Testing PMTs for Preparatory Measurements and Modeling Xenon Purification for the XENON nT Dark Matter Detector

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1 Introduction

1.1 Dark Matter

The body of evidence for dark matter is substantial. In particular observations of rotation rates of galaxies and galaxy clusters make it hard to refute that some form of dark matter likely exists.

A simple calculation with newtonian mechanics will predict that the rotation rates of galaxies should be dependent on distance to the center of the galaxy, \( r \), and that rotational velocities should drop off proportionally to \( r^{-1/2} \), based on the density of visible matter. However this is not what we observe, as figure 1 shows. This relatively flat galactic rotation curve suggests that either there is far more mass than we are accounting for in our galaxy or our theory of gravity is incorrect.

![Figure 1: Galaxy rotation speed as a function of radius [4]](image)

Observations of galaxy clusters regularly find that there must be more mass than is visible in the cluster. These observations range from observing velocity distributions in the galaxy cluster, much like observing velocity distributions within a galaxy as discussed above to observations of gravitational lensing due to clusters. The gravitational lensing observations measure the total mass without relying on observing velocities accurately. Both methods however agree that the total mass in these galaxies is roughly a factor of 5 larger than the
visible baryonic matter in these galaxies. [2]

Certain galaxy clusters, like the bullet cluster, have notable differences in the center of mass of the cluster determined from observations of the gravitational dynamics of the cluster and the center of mass of the cluster determined from accounting for all visible baryonic matter in the cluster. These examples make the case for the existence of some dark matter much more compelling than a modified theory of gravity. [2]

We don’t know what dark matter is or how it may interact with ordinary matter. Our observations suggest that any dark matter particle should be neutral, non-relativistic, long lived, and rarely annihilate. There are a number of possible dark matter candidates that extend somewhat naturally from pre-existing theories. The XENON experiment attempts to detect some of these candidates as they interact with xenon nuclei. [2]

1.2 XENON

The XENON collaboration has been building detectors for dark matter starting with XENON10 in 2006. Since then, several more experiments have been conducted. Most recently, the XENON 1T experiment was just decommissioned and the existing XENON 1T infrastructure is being reused and built onto in order to build the bigger, more sensitive XENON nT experiment. The Xenon nT experiment will have a larger target mass of xenon (increased from 3 to 8.5 metric tons), a neutron veto system to help reduce neutron background signals which can be similar to dark matter candidate signals, and liquid purification system to achieve the higher purity required for the larger quantity of xenon. [1]

The nT experiment utilizes the same working principle as previous xenon experiments. Essentially, particles come in and interact with the xenon atoms. This interaction excites the atoms, producing a pulse of emission as the atoms de-excite. This interaction can also ionize xenon atoms, producing free electrons. The liquid xenon in the detector is set in a strong electric field from electrodes placed in and around the detector. This electric field separates ionized electrons from the xenon atoms, causing them to drift towards the top of the detector. At the top, additional electrodes strengthen the field and the electrons are accelerated into the gas phase xenon in the top of the detector where they produce a second signal. These two signals are used to identify the particle that interacted with the xenon and reconstruct the events that occurred in the detector when they are picked up by arrays of photomultiplier tubes (PMTs) at the top and bottom of the detector. In order to ensure
that the light will be detected by a PMT, the detector’s interior is made of reflective teflon panels. \[1\]

Figure 2 shows this process unfolding within the detector in conjunction with what the two signals look like for different particles.

1.3 Motivation

The significance of my work as it pertains to the operation of the detector stems from the importance of the resolution of the second signal, the one produced by ionized electrons interacting with gas phase xenon. Two factors that influence the resolution of this signal are xenon purity and the electric field strength in the detector. The balance between electric field strength and scattering off of xenon atoms sets an electron drift velocity through the liquid xenon. This drift velocity determines how long the electrons will spend in the liquid xenon, before they are accelerated into the gas portion of the detector.

The presence of electronegative impurities in the xenon causes electrons to be absorbed before they can produce a signal. For a given level of impurity, electrons have a given mean lifetime before they are absorbed by impurities. Accordingly, the xenon purity level determines how long electrons can survive in the detector. An appropriate combination of electron lifetime and electron drift velocity are critical to picking up the second signal with a high enough resolution.

In August the electrodes will be placed in the detector cryostat, and the system will be cooled down for the first time. High voltage will be applied to the cathode, and it will be
tested for any emission or hot spots. Because the detector reconstructs particle interactions from signals produced by emission, the voltage applied to the cathode must remain below any value that produces any emission. This limiting potential is also a limiting factor in the electric field strength within the TPC and could impact other systems: if the electric field is too low and it takes too long for electrons to drift across the detector, a higher xenon purity could be required, for example. PMTs are necessary to measure any such emission, which is where my project of testing the PMTs that will be used in this test comes in (section 2).

When everything is cooled down, the liquid purification system will also be tested. The liquid purification system is new to the nT experiment and will allow the experiment to achieve higher xenon purity with a much smaller rise time. However, we do not yet know what flow rate or filter efficiency the liquid purification system will be able to achieve. We do not yet know the rate at which impurities will accumulate in the system. Accordingly, in order to determine how we can expect the system to behave for different possible values of poorly known parameters, I built a model of the whole system (section 3). Understanding how the xenon purity will evolve allows us to understand when, in the timeline of putting the experiment together, we can expect to have a high detector sensitivity.

## 2 Testing PMTs

### 2.1 Project Goal

The goal of this project is to determine the characteristics and functionality of 7 old Hamamatsu R8520-406 PMT’s that were modified for use in the Xenon 10 and Xenon 100 experiments.

### 2.2 Test System

In order to test the PMT’s the following configuration is used (Figure 3).

The PMT’s themselves are placed in a light tight box. The light tight box has a feed through to transmit the voltage supply, the signal, and light from the LED into and out of the box. The box is wrapped in black tarp several times to prevent any light leakage into the box. The tarp is taped together and the cables are taped along the seams to make sure there are no gaps. The LED is in a box that is wrapped in black tape and also placed inside
the black tarp to ensure that no extraneous photons enter the LED box and to ensure no LED photons can enter the PMT light tight box via a path other than the optical fiber. A physical image of the box and these connections is given in figure 4.

The components and their exact configurations will be discussed more in the next section but the general idea is as outlined in the block diagram in Figure 3. The PMT is connected to the voltage supply and signal output within the light tight box as described. The LED is connected to a pulse generator that sends a 10 ns pulse. The signal cable from the PMT is routed to a digitizer. The pulse signal sent to the LED is split and also sent to the digitizer to trigger data collection. A 30 ns time delay is placed on this trigger signal because of problems encountered with the digitizer (see section 2.2.5). The CAEN digitizer (DT5724) is configured with an FPGA which interfaces with CAEN’s software on a computer. The computer is used to set the characteristics such as trigger threshold and sample size and to collect the data that will be processed later. Figure 4 shows the an image of the physical box, PMT, and cables fed into the box.
2.3 Testing and Configuring components

2.3.1 PMT’s

The PMT’s were 7 Hamamatsu R8520-506 PMT’s originally designed and used in Xenon 10. The first task was to examine the divider circuits and determine if the PMT takes positive or negative high voltage. By examining the circuit board, testing the connections, and drawing the circuit, we found that the configuration corresponded to a negative high voltage: In a positive high voltage circuit, the signal, which is read out at the PMT anode, begins at a potential equal to the high voltage applied to the circuit. Accordingly, in order for an external circuit, such as a digitizer or an oscilloscope to process the signal, a capacitor must be placed between the anode and the grounded external circuit to preserve the relatively small signal.

The circuit diagram is shown in figure 5.

Figure 4: The inside of the light tight box and its connections to the voltage supply, LED, and signal output. The LED is in the black box below the input/output cables. The PMT is placed on insulating styrofoam.

Figure 5: The Voltage divider circuit for the old Xenon 100 PMT’s
The resistors in the circuit form a resistor divider with nodes connected to the dynodes of the PMT that set the potential difference between adjacent dynodes and thus the internal electric field of the PMT. This electric field determines the PMT’s response characteristics. The capacitors among the last few dynodes are used to supplement the charge on the last few dynodes when a large current is flowing. Such a current can reduce the amount of electrons able to be ejected off of a dynode and alter the field strength between dynodes. The PMT signal comes out of the PMT anode. From the anode, the signal has two parallel paths to ground. The first path and has a 50 Ω resistor and flows to external circuits that process the signal. The 50 Ω resistor is chosen to match the impedance of the cables and terminating resistor that read out the signal in order to minimize any reflections. The other path has a 1KΩ resistor to the ground in the circuit. This resistor value is chosen to ensure that most of the signal flows along the other path to external circuits. The whole voltage divider circuit just described is in parallel with a single capacitor. This capacitor does not have a significant role in this measurement. However, in the Xenon experiment the capacitor is used to ensure the PMT has high resolution for events with higher photon intensities. WIMP signals are relatively small and will not strip many photoelectrons from the photocathode. However, larger events such as alpha decay of radon in the detector will quickly strip more of the photocathode electrons, which can be supplemented by the capacitor charge, preserving the signal quality.

Once the nature of the circuits was determined, we soldered the HV and signal connections onto the printed circuit board and insulated the exposed wire with capitone tape. We then placed the PMT in a light tight box, applied varying high voltages (< 900 V) and looked at the dark rate and dark current on the oscilloscope to ensure the PMT's were working as expected. From here we continued on to configure the rest of the measurement.

Figure 6 gives an image of one of these PMTs.

2.3.2 High Voltage Supply

A NIM Caen N126 high voltage supply was used to supply the voltage. As the PMT manufacturer specified to not apply a voltage above 900 V, the voltage supply was set to turn off the high voltage and ramp down at 100V/s if this value was exceeded. Initially the digital current reading seemed to have an offset relative to the analogue current reading and displayed values that differed from what we would expect having already measured the resistance of
the circuit. To ensure everything was working as expected we tested the high voltage supply on a high resistance circuit (5GΩ). To ensure there would be no unsafe discharge through the air we used capitone tape to insulate the wire in the box. From this we were able to determine the scale and offset (roughly 6 µA) and therefore confirm everything was working as expected before applying high voltage to the PMT’s. An image of this circuit is given in figure 7.

When later problems were encountered (see section 2.5.1) a 4 channel CAEN 1470 power supply was used. This power supply was tested with the same high voltage circuit and with a multimeter.

2.3.3 Pulse Generator

The Pulse generator used was an Agilent 33250A which could supply pulses with as narrow as 8 ns widths. One of our first tasks was to determine reasonable parameters on the pulse generator to get the desired signal from the PMT (a signal in the single photon regime).
To do so we first configured the pulse generator and the PMT signal output into an oscilloscope and looked at the signals. With the output of the pulse generator turned off, we were able to observe the dark rate events from the PMT which gave us an idea of what a single PE event should look like. We reduced the pulse width to 10 ns and increased the amplitude until we started seeing similarly sized events at a consistent time position. We were later able to compare dark events to the LED events more clearly with acquired data (see section 2.5.2).

2.3.4 LED

The LED emits blue light and is configured as described in the introduction. Figure 8 gives an image of how the box is closed from external light sources.

![Figure 8: The box containing the pulsed LED](image)

2.3.5 Digitizer

Initially a Caen DT5724 digitizer was used. The digitizer was used at its maximum sampling rate of 100 MS/s. The digitizer has 14 bits and a Vpp range of to 2.25 V. The digitizer takes positive or negative high voltage and 0 V corresponds to a digital value of $8192 = 2^{14}/2$, the midpoint of the system’s range. The CAEN Wave Dump software was used to take data and interface with the PMT. Editing a configuration text file set the operating parameters of the digitizer.

Initially we simply started to try to figure out where the signal would show up in the output file. We ensured a file was writing each by varying parameters like sample length and what sort of header would be displayed for each event and then looking at the resulting files. We could not find the PMT signal however.
We extended the pulse length and pulse amplitude and looked again at the signals on the PMT. We set the pulse length and amplitude to high values so that we were seeing a large signal almost every-time on the oscilloscope. With the oscilloscope, we determined that the PMT signal came roughly 150 ns after the trigger signal. We set the POST-TRIGGER parameter to 100 so all of the data collected would occur after the Trigger. If everything was working as expected, we should see the PMT signal 15 samples into the data file. However, we still saw nothing.

We stopped using the digitizer’s trigger input and used the configuration file to trigger at a certain voltage on one of the digitizer’s data collection channels. This allowed us to look for the square trigger-pulse in the output files. We only saw the trigger signal in the last 25 or so samples of the output file. remained the case regardless of what we did to the POST-TRIGGER parameter value.

There must be some unchangeable latency in the digitizer. We could see the PMT signal approximately 15 samples (150 ns) after this trigger signal on the data file for that channel. However, a given pulse had a width of about 5 samples, so this was a problem as some of the pulse data may be lost at the end of the data sample.

Accordingly, we added a 30 ns delay using a passive NIM module to the pulse that was sent to trigger the digitizer. The delay simply comes from routing the signal through additional cables of a set length. This meant that the trigger signal would be 3 samples behind the signal sent to the LED, ensuring that the PMT signal peak would be comfortably within our data collection time frame.

We later also took data with a Caen DT 5751 which has a 10 bit resolution and a 1 VPP range for each channel but a 1 GS/s sampling rate. This was done to see if we might get better resolution from which we could determine PMT gain. This digitizer behaved as expected, and we placed the pulse towards the middle of the 518 ns collection window.

### 2.4 Setting up the measurement

There were two types of measurements to conduct. The first type just required ensuring that all of the PMTs and their circuit boards worked. To do this we used the equipment that has been described so far and incorporated each PMT and circuit board into the system together. On the oscilloscope we could observe the dark rate events as we increased the voltage supplied to the PMT. At 700 V we turned on the pulse generator’s output to ensure
we would see LED signals at the expected time.

The second measurement involved taking data with the digitizer. Once all of the equipment was configured, I had to write the analysis code and ensure that the pulse generator was sending an appropriate pulse to the LED for single photon detection with larger samples of data, rather than just looking at the oscilloscope. This was done by comparing dark rate events to events from the LED and is discussed more thoroughly in section 2.5.2.

2.5 Confirming all of the PMTs work

First I will discuss the process of ensuring that all of the PMT’s worked as expected. We successfully tested and collected data for 5 out of the 7 PMTs without problem. We increased the voltage supplied to somewhere between 700 and 800 V, observed the dark current, and turned on the pulse generator to ensure the PMTs were detecting light as expected. They were all in working order. Figure 9 gives an image of what this pulse looks like with a high waveform intensity to make the image quite clear.

Figure 9: An image of what the single PE peak looks like on the oscilloscope. The waveform intensity is very high in this image, so a number of previously detected peaks are visible. The peaks occur 150 ns after the pulse is sent to the LED and deviate from the baseline voltage from around 7 to around 20 mv. The larger signals obscure the smaller signals in the image.

We encountered problems when testing PMT 6. As I increased the voltage by 100 V at a time, I noticed the system overloading just above 160 V. The Current provided by the HV supply had jumped up instantly by nearly 8 µA. (With the roughly 125 MΩ resistances of the voltage divider circuits we expect the current to increase by about .8 µA for every 100 V).
We needed to isolate the problem the system was encountering. I started by checking to see if the problem came from the PMT or the board by testing the malfunctioning board and PMT with working boards and PMTs.

We continued to find the circuits shorting at some high voltage (160 V for PMT 6 and above 500 V for other PMTs regardless of the circuit board used). There were no problems with the circuit board for PMT 6 that were detectable with a multi-meter. So, to make sure nothing weird was happening, I tested a previously working PMT and circuit board pair. Despite having had no issues the previous week, the system continued to short at some high voltage (still above 500 V). I tried other previously working PMT-board configurations and they all shorted at some high voltage, even though they had previously been working. So either my previous tests had been flawed in some way or now some other part of the system was malfunctioning.

Eventually in trouble-shooting, I applied high voltage to a board without a PMT attached and observed the board as I kept on eye on the current reading. As I increased the voltage, around 600 V, the occasional PMT-signal like pulse would appear on the oscilloscope even though there was no PMT attached! It took reaching 930 V to see the current jump dramatically, but at this voltage, a visible discharge appeared on the board (figure 10). The high voltage supply was configured to maintain operation at safe settings, so it quickly lowered the voltage to 700 V, where the discharge became less pronounced but was still visible and frequent.

Looking at the circuit board in figure 10, we can see the location of the discharge. Inspecting the board revealed that the discharge is occurring between the PMT anode (1KΩ away from the ground) and the -HV node on the board. There were no markings on the board, so it seemed that this discharge must be occurring through the air. To determine the approximate electric field strength to see if this behavior made sense, I measure the distance between these points on the circuit board with calipers. The distance was 0.4. At the potential where we fist saw the discharge, 930 V, this would correspond to an electric field strength of 2.3 kV/mm. The dielectric strength of air is about 3 kV/mm. The PMTs had been working and only malfunctioned on two particularly humid and rainy days. Accordingly, it seemed that the problem is more of a misunderstanding of board design: the boards are not designed to be used in air but in liquid xenon which has a dielectric strength that is two orders of magnitude larger.
It later turned out that the high voltage supply was malfunctioning: I left the high voltage supply on for an extended period of time and at some point the voltage reading changed dramatically. When I reset it to 700 V and looked at the oscilloscope, I was seeing peaks of a very different size. The obvious conclusion was that the shortage problems (and the problems with determining gain discussed in the next section) were due to the malfunctioning high voltage supply. I replaced the high voltage supply for testing the remaining PMT’s. This resolved all previous issues, and the remaining testing was completed. 7 working PMTs were found.

2.6 Determining the PMT characteristics

2.6.1 Analysis System

The analysis was done using the Python-Root interface. The ASCII file from the lab computer was read in creating a list of the digitized voltages for each sample. Then each list was used to construct branches that were written into a tree in a root file. There was a leaf for each pulse sent to the LED. The first branch simply converted the digitized voltage reading from each sample to the actual voltage value. Additional branches were created to contain the baseline voltage, the gain, and the maximum deviation from the baseline voltage. A sample raw wave form from an LED event is given in figure 11 and will make some of the
As determined with the oscilloscope and raw wave form branches, when a photon was detected, the pulse occurred roughly 120 ns after the trigger signal. As configured, this meant that for the both digitizers, a pulse initiated at some point after sample 320. The first 150 samples are summed and averaged to determine the baseline voltage for the system by averaging out the noise in the reading. We can see what the noise in this region looks like in figure 11. In general this value fit quite well with inspecting the graphs but occasionally, if there was a dark pulse in the first 150 ns, which was very uncommon, the value would be slightly off, affecting later analysis of parameters like gain. However, this was generally only a few branches of 30,000, so had a minimal affect on the overall distribution.

The gain branch was slightly more difficult to configure. I first had to isolate exactly which timing window should be used to integrate the current over and find the charge. In order to do so, I had to sift through large numbers of raw wave forms, and find the appropriate width and location for the timing window. For example in figure 11 the pulse begins around 320 ns and ends around 340 ns. For the faster digitizer the window depended on the voltage applied to the PMT and ranged from covering samples 620-655 (the peaks were generally around 20 ns but did not always occur at the same time) to only covering samples 620-640. For the slower digitizer, the slower rate meant timing variations become more pronounced and a broader range of samples 496-504 (80 ns) was used. Of course, this method assumes all of the events in the time frame are LED events.

The integration of the digitized signal is quite straightforward: the terminating resistor in the digitizer is 50 ohms as specified by the manufacturer in each case, and a 10 ns or 1

Figure 11: A raw wave form taken with the 1 GS/s digitizer containing an LED event.
ns time window depending on the digitizer. Simply converting to current using the value of
the terminating resistor and multiplying by the time window finds the total charge from the
pulse. This value can then be scaled to $10^6$ electrons, or units of the expected gain value at
800 V.

The maximum voltage deviation from the baseline is determined by selecting the max-
imum deviation in the same window. This was useful for trying to isolate the single PE
event peak with the slower digitizer and address any problems encountered with the analysis
system or the physical system.

### 2.6.2 Performing the Measurement

The original characterization goal had been to determine the gain vs. voltage curve of the
PMTs and possibly place an upper limit on the dark rate. In order to correctly analyze gain
we had to compute the total amount of charge collected from an initial single PE event. In
order to ensure the majority of events were single PE events I looked at the overall gain and
maximum voltage branches. I then looked at specific raw wave forms in conjunction with
the gain and maximum voltage distributions to ensure I was looking at typical LED events
(again, isolated by timing relative to the trigger signal). I compared these to all of the dark
rate events I found by searching for peaks outside of the desired timing window. Since dark
rate events are generally from thermal electron emission from the photocathode or dynodes,
we can expect these events to generally correspond to single PE events (or single electron
events from later dynodes). So the dark rate pulses will generally be the amplitude of a
single PE peak or smaller. Comparing the dark events to the LED events made it clear that
we were looking at single PE peaks as figures 12 and 13 show:

The remaining efforts were centered around trying to find the single PE peak in a gain
spectrum. Initially, with the 100 MS/s digitizer, this peak could not be adequately distin-
guished to do any analysis on (Figure 14). From here there were two options: to try to
employ some sort of peak finding technique to each of the raw wave forms to determine
which peaks to integrate. But any such method will inherently bias a gain distribution. Per-
haps multiple thresholds or methods could be employed to obtain a general picture of what
is happening however. The other option was to try to take data with a faster digitizer and
see if the peak is more distinguishable. Figure 14 shows the data taken with the 100 MS/s
digitizer. The single PE peak is visible but not distinguishable or isolated.
Figure 12: A typical dark event. The event is a dark event because it occurs outside of the timing window of events triggered by the LED. The peak has a very similar form to that of an LED event (figure 13).

Figure 13: A typical LED response. The similarity in shape and amplitude to a typical dark event (figure 12) is immediately clear.

Figure 14: A logarithmic gain spectrum taken with the 100 MS/s digitizer before the voltage supply started malfunctioning.

As discussed earlier, we also took data with a 1GS/s digitizer. However, this was done when we were having problems with the high voltage supply. Nonetheless, in some ways the
resulting data looked promising: the single PE peak was clearly visible (figure 15). However, the gain value had changed significantly, as one can see by looking at the x-axes of figure 14 and figure 15. It took about a week of trying to address and find any possible issues with the analysis system or the physical system before discovering that the high voltage supply itself was the problem. Again, after leaving the high voltage supply running for a long time, the values shifted dramatically at some point. Resetting the voltage to the value before the change, 700 v, the peak size on the oscilloscope had changed. The only possible conclusion was that this 700 V was not the same as the 700 V that had been applied earlier.

With a new high voltage supply that was determined to be working correctly by testing at lower voltages with a multimeter and the faster digitizer more gain spectra were analyzed. We can see such a spectrum in figure 16. The peak appears to occur around the expected gain factor of $10^6$, but is still not very separated from the zero PE peak.

2.7 Conclusion

7 working PMT’s and circuit boards were found for use in the cold test. The data analysis and characterization of PMT’s ran into complications and the desired analysis was not completed. However, after all problems were resolved, the data and PMT gain values looked as expected.
3 Modeling the xenon purification system

3.1 Background

For the xenon experiments it is necessary to continuously purify the xenon in the detector to achieve and maintain a sufficiently high electron lifetime because there is a continuous influx of electronegative impurities due to outgassing from the teflon panels on the interior of the detector. In Xenon 1T this purification was done in the gas phase, drawing from both the liquid and gas-phase xenon in the detector, purifying the xenon, and passing it through a heat exchanger before returning liquid and gas phase xenon to the detector. This method is slow and insufficient for Xenon1T because of the limited flow rates of the gas-phase pumps and gas-getters from the TPC. The addition of the liquid phase purification system allows for the system to reach a higher purity with a faster rise time, which is important for competing with other dark matter detectors that are being developed concurrently. Figure 17 shows a simplified outline of the overall purification system.

A previous study done based on Xenon 1T Science Run 1 was used to determine what sort of electron lifetime/purity level would be necessary for Xenon1T. In general, WIMP sensitivity will not improve significantly after an electron lifetime of 1 ms. This is because the time it takes an electron to cross the TPC in the direction of the electric field is 1ms. However, for some lower WIMP masses, it is important to have an electron lifetime of 2ms. So this was the desired electron lifetime throughout the modeling process.

It seemed potentially significant to build a model of the whole system that incorporated

Figure 16: A logarithmic gain spectrum taken with the 1 GS/s digitizer with the functioning voltage supply.
phase exchange because the rate of outgassing into gas phase xenon is expected to be roughly 100 times greater than the outgassing into liquid xenon, based on previous work.

The mass of teflon in the larger detector is increasing by a factor of roughly 3. It is expected that the outgassing rate will also be roughly 3 times larger than the outgassing rate in the Xenon 1T experiment, because outgassing is more dependent on volume than surface area of material. However, this value is certainly not guaranteed. Similarly, we expect the liquid xenon pumps to be able to achieve a flow rate of 5 LPM. But again, we are not certain that this will be possible. The ultimate goal of my project was to determine what sort of behavior we could expect from the system with respect to rise time and final purity as a function of outgassing rate and liquid xenon filtration system flow-rate.

### 3.2 Building a Model

We can model the amount of oxygen/electronegative impurities in the system with the following equation:

\[
M_L \frac{dn_L}{dt} = -F_C \varepsilon_c n_L - F_{L} n_L + \Lambda_L + F_{G \rightarrow L} n_G P_{\text{cond}} - F_{L \rightarrow G} n_L P_{\text{evap}}
\]

\[
M_G \frac{dn_G}{dt} = -F_G n_G + \Lambda_G - F_{G \rightarrow L} n_G P_{\text{cond}} + F_{L \rightarrow G} n_L P_{\text{evap}}
\]

where \( M_G \) and \( M_L \) are the masses of the gas phase and liquid phase Xenon respectively. \( F_C \) is the mass flow rate of liquid xenon into the cryogenic filter. \( F_L \) and \( F_G \) are the mass flow rates.
flow rates into the gas phase filter from the liquid phase and into the gas phase filter from the gas phase respectively. \( \epsilon_c \) is the efficiency of the cryogenic filter. \( F_{G \rightarrow L} \) and \( F_{L \rightarrow G} \) are the condensation and evaporation rates. \( \left| P \right|_{\text{cond}} \) and \( \left| P \right|_{\text{evap}} \) are the probabilities of oxygen participating in each phase transition. \( n_L \) and \( n_G \) are the ppb concentrations of oxygen in the liquid and gas phase respectively. The initial outgassing rate in the liquid phase and gas phase are \( \Lambda_L \) and \( \Lambda_G \).

The time dependent outgassing model is given by

\[
\Lambda(t) = \frac{\Lambda_0}{1 + t/t_{1/2}}
\]

in which the initial outgassing rate \( \Lambda_0 \) decays over time with half life \( t_{1/2} \). This initial outgassing rate is different for the liquid and gas phases as discussed above.

The goals of this model were to determine the effect of the exchange of impurities between phases on the development of the system and to look at the initial behavior of the system: What conditions lead to what rise-times and final purities? Because the initial stages are most important, much of the modeling is done by approximating the outgassing rate as constant. The significance of this assumption is discussed in the next section.

Before explaining the development of the model, the following are the values for the system’s parameters obtained from previous:

\( \Lambda_L = 1330 \, \text{kg ppb/day} \) (3 times the Xe 1T outgassing value)

\( \Lambda_G = 100 \times \Lambda_L \, \text{kg ppb/day} \) (approximated from outgassing data in consultation with Masatoshi)

\( \epsilon_c = 0.9 \) or 0.55 models were constructed for both values

\( F_L = 105 \, \text{SLPM} \)

\( F_G = 5 \, \text{SLPM} \)

\( n_{L0} = 257 \, \text{ppb} \)

\( n_{G0} = nL0 \times 100 \, \text{ppb} \)

The phase exchange parameters are less well known, so these values are varied in the next section to determine their significance. This analysis determined their values were not very
significant and the following values were used for the rest of the modeling:

\[ F_{G \rightarrow L} = F_{L \rightarrow G} = 2 \text{ SLPM (converted to mass by multiplying by the STP density of Xe)} \]

\[ P_{evap} = .2 \]

\[ P_{cond} = P_{evap}/800 \text{ based on our understanding at the time the model was made (see figure 21).} \]

### 3.3 The Model and Results

Before building a new model I restricted this model to one that ignores phase exchange between the systems in order to compare to previous work. If we neglect phase exchange we can model the purity of the liquid with the following:

\[ M_L \frac{dn_L}{dt} = -F_c c_L n_L - F_L n_L + \Lambda_L \]

Because the goals of this project were to examine the initial development of the system, in the first few weeks or so, a constant outgassing rate was used because the half life is on the order of 180 days, which is much larger than a few weeks (the significance of this assumption is later examined). With a constant outgassing rate, a graph of the evolution of the purity of the system over the first 100 days for a cryogenic filter efficiency of 0.55 is given in Figure 18. The result was fit well with a previous study, so we continued on from here.

![Figure 18: The time evolution of the electron lifetime in the liquid xenon for different filter efficiencies. This model neglects phase exchange](image-url)
As I began to incorporate phase exchange, I first worked to determine the significance of the evaporation and condensation parameters, because we do not know exactly what values to expect and the rate of outgassing in the gas phase portion of the chamber is far higher. We are assuming the system is in equilibrium, so $F_{L\rightarrow G} = F_{G\rightarrow L}$, ignoring the overall circulation of the system for this model. Figure 19 shows the time development of the system’s purity with different lines corresponding to different evaporation rates, as listed in the legend.

![Figure 19: The time evolution of the electron lifetime in the liquid xenon for different values of $P_{\text{evap}}$. This graph shows the insignificance of the value of $P_{\text{evap}}$.](image)

As we can see a huge range of evaporation rates have little effect on the final purity of the system. Varying the mass flow rate of the phase exchange also had a similarly negligible effect. Figure 20 shows the evolution of the system’s purity over the first 50 days for phase exchange rates ranging from 0 to 20 SLPM (this is converted to the mass flow rate by multiplying by the STP density of xenon). Once again the system is in equilibrium, so $F_{L\rightarrow G} = F_{G\rightarrow L}$.

Varying the condensation rate on the other hand had a more notable effect because of the high outgassing rate in the gas phase xenon. A range of 6 to .0006 percent were explored because we expect the rate of condensation to be around 1/1000 that of the evaporation. Figure 21 shows that if the condensation probability is much higher than we expect (such as 1/10 or even 1/100 of the evaporation rate) there is a significant effect in the final purity of the system. However, for rates below 1/100 of the evaporation probability varying condensation probability does not produce a significant effect.

This model was made when we expected the condensation probability value to be around 1/1000 of the evaporation probability value. This is the case for radon for example. However,
Figure 20: The time evolution of the electron lifetime in the liquid xenon for different phase exchange rates. Again we see the insignificant effect of the value of the phase exchange rate.

for oxygen, the condensation probability was later determined to be closer to 1/30 of the evaporation probability. This sort of value actually corresponds to a lower final purity, as we can see in figure 21. This is newly discovered a flaw in the remaining modeling and analysis.

Figure 21: The time evolution of the electron lifetime in the liquid xenon for different values of $P_{\text{cond}}$. This parameter is insignificant in the regions we expect it to fall into.

Because the goal of this portion of the analysis was to determine the significance of the exchange rate alone, the other parameters were not varied. (or were varied but aren’t displayed here and showed similar effects). As we can see, in the ranges we expect these parameters to fall in, determining their exact values is not particularly important.

Now that these parameters have been examined, I can construct an overarching model of the system, accounting for phase exchange. I compared this model to the model for
the system that neglects exchange and filtering of gas-phase xenon. Both models cover the same 100 day time period, use constant outgassing values, and have distinct lines for the same cryogenic filter efficiency values. Figure 18 showed the evolution of the system without exchange. Figure 22 shows an identical graph that accounts for exchange.

Figure 22: The time evolution of the electron lifetime in the liquid xenon for different filter efficiencies without phase exchange.

Comparing figures 18 and 22 shows that the systems are very similar, as we might have expected because the values of the phase exchange parameters was not found to be significant. Nonetheless, the addition of the phase exchange and gas filtration present a slightly more accurate view of the system. With this understanding and contextualization for the model, I turned to analyze more deeply relationships of significance for the development of the experiment.

Because a constant outgassing rate allows us to look at the time evolution of the system analytically and algebraically, we wanted to understand how this model deviates from the time dependent model, despite the initial similarity to a previous study without phase exchange. Figure 23 shows the time development of the difference in purities between models that account for time dependent and time independent outgassing rates.

Although these differences certainly accumulate, after 25 days, roughly the time scale we are interested in, they are less than 5 percent of the system’s purity at this time, and since we are concerned with the system’s initial behavior, these deviations seemed acceptable, particularly as the outgassing rate decays over time, so this presents a more conservative model.
Figure 23: The difference in liquid xenon purity between the model that accounts for time dependent outgassing and the model that approximates the outgassing rate as constant. A positive difference corresponds to a better purity for the time dependent model.

The most significant values for the experiment are the equilibrium purity and the rise time. I first examined the equilibrium purity which I found algebraically by setting the derivatives to 0 and using a constant outgassing rate as a function of cryogenic filter flow. The system found the final purity for a given flow rate and a set of different outgassing values. Figures 24 \((\epsilon_c = 0.9)\) and 25 \((\epsilon_c = 0.55)\) display the results with distinct lines corresponding to the different outgassing values. The figures show the significant effect of the filter efficiencies: in Figure 24 \((\epsilon_c = 0.9)\) a cryogenic filter flow rate of 3 LPM is sufficient to achieve a minimum of 1 ms electron lifetime for all outgassing rates while a flow rate > 5LPM is required to achieve the same purity in Figure 25 \((\epsilon_c = 0.55)\).

Figure 24: The equilibrium electron lifetime as a function of flow rate of the cryogenic filter. The cryogenic filter efficiency here is 0.9.
Figure 25: The cryogenic filter efficiency here is 0.55

Rise time was defined as the time taken to reach 90 percent the equilibrium value. The model determined rise time by first finding the equilibrium purity algebraically, as described above. The model then numerically integrated the system to have a way of searching for the time at which 90 percent of this equilibrium value is reached. The program finds the value closest to 90 percent of the equilibrium value and records the corresponding time. The dependence of rise time on flow rate of the cryogenic filter was also plotted for different outgassing values. Figures 26 ($\epsilon_c = .9$) and 27 ($\epsilon_c = .55$) display the results for each filter efficiency. Interestingly, for a given flow rate, higher outgassing rates have shorter rise times than lower outgassing rates. That is, the faster impurities enter the system, the faster the system approaches its equilibrium value. However, as we saw in the previous section, the equilibrium electron lifetime is lower for the higher outgassing rate, as one would expect.

Additionally, we can see that after a cryogenic flow rate of 3 LPM with $\epsilon_c = .9$ (Figure 26), there is little improvement in the system’s rise time. On the other hand with $\epsilon_c = .9$ (Figure 24), the graph doesn’t show similar asymptotic behavior until around 5 LPM.

For the development of Xenon nT it was most important to determine what flow rates would allow us to achieve the desired system characteristics for different outgassing rates. Accordingly I determined the cryogenic filter flow rate required to reach an equilibrium electron purity of 2 ms with different rise times. To determine these relationships with constant outgassing rates, I first algebraically solved for the flow rate for which equilibrium electron lifetime is 2ms. I then checked the rise time of the system under those conditions numerically. If the rise time was larger than a given time threshold, I incremented the the flow
Figure 26: The time taken to reach 90 percent of the equilibrium electron lifetime as a function of cryogenic flow rate. The cryogenic filter efficiency here is 0.9

Figure 27: The cryogenic filter efficiency here is 0.55

rate as necessary to reach 90 percent 2ms in the given time threshold. Of course, however, increasing the flow rate here to improve the rise time also improves the equilibrium purity. Figures 28 ($\epsilon_c = .9$) and 29 ($\epsilon_c = .55$) show this relationship between outgassing rate and flow rate for each filter efficiency. The different lines show the relationship for different time thresholds. The x-axis is presented in units of 3 times the initial Xenon 1T outgassing rate. With this model Figure 28 shows that at an outgassing rate of 3 ×(the Xe 1T outgassing rate), a filter efficiency of 3 LPM is sufficient to achieve even a 7 day rise time for $\epsilon_c = .9$. In Figure 29 we can see that this value is closer to 5 LPM with $\epsilon_c = .55$

At first the negative slope for the more restrictive time thresholds at lower outgassing
rates seemed odd. But as we saw in the graphs of rise time as a function of flow rate, a higher outgassing value actually leads to a smaller rise time. So in these graphs, the flow rate must be increased more for lower outgassing rates to have the same rise time as higher outgassing rates. This effect is only present when rise time, rather than final purity, is the more restrictive factor.

In the event of a significantly higher outgassing rate, I was curious to see how the time development of outgassing would effect the flow rate necessary to achieve the desired purity. It turned out to allow for a slightly smaller cryogenic filter flow rate than the model with constant outgassing rate parameters, as we can see in figures 30 and 31. Once again the
model displays the flow rate as a function of the outgassing rate. Here the x-axis covers a different range, starting at 1 unit of $3 \times$ the Xe 1T outgassing rate. The different lines correspond to the flow rates required to reach 1.8 ms electron lifetime at the end of the given time threshold. These calculations were done by integrating numerically and incrementing the cryogenic filter flow rate until it reached a sufficiently high value. Figures 30 ($\epsilon_c = .9$) and 31 ($\epsilon_c = .55$) display the results for each filter efficiency. For each filter efficiency the flow rate required to achieve a 7-day rise-time is reduced by about .5 LPM at an initial outgassing rate of $3 \times$ (the Xe 1T outgassing rate) relative to figures 28 and 29. There is even more significant improvement and larger differences for smaller time thresholds in ways we did not see in the constant outgassing rate model.

![Graph showing flow rate required to reach 1.8 ms purity after the given time thresholds for time dependent outgassing](image)

**Figure 30:** This graph shows the flow rate required to reach 1.8 ms purity after the given time thresholds for a higher range of outgassing values with a time dependent outgassing model. The cryogenic filter efficiency here is 0.9

### 3.4 Conclusions

For one, phase exchange does not have a significant impact on the final purity of the system unless the condensation probability is at least an order of magnitude larger than we expect it to be. We also have a better understanding and reference for the relationships among cryogenic filter flow rate, outgassing rate, rise time, and final purity.

Perhaps the best numerical summary are the following conclusions from the final models that accounted for time dependent outgassing. For a cryogenic filter efficiency of 0.55 to achieve $3 \times$ (the Xe 1T outgassing rate), a cryogenic filter flow of 3.3 LPM is required (< 14 day rise time). To achieve a 7 day rise time, a flow of 4.3 LPM is required. For a cryogenic
Figure 31: This graph shows the flow rate required to reach 1.8 ms purity after the given time thresholds for a higher range of outgassing values with a time dependent outgassing model. The cryogenic filter efficiency here is 0.55.

filter efficiency of 0.9 to achieve $3 \times$ (the Xe 1T outgassing rate), a cryogenic filter flow of 2 LPM is required (<14 day rise time). To achieve a 7 day rise time, a flow of 2.86 LPM is required. Higher flow will be required for higher outgassing rates.

Or alternatively, another way of looking at this is that if we achieve the desired flow rate (5 LPM) with the expected initial outgassing conditions and initial impurities, we will reach a 2 ms electron lifetime in a matter of days. Again, this maybe slightly skewed by an incorrect understanding of $P_{\text{cond}}$ parameter at the time the model was made in a way that enhances the performance of the system.

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5 Works Cited