other candidate is the axion. There are excellent reasons to expect that if low-energy supersymmetry exists in Nature, then dark matter should be composed of the lightest
superpartner or neutralino ($\chi$). An approximate solution to the Boltzmann equation, which determines the WIMP relic cosmological abundance, yields the following estimate for the current cosmological abundance of the WIMP [3]:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \left( 3 \times 10^{27} \text{ cm}^3 \text{ s}^{-1} / \langle \sigma v \rangle \right) \quad (1.2)$$

Where $h$ is the Hubble constant in units of 100 km/s Mpc (1 pc = 3.26 lyrs), $m_\chi$ is the mass of the neutralino, $n_\chi$ is the number density, $\rho_c$ is the critical density and $\langle \sigma v \rangle$ is the thermally averaged total cross section for the annihilation of neutralino and its antiparticle into lighter particles times their relative velocity. From this equation, WIMPs will have a cosmological abundance of order unity today if the annihilation cross section is roughly $10^{-9}$ cm$^2$. The value of the cross section in Eq. (1.2) needed to provide $\Omega_\chi \approx 1$ comes essentially from the age of the Universe. Curiously, this is the order of magnitude expected from a typical electroweak cross section. This "coincidence" of the cross section suggests that if a new stable massive particle with electroweak interactions exists, then it should have a relic density of order unity, with a mass of $m_\chi \approx 100$ GeV, and therefore provides a natural dark-matter candidate. This is the argument that drives the effort to detect WIMPs in the galactic halo.

The local dark matter density can be calculated by the application of Newton's laws to our galaxy. Considering that the galaxy is immersed in a nearly spherical dark matter halo, the density of this halo can be assumed to have a distribution somewhat like [3]:

$$\rho(r) = \rho_0 \left( r_0^2 + a^2 \right)/(r^2 + a^2) \quad (1.3)$$
where $r$ is the radius, $r_0 \approx 8.5$ kpc is our distance from the center, $a$ is the to be determined core radius of the halo, and $\rho_0$ is the local halo density. Such a halo would give rise to a rotation curve,

$$v^2(r) = 4\pi G \rho_0 (r_0^2 + a^2) [1 - (a/r)\tan^{-1}(a/r)]$$  \hspace{1cm} (1.4)

where $G$ is the Gravitational constant. If the rotation speeds contributed by the halo at two points are known, the local density of the halo and its core radius can be determined. Using these equations and the rotation curve results at large radii for the Milky Way it is found that the local dark matter density is $\rho_0 \approx 0.4 \text{ GeV}/c^2\text{cm}^3$ [3] and that the dark matter particles move with velocities comparable with the local solar system circular speed of $\sim 220 \text{ km/s}$.

Dark matter can be detected in one of two ways: directly or indirectly. Each detection involves detecting particles in the laboratory through scattering and collisions. Direct detection involves searches for the $\sim 10 \text{ keV}$ recoils produced by elastic scattering of neutralinos from nuclei in low-background detectors. The expected cross section for the elastic scattering of this particle from a nucleus is model-dependent, with typical values of $\sigma \sim 10^{-42} \text{ cm}^2$ [5]. Figure 1.2 shows the expected event rate, integrated above energy threshold, for Xe, Ge and S; it can be seen that xenon is the most favorable target for recoil energies in the range of $0 < E_r < 20 \text{ keV}$. The event rate has an inverse dependence on the masses of both, the neutralino and the target nucleus:

$$E_r \sim \rho_0 \sigma v / m_{\chi} m_N$$  \hspace{1cm} (1.5)

The main difficulty in these kind of experiments comes from the fact that the WIMP events are rare and there are many backgrounds that deposit similar amounts of energy on much more frequent time scales. On the other hand in indirect detection the
neutralino is never seen directly; the technique for its detection is the use of neutrino telescopes aimed to detect energetic muon neutrinos which are among the decay products of these particles as they annihilate in the center of the Sun, where they have been gravitationally bound after scattering elastically from a nucleus. The energies of these muons will be typically $\frac{1}{3} - \frac{1}{2}$ the neutralino mass so they will be much more energetic than ordinary solar neutrinos, i.e. they could be clearly identified [3].

![Graph](image)

Figure 1.2. Expected event rate, integrated above energy threshold, for Xe, Ge and S, for a 100 GeV WIMP with cross section $\sigma = 3.6 \times 10^{-42}$ cm$^2$, under standard assumptions of dark matter halo.
1.2.-Radiation Detectors.

All radiation detectors are based on the same fundamental principle: the transfer of a fraction or the total of the energy of an incident particle to the active medium in the detector where this energy is converted into a measurable signal.

Particles entering the detector transfer their energy through collisions with atomic electrons if they have a charge or if they are neutral by undergoing some sort of reaction both of which in turn ionize and excite the active medium atoms.

In the case of ionization detectors, as the one used in this project, the detector is designed to directly collect the ionization electrons on the anode to form an electric current signal which can be treated by electronic means.

The specific type of ionization detector used in this project is a gridded ionization chamber. This detector consists of a shielding grid, which is a metal mesh, placed between the cathode and the anode, and used to shield the anode from the electrons drifting in the grid-cathode region, this way allowing the electron signal to be induced only after the electrons have crossed the grid. The cathode is kept at a more negative potential with respect to the anode, and the grid is placed at an intermediate potential. A charge sensitive preamplifier is connected to the anode as the first stage on the electronic treatment of the signal.
Figure 1.3. Expected pulse shapes on the electrodes of a gridded ionization chamber.

The average energy required to produce an electron-ion pair depends on the medium used, this energy is usually denoted by “W”. In the case of gaseous xenon this value is equal to 22 eV per electron-ion pair and for liquid xenon it is found to be 15.6 eV per electron-ion pair [6]. The “W” value is important since it determines the energy resolution of the detector. The resolution for a particle of energy E is:

$$\Delta E = 2.35 \left( \frac{FW}{E} \right)^{1/2}$$  \hspace{1cm} (1.6)

Where F is the Fano factor of the gas, for liquid xenon it has a calculated value of $F = 0.04$ [7]. This factor is a function of all the various fundamental processes which can lead to an energy transfer in the medium, including reactions that do not lead to ionizations, for example, phonon excitations, etc. Theoretically, F is difficult to
calculate accurately as it requires a detailed knowledge of all the reactions which can take place in the medium.

Once ionization happens the electrons will be pulled to the anode and ions will be collected at the cathode. Since the mobility of ions is more than a factor of 1000 smaller than the mobility of electrons in LXe, only electron signals are usually used for measurement.

As electron-ion pairs are created in the detector it is of capital importance that electrons be separated from the ions and drift freely. There are two processes that hinder the life-time of free electrons: recombination and electron attachment.

The rate of recombinations can be represented by the equation:

\[ \frac{dn}{dt} = bn^-n^+ \]

(1.7)

where \( b \) is a constant dependent on the type of gas and \( n^+ \) and \( n^- \) are the ions and electron number densities. If \( n^+ = n^- \) the integration yields the result:

\[ n = n_0 / (1 + bn_0 t) \]

(1.8)

where \( n_0 \) is the initial ion density at \( t = 0 \).

*Electron attachment* involves the capture of free electrons by electronegative atoms to form negative ions. These atoms have an almost full outer electron shell so that the addition of an extra electron actually results in the release of energy making the resulting negative ion energetically stable. The energy released in this capture is known as the electron affinity. From this it is clear that the presence of any electronegative gases in the detector will severely diminish the efficiency of electron collection by trapping the electrons before they can reach the electrodes. Some well known electronegative gases are O\(_2\), H\(_2\)O, N\(_2\), CO\(_2\).
The way recombination and attachment of free electrons in ionization chambers is overcome is by the application of a high electric field between the electrodes so that the total field felt by the electrons is higher in the drift direction than between the ions and electrons resulting from the interaction, this high field will also give electrons enough energy to avoid attachment as can be seen in Figure 1.4. where attachment rate constants for oxygen, the most likely electronegative impurity to be found in LXe, and other impurities are plotted and it is clear that as the E field increases the attachment due to O₂ molecules decreases.

![Graph](image)

**Figure 1.4.** Attachment rate constants of impurity molecules in LXe [8]

Two phenomena related to the motion of electrons in the active medium are of particular importance: *diffusion* and *drift* in the applied electric field. The drift velocity of electrons determines the time response of detectors and their diffusion along their
tracks gives a limit to the accuracy in the case of X-Y position measurements. A plot for the value of drift velocities in liquid xenon is given in Figure 1.5. It can be seen that in the case of LXe this velocity is larger than in gas and has just small variations with respect to the E field applied in the volume compared to its steep increase in the case of gaseous xenon. For liquid xenon drift velocity for electrons is ~ 2 mm/μs under a field of ~ 1kV/cm. The phenomenon of diffusion in liquid xenon is very small compared to the ~ 1 mm x-y resolution that can be achieved by current high resolution readouts [9].

Figure 1.5. Drift velocity of electrons in liquid xenon. Plots for LXe and LAr are shown for comparison.
1.3.- Gas Electron Multiplier (GEM).

The gas electron multiplier is a novel structure used for charge amplification [10]. The active element of the GEM is a thin, self-supporting composite matrix of holes, realized by photolitographic methods. A thin insulating polymer foil (kapton), metalized with copper on each side is passivated with photo resist and exposed to light through a mask. After curing, the copper is patterned on both sides by acid etching and used as a self-aligning mask for the etching of the insulator, opening channels all the way through. The GEM used in this experiment was obtained from CERN and is a square mesh of 10 cm on each side, it has a copper layer on both faces and they are plated over a 50 μm kapton foil. The holes have a conical shape and diameters of 70 μm on the metal side and 50 μm at the kapton. The lattice has a pitch of 140 μm (Fig. 1.6).

![Image of GEM electrode]

Figure 1.6. Close view of a GEM electrode with holes 70 μm and pitch 140 μm.
Upon application of a suitable difference of potential between electrodes, with the mesh inserted between two plates at symmetric potentials, the electric field in a channel of the GEM develops as shown in Figure 1.7. For example, if the field applied on the electrodes is 200V the magnitude of the field along the central line reaches 40 kV/cm.

![Diagram](image)

Figure 1.7. Computed electric field in the multiplying channel. Only the central field lines have been plotted [11].

Due to the focusing effect of the field, full transfer efficiency for charge is obtained, also the high density of channels reduces distortions on the X-Y plane for the localization of the charge to values similar to the intrinsic spread due to diffusion in the gas. Focused by this high field inside the channels, electrons released by ionization in the drift region of the gas volume drift into the channels where they avalanche (Fig 1.8) i.e. the incoming charge is amplified in the channels and then it drifts towards the anode.
in the collection region. Ions generated during the avalanche drift process also drift along the central field lines, avoiding charging up problems.

GEMs have a variety of applications. Due to their construction they can be easily incorporated in other structures even with small mechanical tolerances, they are also very suitable for covering large areas. Its amplification properties can be exploited in any voltage-critical detector where the detection of minimum-ionizing particles is required or they can be used in multistage constructions which can give very high gains of the order of $10^4$ in three stage structures [12], similar to multigrid vacuum tubes, but with a structure substantially simpler and cheaper to manufacture. They are also suitable to be used as photomultipliers by covering one of the faces with a photocathode (e.g. CsI) and extracting the photoelectrons generated by incoming photons through the GEMs in order to have charge amplification.

![Diagram of GEM structure](image)

Figure 1.8. A scheme of the electric fields and electron paths and multiplication through GEM electrodes.
1.4.- XENON Project.

XENON is an experiment based on the use of liquid xenon as a novel technique for direct dark matter detection. The design is based on the use of scintillation and ionization signals detected simultaneously in order to achieve the detection and the needed background discrimination level of 99.5 %. XENON will consist of a 1-tonne active target distributed in an array of ten independent time projection chambers (Fig. 1.9). The projected sensitivity of this array is intended to be of 0.0001 events/kg/day, after 3 years of operation installed in the proper underground location.

As it was mentioned in Section 1.1, non-baryonic dark matter is searched mainly in the form of WIMPs (Weakly Interacting Massive Particles) or neutralinos. The direct detection of this particle is expected to be possible via elastic scattering of a WIMP on a suitable target.

Liquid xenon is an attractive target for this interaction. Table 1.1 shows the main physical properties of this element. Its high density of 3 g/cm³ and high atomic number; Z = 54, A = 131, make the Xe nucleus highly favorable for WIMP scalar interactions, the cross section for this interaction is proportional to A², allowing also for a compact detector geometry. As detector material liquid Xe has excellent ionization and scintillation properties. These properties permit the simultaneous measurement of charge and ionization together with the 3D position in a time projection chamber. This way the background identification and discrimination power is maximized while maintaining most of the target active. Besides Xe can be obtained from the atmosphere in large quantities at a reasonable cost.
Figure 1.9. The LXeTPC module for XENON. The 100 kg fiducial target is surrounded by an active LXe shield enclosed in a Cu vessel.

A difficulty to be overcome using xenon as the target material is the high degree of purity required. Various techniques have demonstrated the possibility of obtaining liquid xenon in which a lifetime above 1 ms can be achieved allowing for the drifting of electrons over 30 cm. Xenon has no long-lived radioisotopes, and krypton contamination (background radiation source) in natural xenon can be reduced to the required ppb (part per billion) level using distillation towers and cold traps.

Background discrimination in LXe is accomplished as follows. The elastic scattering of a WIMP with a Xe nucleus inside the active volume results in a low energy recoil that produces both ionization electrons and fast UV scintillation photons at 178 nm from the de-excitation to the ground state of the excited diatomic Xe molecules. The number of UV photons associated with direct Xe excitation by a
nuclear recoil is much larger than those emitted by an electron or gamma ray with the same kinetic energy. Also the number of electrons liberated by the recoil of the Xe nucleus is very small, even with a strong electric field applied in the liquid, this due to the fast (ps) recombination of the ionization electrons. Thus under a high electric field, a nuclear recoil will yield a very small charge signal and a much larger light signal compared to that of an electron recoil of the same energy.

\[(Q/L)_{\text{electron}} >> (Q/L)_{\text{recoil}}\]  \hspace{1cm} (1.9)

This difference in the charge/light ratio is the basis for nuclear recoil discrimination in a liquid xenon detector. The small charge signal involved is typically detected by using the electroluminescence process of the electrons extracted from the liquid to the gas phase where in the strong electric field around thin wires they induce proportional scintillation light. These photons are detected by using photomultiplier tubes. The biggest challenge of the project is the detection of both the charge and light signals with high efficiency down to the lowest possible energy threshold.

The basic design of the XENON TPC for dark matter consists of an array of PMTs placed above the liquid-gas interface used to detect the primary UV photons. To increase the solid angle and thus the detection efficiency, a CsI photocathode is deposited on the bottom plate to convert downwards heading photons into photoelectrons. The efficient extraction of photoelectrons from CsI in liquid noble gases has been demonstrated [5]. To further increase the primary light collection efficiency and consequently the detector energy threshold, the TPC walls are made of Teflon which has about 90% diffuse reflectivity at 178 nm. At the liquid-gas interface, the charges are extracted into the gas phase and are detected via the proportional
scintillation signal induced around the wires of a grid placed in front of the PMTs, Figure 1.10.

Figure 1.10. The LXeTPC module for XENON and WIMP scatter interaction with Xe nucleus.

Using this setting, the discrimination of background events can be done by looking for signals with the timing scheme shown schematically in Figure 1.11. The first is the prompt scintillation signal detected directly by the PMTs. The last is the proportional scintillation signal form the CsI photoelectrons drifting the entire liquid gap. These two signals are separated by the maximum drift time that in this case is of 150 μs for the 30 cm drift gap of the TPC. The proportional scintillation signal from the drift of ionization electrons can occur anywhere in between these two. The difference in arrival time between the second signal and either the primary or the tertiary signal measures the interaction depth of the event, meanwhile since the electron diffusion in LXe is small, the proportional scintillation pulse is produced in a small spot with the
same X-Y coordinates as the interaction site allowing for the full 3D localization of the events to about 1 cm precision in x-y, and ~1 mm precision in z.

![Diagram showing shaped light profiles from an electron recoil (top) and nuclear recoil (bottom) in the XENON LXeTPC.](image)

Figure 1.11. Shaped light profiles from an electron recoil (top) and nuclear recoil (bottom) in the XENON LXeTPC.

This thesis deals with research related to an alternate read-out scheme that substitutes the photomultiplier tubes and the grid structure by Gas Electron Multipliers(GEM). Rather than converting the charge signals into light signals, a three GEM structure in the gas volume on top of the liquid (Fig. 1.12) is used to amplify the charges resulting from the ionizations in the active volume and from the photoelectrons from the CsI photocathode on the bottom of the chamber; these charges are to be read on a 2D strip anode. For the conversion of primary scintillation photons, the lowest GEM can be coated with CsI. Recent results of multi-GEM structures coated with CsI have shown an excellent performance of this construction as a gas avalanche photomultiplier [5]. This construction has the advantage of its compactness, its low
intrinsic radioactivity compared to PMTs, its high efficiency and high spatial resolution besides having a tested performance in large scale applications as COMPASS, HERA-B.[9].

Figure 1.12. GEM implementation in the XENON detector.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Number</td>
<td>54</td>
</tr>
<tr>
<td>Atomic Weight</td>
<td>131</td>
</tr>
<tr>
<td>Electron Configuration</td>
<td>[Kr] 5s^2 4d^10 5p^6</td>
</tr>
<tr>
<td>Melting Point</td>
<td>-111.8 °C</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>-108.1 °C</td>
</tr>
<tr>
<td>Liquid Density</td>
<td>3 g/cm³</td>
</tr>
<tr>
<td>Gas Density (1 bar)</td>
<td>0.0055 g/cm³</td>
</tr>
<tr>
<td>Latent Heat Of Vaporization</td>
<td>96.29 KJ/kg</td>
</tr>
<tr>
<td>Latent Heat Of Fusion</td>
<td>17.6 KJ/kg</td>
</tr>
<tr>
<td>Heat Capacity Cₚ (1 bar, 21°C)</td>
<td>0.035 KJ/mol °K</td>
</tr>
<tr>
<td>Heat Capacity Cᵥ (1 bar, 21°C)</td>
<td>0.012 KJ/mol °K</td>
</tr>
<tr>
<td>Pressure At -108 °C</td>
<td>1 bar</td>
</tr>
</tbody>
</table>

Table 1.1. Xenon physical properties.
Chapter 2

Xenon Purification System.

2.1. Purification System.

It has been mentioned earlier that in order for an ionization detector to efficiently collect the charge created in the active medium by the incident radiation it is of capital importance, especially in the case of liquid xenon, to eliminate the electronegative impurities (O₂, H₂O, N₂, etc.) from the gas. This implies the need of a flexible and efficient gas purification and handling system capable of reaching the high level of purity required for the proper functioning of the detector.

In general it has been found that LXe is harder to purify than other noble gases as LAr or LKr. This is probably due to the different condensation temperatures and different attachment cross-sections to impurity molecules. For a detector with a drift gap of a few cm or more the purity (O₂ equivalent) of the LXe must be in the part per billion (ppb) level in order to keep the lost charge in the range of only a few percent along the drift path. In this project we have developed a system capable of purifying xenon at a rate of 1.8 kg/hour by the use of a “hot getter” and a whole stainless steel construction of the flow lines. The system is shown schematically in Figure 2.1.

The main component of the purification system is a “hot getter” (SAES) capable of reaching concentrations of electronegative impurities of less than 1 ppb (O₂). The getter works by the principle of adsorption. This means that the getter materials
irreversibly trap the gaseous molecules of the contaminants on their surface. An especial characteristic of the “hot getter” is that when this is heated (350°C to 400°C) the impurities diffuse into the bulk of the materials, giving this type of getter superior capacities and longer impurities life times over those working at room temperatures and which adsorb the molecules only on the surface.

![Figure 2.1 Purification system schematics](image-url)

Other components of the system are two high pressure cylinders made of stainless steel for the storage of the Xe gas. They have an internal volume of 3.7 L and are rated at ~124 bar. They are joined to the getter by a circuit of SS (stainless steel) pipes (1/4") that were specially cleaned in order to avoid the contamination of the circulating gas. The cleaning procedure was as follows: first the pipes were blown with
high pressure air to get rid of dust and other big particles, next each of them was washed using hot water and soap. After this step the pipes were cleaned immersing them for 1 hour in an ultrasonic cleaner in order to get rid of all traces of organic contaminants (e.g. grease). Once this step was completed they were rinsed again with water and then immersed in an alcohol bath. As a final step the pipes were rinsed with deionized water and finally blown with argon and kept inside a clean room.

The need for extreme purity in the gas system requires that the pipes are joined by using fittings capable of reaching pressures in the ultrahigh vacuum levels. The industry standard used for these requirements are the VCR (Swagelok®) fittings. They offer the high purity of a metal-to-metal seal providing leak-tight service from vacuum to positive pressure along with a minimal clearance requirement for removal. The seal on a VCR assembly is made when a SS gasket is compressed by two beads during the engagement of a male nut or body hex and a female nut.

The purification system is divided in two sections: a high pressure (≤ 68 bar) and a low pressure (≤ 5 bar) section. In the high pressure section there is, in addition to the gas cylinders, four bellows-sealed valves rated for pressures up to 172 bar. A two-stage regulator with a SS construction was used for connecting this section to the low pressure part of the system where there are 10 valves, also bellows-sealed type but with a lower pressure rating (35 bar). Two of these valves are metering valves used to regulate the flow of the gas through the system.

Two more components of the purification system are one flowmeter for mass flow measurement and one ion gauge for pressure measurement. The flowmeter is a Hastings Metaline 300 series designed for high purity service (all wetted parts made of
SS and VCR fittings) and with an accuracy better than ± 0.75% of full-scale for 0.005 to 5 slpm (standard liters per minute). This instrument is specially calibrated for xenon flow use.

The ion gauge used in the gas system is a Hot Ion Combination gauge that combines a Bayard Alpert ionization measurement system for \( P < 2.0 \times 10^{-2} \) mbar and a Pirani measurement system for \( P > 5.5 \times 10^{-3} \) mbar. This result in a continuous measurement of pressure from \( 5 \times 10^{-10} \) to 1000 mbar. Bayard Alpert gauges have heated filaments biased to give thermoionic electrons of \( \sim 70 \text{eV} \), energetic enough to ionize any residual gas molecules with which they collide. The positive ions formed move to an ion collector held at \( \sim -150 \text{V} \). The current varies with the gas number density, which in turn is a direct measurement of gas pressure. Pirani gauges have two filaments made of platinum that are used as two arms of a Wheatstone bridge. The reference filament is immersed in a fixed-gas pressure while the measurement filament is exposed to the system gas. Both filaments are heated by a current but maintaining the reference filament at a constant temperature. As the gas molecules hit the immersed element, they take energy away which is detected and replaced by the feedback circuit to the power supply. The amount of energy taken away depends on the density of the gas and this allows for an accurate calculation of pressure.
Figure 2.2. This image shows the front of the purification system. The turbopump is on the left.

A very important component for the purification system, as well as for the chamber, is the pumping station. This station consists of an EcoDry M 15 (Leybold) oil free compressing vacuum pump used as a fore pump, with an ultimate pressure rating of $3 \times 10^{-2}$ mbar. This pump is connected to a turbo pump, TURBOVAC TW 300H (Leybold), with pumping speed of 160 l/s (H$_2$) and an ultimate pressure of $2 \times 10^{-10}$ mbar. These pumps are operated by a TurboSystem controller from Leybold.
2.2.- Purification Process.

Once the whole purification system was assembled the first step was to test for leaks using a Residual Gas Analyzer (RGA) unit with helium as the tracer gas. All the pipes and components connections were checked using this method and after fixing some that were found to be leaking, the gas system was declared leak free and prepared to be baked at 200°C for a number of days. The baking is done using heating tape around the pipes and valves and wrapping the system with glass fiber insulation and aluminum foil as the outer layer. Special care was taken with the flowmeter electronics, removing most of the sensible parts and insuring the proper cooling of the rest of the electronics (high temperature limit of 70°C) that could not be removed. After approx. two weeks of baking and pumping the pressure in the gas system reached the 10^{-7} mbar range.

The purification of the xenon gas is done by transferring the gas from one cylinder to the other through the getter at a maximum rate of ~5 slpm many times in order to get the best possible purity. The transferring is done by "cryogenic pumping"; this means that the empty cylinder is frozen by immersing it inside a dewar full of liquid nitrogen (LN), this causes the molecules inside this cylinder to lose their energy to the frozen walls creating a vacuum that "sucks" the gas molecules from the other cylinder that is at room temperature. Once the frozen cylinder fills up with all the gas, it is taken out of the dewar and the process is reversed as many times as needed. The amount of mass inside each cylinder is controlled with good accuracy by using two weight transducers coupled to each of them.
Figure 2.2. Cylinder being immersed in liquid nitrogen during the transfer process.
Chapter 3

Chamber Description.

3.1.- Chamber Materials and Construction.

The sensitive component of the experimental setup is the vacuum chamber to be used as an ionization detector. The chamber system as a whole has two elements that allow its proper functioning in a double phase Xe experiment, they are: a stainless steel container filled with the active medium and a cooling system used to maintain the temperature of the xenon in the proper range (-108°C to -110°C), with its main element being a big dewar. The flange on top of the vessel has five ports; four are used for the installation of signal and power feedthroughs and one in the center is used as the filling and pumping port of the chamber. All the flanges used are ConFlat (CF) flanges rated for UHV applications. A copper “cold finger” with a base made of the same material is soldered to the bottom of the chamber, its function is to conduct heat from the chamber while the “finger” is partially immersed in liquid nitrogen. The filling port is connected to a CF cross with one of its ports used for the attachment of a Bayard-Alpert ion gauge, a second one connects to the filling line, via a CF-VCR hybrid adaptor (Fig.3.1). The filling line forms a coil inside the dewar, to allow for a pre-cooling stage of the xenon gas, making the filling and liquefaction faster. The third port goes directly to a bellows used to prevent excessive thermal stress on the CF flanges in the pumping line. Our first experience with a rigid tube showed that small leaks opened by excessive stress
due to the frequent large changes in temperature to which the chamber has to be exposed. This bellows is attached on its other end to a second flange that serves as the cover of the dewar being used to cool down the chamber to liquid xenon temperatures.

The dewar’s flange has a CF port in its center on both sides, this is the port used for the pumping line with the bellows in the inside and an angle valve on the outside (Fig 3.2.). Additionally to this port there are also six KF (kwik flange) ports on this flange. As a part of the cooling system the chamber has two thermocouples attached to its side and bottom to monitor temperature, it also has three heating pads of 25 Watts each on the bottom and two heating bands of 12 Watts each on the side which allow us to control the temperature in the chamber. All the connection cables for these components go through one of the KF ports. Two of the other ports are used for passing one high voltage cable that connects to the cathode, the cable from the ion gauge and the signal cables from the chamber. Additionally one of the ports is used for the attachment of a liquid nitrogen level sensor. This is a capacitance-based sensor as part of an auto filling system with a solenoid valve and process controller. Of the two remaining ports one is used to insert the radioactive source and the other is used to attach a multi-feedthrough with two VCR fittings on the air and on the “vacuum” side. Here is where the filling line coming from the gas system is connected to the chamber together with a pressure sensor which monitors the xenon pressure inside the chamber. There are two purposes for having this sensor; one is for monitoring the evolution of LXe towards thermodynamic equilibrium and the other is avoiding the danger of an overpressure that could cause a major leak, it has a range from 0 to 7 bar (Fig. 3.2.). We consider our danger zone above 3 bar.
Figure 3.1. Chamber close view. The filling coil, bellows connection and ion gauge cable can be seen on this picture.
Figure 3.2. View of the dewar used for the cooling of the chamber. Other components can also be seen as the filling line from the gas system, the angle valve in the pumping line, the pressure transducer, the liquid nitrogen filling line and the upper part of the LN level sensor.

3.2.- Inside Construction.

The main criteria used for the inside construction of the chamber was based on various requirements: the cleanliness of the components, the stiffness of a construction capable of holding a stretched GEM with its frame, together with the electrodes and meshes and the ability of withstanding frequent thermal cycles with temperatures ranging from ~ 200 °C to ~ -110 °C. The most obvious and easy choice of a construction material was for the electrodes as they can be made of stainless steel. The
meshes used are made of nickel as well as their frames. Both of these metals are widely demonstrated as being appropriate for their use in UHV and cryogenic applications. The rest of the construction needed to be made of some dielectric material in order to have a minimum distortion of the electric field between the electrodes together with the proper insulation of these components. According to M. Capeans [13] and the list of low outgassing materials found in his article we decided that the high performance thermoplastic, PEEK (Polymethylketone) was a good choice for the material to be used in our construction. It has a low outgassing rate, high temperature resistance and it is even sturdy enough to be machined for screws or threaded rods. It is not as soft as PTFE which is a commonly used material in liquid xenon experiments, and it is less brittle than machinable ceramics such as MACOR.

Figure 3.3. Close view of the chamber’s inside construction in one of its configurations. There are two “star” shaped frames made of PEEK, the electrodes and two meshes with its frames. The whole construction is held from the flange by three PEEK threaded rods.
The chamber's interior was designed such that it could have various configurations (Fig. 3.3-3.4) but in general it consists of two PEEK structures, two electrodes, one or two guarding rings, two electroformed meshes and a GEM with a stainless steel frame. The PEEK structures have a shape with three arms and a central ring (Fig. 3.3.), one is placed on the bottom and the other on top of the structure. The piece on the bottom holds the cathode and its guarding ring and the one on the top is used to hold a segmented anode. Around the ring of the bottom PEEK structure there are three threaded rods that together with the use of nuts keep the cathode fixed to the structure and also hold the two meshes at their corresponding heights above the cathode. Each mesh is stretched by the use of a nickel ring with two matching pieces which by joining them with the mesh in between stretch it in an evenly way and serve as a frame for each of the meshes (Fig. 3.5). The anode consists of three pieces; they are a central disk, a ring anode and a guarding ring, being all of them held from the upper PEEK structure using screws.

Figure 3.4. Close view of the chamber's inside construction in a configuration with a GEM included in the structure.
Figure 3.5. Schematic of the type of rings used to hold and stretch the nickel meshes.

In the case of the GEM the method used to stretch it is similar to the one used for the meshes. It also consists of having a ring with two mating pieces press the GEM on both sides such that it gets evenly stretched. At the beginning our first choice for the material to be used for this ring was PEEK. Apart from its good characteristics that make it suitable for UHV use, it is a dielectric making the insulation of the two electrode faces of the stretched GEM straightforward. We followed this line and designed a PEEK frame that at room temperature and with its two pieces joined by PEEK screws gave a very good stretching. The tests of the frame stretching capabilities were done with a kapton (Polyimide) foil which is the same material from which GEMs
are fabricated so we didn’t have to spoil the few GEMs we had available. After testing at room temperature the frame was tested at cryogenic temperatures hanging it from a canopy inside a dewar partially filled with liquid nitrogen. We observed that after reaching a temperature below $-90 \, ^{\circ}\text{C}$ the kapton foil started to show wrinkles as it is shown in Figure 3.6.

![Figure 3.6. View of a Kapton foil being tested at low temperature (~ -110°C) with a PEEK frame. It is evident that wrinkles appear on the surface of the foil due to thermal stresses.](image)

Because the experiment requires the GEM to be evenly stretched in order to have the more uniform field possible in the collection region we had to discard PEEK as the material for the frame and look for a different material which could be a better match for kapton thermal expansion coefficient (Table 3.1).
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>COEFF. THERMAL EXPANSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton (Polyimide)</td>
<td>$20 \times 10^{-6}\degree\text{C}$</td>
</tr>
<tr>
<td>PEEK</td>
<td>$46 \times 10^{-6}\degree\text{C}$</td>
</tr>
<tr>
<td>Stainless Steel (304)</td>
<td>$17 \times 10^{-6}\degree\text{C}$</td>
</tr>
</tbody>
</table>

Table 3.1. Comparison of the thermal linear expansion coefficients for the three materials involved in the handling of GEMs.

Stainless steel is a very good thermal match for kapton but in a first approach it has the inconvenient property of being a conductor, so the electrical insulation of the GEM electrodes becomes an important issue. Considering that GEMs are made of a thin kapton foil capable of withstanding up to 700 V between the two copper faces [14] we thought that we could use its insulation properties with a SS frame (Fig. 3.7). The two metal rings forming the frame would be separated by the insulation foil from the GEM itself and the two rings would be joined by the same PEEK screws used before to insure the maximum insulation possible through the holes on the frame. The holes for the screws in the kapton foil had to be punched very carefully such that the metal surface of the ring was always properly insulated by the kapton foil.
Figure 3.7. Schematic of the stainless steel frame used to stretch and hold the GEM.

This frame was tested again at cryogenic temperatures using the same method as for the PEEK frame. This time the frame behaved very well maintaining the kapton foil stretched without losing the tension it had at room temperature. After this result the frame was also tested at high temperatures up to 170 °C and the results were also very good with no effect of the heating on the stretching capabilities of the frame. Considering the good results obtained with this frame we also tested it directly on a GEM to be sure of its good properties and the results were equally satisfactory (Fig 3.8).
Figure 3.8. View of a GEM and its stainless steel frame being tested at low temperatures (-110 °C). There are no signals of wrinkles on its surface.

After the thermal testing, the frame, with the GEM stretched, was tested for sparks or leakage currents. This was done with the help of a multimeter capable of measuring currents down to the 100nA level and a high voltage supply with an argon atmosphere surrounding the GEM (Fig. 3.10). The voltage was taken up to 700 V a number of times while the current was monitored with the multimeter and no leakage current or discharges were measured on the GEM.

Once the testing of the GEM was completed it was fixed to the PEEK structure inside the chamber (Fig. 3.9-3.10) using the same rods that are used to hold the whole structure from the top flange of the chamber. All the components of the construction are held at their respective heights with respect to the cathode by nuts. The copper wires are connected to the pins of the feedthroughs by push on connectors and they are connected by crimping to their respective components. Soldering is avoided completely to reduce the contaminants in liquid xenon.
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel Height</td>
<td>8.2 cm</td>
</tr>
<tr>
<td>Vessel Diameter</td>
<td>20.0 cm</td>
</tr>
<tr>
<td>PEEK Structure Diameter</td>
<td>16.6 cm</td>
</tr>
<tr>
<td>Cathode Diameter</td>
<td>5.8 cm</td>
</tr>
<tr>
<td>Mesh Ring Diameter</td>
<td>5.8 cm</td>
</tr>
<tr>
<td>GEM Frame Diameter</td>
<td>16.47 cm</td>
</tr>
</tbody>
</table>

Table 3.2. Chamber and its internal components dimensions.

Figure 3.9. Schematic of the chamber interior. The PEEK structure with the electrodes and GEMs hangs from the top flange.
Figure 3.10. View of the set up for the electric testing of the GEM and its frame. The GEM is inside an enclosure filled with an argon atmosphere.

Figure 3.11. The chamber interior shown together with the outside construction.
Chapter 4

Experiment.

4.1. – Electronics.

The chamber was designed with four ports on top to attach signal and high-voltage feedthroughs used to read the charge signals collected and to apply the bias voltages on the electrodes. In our initial setting the four feedthroughs installed were:

<table>
<thead>
<tr>
<th>Feedthrough</th>
<th>Properties</th>
<th>Max. Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-PIN</td>
<td>Signal</td>
<td>700 V</td>
</tr>
<tr>
<td>7-PIN</td>
<td>High Voltage-Signal</td>
<td>12 KV</td>
</tr>
<tr>
<td>1-PIN</td>
<td>High Voltage</td>
<td>20 KV</td>
</tr>
<tr>
<td>10-PIN</td>
<td>Signal</td>
<td>700 V</td>
</tr>
</tbody>
</table>

Table 4.1. Initial feedthrough configuration used and their characteristics.

All of them have their own connector; cables were specially made for each of them, except for the 10-PIN feedthrough that was left disconnected. The 4-PIN feedthrough has two cables with BNC connectors that are mainly used for the grounding of the guard rings used in one of the configurations, the other two cables have SHV connectors rated at 5 KV and are used to read the signal from the segmented anode in one configuration and from one of the meshes in another configuration. For the 7-PIN feedthrough, 7 RG59 B/U coaxial cables (75Ω impedance) with SHV
connectors on each of them were connected to each pin. These pins serve for the connection of the two GEM electrodes when this element is installed, and also for connection to the meshes. The 20 KV (Reynolds) connector is used to feed high voltage to the cathode.

High voltage is applied from two different sources. The cathode is connected to a H.V. power supply (Mod. MP 15, Spellman) designed to produce a high quality dc output (150 mV p-p, full load) and capable of supplying up to -15 KV (negative voltage). The controls (manual & digital), enclosure and display for this power supply were built and connected in the laboratory. The cable coming from the cathode is connected using a Lemo style H.V. connector and receptacle. Additionally, we added an RC filter to the H.V. line to minimize the high frequency noise. This filter has a 5 nF H.V. capacitor rated at 15 KV, two resistors of 100 MΩ are connected to the input and output of the filter. The other voltage supply is a NIM module with a dual H.V. supply (Mod. 3125, Canberra), this is low noise (≤ 10 mV p-p) and with a very good stability suited for high resolution detectors. It has a voltage range of 0 to 5 KV (positive or negative) and it is used mainly to supply voltage to the GEM and meshes.

The signal from the charge collected inside the chamber is transmitted first to two charge sensitive preamplifiers (Mod. 2004, Canberra). These preamplifiers provide a unipolar linear voltage peak proportional to the inverted charge input. They have a decay constant of 50 μs and a charge sensitivity of 0.2V/pC. The output of the preamplifiers is fed to a digital spectrum analyzer (DSA-1000, Canberra). This unit digitizes the preamplifier signals at the front of the signal processing chain, applies a digital filter to the sampled waveform, and feeds the resulting trapezoidal signal into a
16K multichannel analyzer (MCA). This procedure translates into increased stability, accuracy and reproducibility with respect to the usual method of analog signal shaping in a spectroscopy amplifier followed by a peak-sensing ADC (Analog-Digital Converter) and MCA. The signal from the preamps is also fed in parallel to a digital phosphor oscilloscope (Tektronix TDS 5000) with four independent inputs. Other important part of the electronics is a precision pulse generator (Mod. PB-5, BNC) used for charge calibration and testing purposes.

Figure 4.1. Schematics of the acquisition electronics setup.

Additionally we built a filter to reduce the high frequency noise from the power being supplied to the preamplifiers. The unit has four connectors (D-9) on front of a NIM module with independent filters connected to each of them.
4.2.-Electric Field in a Double Phase Medium.

It has been mentioned before that in order to extract the free charge being produced by ionization events in the chamber it is necessary to apply a suitable electric field between the electrodes. In the case of a dual-phase ionization chamber there exists the extra factor of the different dielectric constants of the two mediums (gas & liquid) between the electrodes. In order to achieve the charge extraction from the liquid the field needs to be high enough. In a general approach this situation can be seen as a capacitor with two different dielectrics between its plates. From this, an analytical expression for the corresponding fields in the two mediums can be derived. If the thickness of one of these is $a$, with a dielectric constant $\varepsilon_1$ and the other has a thickness $b$ with dielectric constant $\varepsilon_2$. The fields after applying a voltage ($V$) between the two electrodes can be derived from the expressions:

$$V = V_1 + V_2 \quad \text{or} \quad V = aE_1 + bE_2 \quad (4.1)$$

and

$$D_1 = D_2 \quad (4.2)$$

with

$$D_1 = \varepsilon_0 \varepsilon_1 E_1 \quad , \quad D_2 = \varepsilon_0 \varepsilon_2 E_2 \quad (4.3)$$

After doing some algebra with these equations the result for the fields is:

$$E_1 = V\varepsilon_2 / (a\varepsilon_2 + b\varepsilon_1) \quad \text{and} \quad E_2 = V\varepsilon_1 / (a\varepsilon_2 + b\varepsilon_1) \quad (4.4)$$

A visualization of these results can be seen in Figure 4.3. Figure 6.1 shows the equipotential lines for a double phase capacitor plotted using Maxwell (Ansoft) software.
Figure 4.2. Equipotential lines in a double phase capacitor. The lower part is filled with LXe and the upper part with xenon gas.

Figure 4.3. This plot shows the variation of the electric field magnitude in the different mediums in a double phase capacitor filled with xenon.
4.3.- Experiment Procedure.

After the chamber has been assembled with its corresponding inside configuration of electrodes the first step in preparation for an experiment is the pumping and baking of the chamber for several days (2-5 days) at ~170 °C in order to minimize the impurities and the outgassing from the interior materials and walls. The outgassing of a vacuum system in general depends on the particular substance, the temperature of the surface and the time of exposure to vacuum. It is defined as:

\[ Q = \frac{(\Delta P/\Delta t)^* (V/A)}{\text{(4.4)}} \]

where \( \Delta P \) stands for the pressure variation in a time \( \Delta t \), \( V \) is the volume of the chamber and \( A \) its internal area.

After baking the pressure inside the chamber is typically in the range of \( 10^{-9} \) – \( 10^{-8} \) Torr at room temperature. We proceed to measure the outgassing of the chamber to check if it is clean enough to allow for the run of an experiment. Outgassing has to be below \( 10^{-10} \) Torr L cm\(^{-2}\) s\(^{-1}\) to consider the chamber clean enough to run the experiment.

Figure 4.3. shows one typical value for the outgassing in our chamber. In general the values we obtained during the various runs of the experiment were very good, with values reaching even the \( 10^{-13} \) Torr L cm\(^{-2}\) s\(^{-1}\) range in two occasions.
After all the connections to the feedthroughs and heating elements are in place together with a pair of thermocouples placed on the bottom and side of the vessel, the chamber is introduced into the dewar, with the help of a crane, to start the gas filling by cryogenic pumping. Before starting the filling the dewar is leveled and the liquid-level sensor is attached to its corresponding port and to the LN\textsuperscript{2} filling line.

The chamber is cooled down for 15-30 minutes until the chamber temperature drops below $-100\,^\circ\text{C}$. Once this temperature is reached the valves connecting the chamber to the gas system are opened and we start the filling, taking care of always passing the gas through the getter in order to maintain the highest purity of the xenon.

The filling stage of the experiment regularly takes about 3 hr with a mean flow rate of 2.5 slpm ($\sim 0.25\,\text{g/s}$). The amount of xenon used is always above 2500 g. Considering the chamber dimensions we have a level increase of $\sim 1\,\text{mm}$ per 100 g of Xe condensed inside the chamber. At the end the final mass used is given by the
electrode configuration in use. The three different configurations used in the various runs of the experiment are shown in Table 4.2.

<table>
<thead>
<tr>
<th>Configuration 1</th>
<th>Configuration 2</th>
<th>Configuration 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode-Mesh : 20 mm</td>
<td>Cathode-Mesh1 : 20 mm</td>
<td>Cathode-Mesh1 : 20 mm</td>
</tr>
<tr>
<td>Mesh-GEM : 4 mm</td>
<td>Mesh1-Mesh2 : 5 mm</td>
<td>Mesh1-Mesh2 : 5 mm</td>
</tr>
<tr>
<td>GEM-Anode : 2 mm</td>
<td>Mesh2-GEM : 2 mm</td>
<td>Mesh2-Anode : 10 mm</td>
</tr>
</tbody>
</table>

Table 4.2. The three configurations used for the different runs of the experiment. The table shows the elements installed and the distance between them.

Once the desired level of LXe has been fed into the chamber the valves are closed and the temperature controllers are set to heat the chamber and take it to a temperature range between $-108^\circ$C and $-111^\circ$C which is the region in which the liquid phase of xenon exists. It takes various minutes before the equilibrium is reached; as it was mentioned before we use the value of the pressure reading from the transducer attached to the filling line to monitor the evolution of liquid xenon towards thermodynamic equilibrium (Fig 4.3.).
Figure 4.3. Snapshot of the monitored conditions inside the chamber during the run of an experiment. The upper window shows the mass of Xe inside the chamber (upper curve) and the flow rate (lower curve, without scale). The window in the middle is the internal pressure, the plot shows the evolution towards thermal equilibrium of the liquid. The lower window is the calculated internal temperature from the pressure reading.

The following step is the connection of the cables to their respective preamplifiers and from these to the MCA and oscilloscope for data and pulse acquisition. Also the pumping station is turned off to avoid any electronic noise coming from its elements as well as microphonics detected mainly on the meshes.

The type of radiation used in the experiment are gamma rays from the sources: Cs-137 and Na-22. Gamma rays from Na have their main energies at 1275 keV and 511 keV. Cs radiation has an energy of 662 keV. These sources are placed inside the dewar close to the center of the chamber.

During the data acquisition stage the drift and collection fields are given various values with the intention of collecting the greatest amount of charge possible. The drift field is that between the cathode and the shielding mesh and it was given values up to 2
kV/cm. Correspondingly the collection field is that between the shielding mesh and the element being used as an anode. This field was given values up to 4 kV/cm.

One important consideration respect to these fields is their influence on the electron transparency of the mesh. According to Bunemman's formula [15]

\[ \sigma = \frac{d^2}{2\pi g(2d-2r)} \log(d/2\pi r) \]  

(4.5)

where \( r \) is the radius of the wire, \( d \) is the wire pitch and \( g \) is the distance between the grid and the sensing electrodes; the transparency of the mesh we used has a value of 99% with the condition of maintaining a ratio for the fields of \( E_C/E_D \geq 2 \). Figure 4.4. shows the equipotential lines for the electric field using Configuration 3 and a field ratio of \( E_C/E_D = 8 \).

Once the acquisition has finished the chamber is evacuated to one of the cylinders in the gas system that has been previously frozen. While evacuating it is important to regulate the gas outflow in order to maintain the pressure inside the chamber above 1 bar and avoid the freezing of xenon. The emptying of the chamber takes about 2.5 hours.
Figure 4.4. Equipotential lines in Configuration 3. The cathode is at $-3$ KV, the lower mesh at $-2$ KV and the upper mesh and anode at $0$ V. It can be observed that the field has a good degree of homogeneity in the center of the drift region.
Chapter 5

Discussion.

For several months we have been running experiments to test the adequate functioning of the entire chamber system and continuously improved the system. The results have been satisfactory regarding the cryogenics and mechanical design allowing us to have the right conditions for a double-phase experiment using xenon.

The main problem we have encountered is the low charge being collected by the internal construction of the chamber. After the many experiments that have been performed we think that the low collection of the chamber traces mainly to the low purity of the xenon gas being used. From the first run of the experiment when we used Configuration 1, which includes the GEM fixed to the internal structure, we had very poor charge collection and also ambiguous signals on the oscilloscope that didn’t correspond to what was expected from a gridded ionization chamber configuration; i.e. first a rising signal on the mesh followed by a decrease corresponding to a rising pulse on the anode. After analyzing the pulses on the oscilloscope and the configuration being used we realized that due to the size of the GEM compared to the sensitive region (i.e. the zone delimited by the cathode and the anode) the field lines from the cathode were terminating on the GEM lower surface outside the sensitive zone and that should be generating many of the ambiguous signals we observed on the oscilloscope. To eliminate this problem we exchanged the guarding ring around the mesh by a guarding
disk shielding the GEM from the field in the drift region. This addition improved the type of pulses we observed but the charge collected was still very poor even after various purification cycles of the gas between experiments. With the goal of having a more unambiguous observation of the signals coming from the drift region entering the collection field we decided to use a new configuration, i.e. Configuration 2 which has two meshes instead of one. This proved to be a good configuration allowing us to observe the two pulses expected from gamma ray interactions between the meshes, with the upper mesh being used as the anode (Fig. 4.5.) but we didn’t see any big improvement on the charge collection, either using the upper mesh as the anode or in "reverse" mode with the lower surface of the GEM as the cathode, that would appear as a clear photopeak on the spectrum acquired. Figures 4.6. and 4.7 show two different "spectra" for Cs and Na where no photopeaks are visible.

Figure 4.5. Example of the pulses observed from charge collected between the two meshes in Configuration 2
Figure 4.6 "Spectra" acquired using the Na source. To the right is the test pulse. The drift field was 2 KV/cm and collection field 4 KV/cm. The equivalent noise charge (ENC) was $2.85 \times 10^3$ e$^{-}$. The MCA is set with a rise time of 4 $\mu$s and flat top of 1 $\mu$s.

Figure 4.6 "Spectra" acquired using the Cs source. To the right is the test pulse. For this data the drift region length was shortened by operating the chamber in an inverse mode and in single (liquid) phase with the GEM as the cathode and the lower mesh as the anode. The drift field was 1.4 KV/cm and collection field 2.4 KV/cm. The ENC was $1.53 \times 10^3$ e$^{-}$. The MCA is set with a rise time of 4 $\mu$s and flat top of 1 $\mu$s.
Because of the very low charge being collected in the chamber with the GEM inside we decided to take out the GEM as a possible source of contamination, may be due to the chemical treatment in its fabrication process and use an internal configuration in the form of a simple ionization chamber with two meshes.

It is also pertinent to mention at this point that we have had various problems with the H.V. lines connecting to the chamber that have limited the maximum voltage that can be applied between electrodes. These problems have ranged from discharges inside the chamber due to having the wires too close to the walls or discharges between the pins in the feedthroughs, to leak currents in the H.V. filter and connector. These problems have been gradually solved though some of them still persist in the current stage.

The experience with the simple ionization chamber has not showed the improvement in the charge collection that we expected, suggesting that very probably the GEM was not the problem in our initial settings but some other source of impurities (PEEK?). Another possibility is that the purification cycles that the xenon has been subjected to have not been enough to achieve to very high purity needed for successful charge collection in these type of detectors, after repeated contamination due to the opening of the chamber and the small leaks due to thermal stresses that we had at the beginning.
Figure 4.7. Pulses observed with the right timing expected from charges inside the drift region, passing through the shielding mesh (upper) to be then collected on the upper mesh (lower). The drift velocity for electrons at the fields applied is $\sim 2 \text{ mm/\mu s}$.

Currently we are working on a recirculation system to be added to the chamber system that will allow us to have the xenon purified while the experiment is still running without the need of evacuating the chamber every time purification is needed and we expect this addition can finally improve the charge collection of the chamber.
Bibliography


