Development and Construction of the IMix apparatus to measure evolution of impurities in liquid Xenon

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Sylvia Greene\textsuperscript{1}, Guillaume Plante\textsuperscript{2}, Michael Murra\textsuperscript{2}

\textsuperscript{1}Macalester College, \textsuperscript{2}Columbia University
XENONnT experiment

• Only 5% of the universe is made up of visible matter

• There is overwhelming cosmological evidence for the existence of Cold Dark Matter which makes up about 25% of the mass of the universe.

• Dark Matter particles are predicted to interact only very weakly with standard model particles, but must be sufficiently massive to account for gravitational effects seen throughout universe.

• Such candidate particles are called WIMPs (Weakly Interacting Massive Particles).

• WIMPs are predicted to have masses in the range 2GeV to 100TeV.
The XENONnT experiment consists of a large detector located at the Laboratori Nazionali del Gran Sasso in Italy. The experiment consists of 3 nested detectors: the first is a large cylindrical water tank that acts as a Muon veto, within the water tank is a separate neutron veto, and within the neutron veto is the Liquid Xenon Dual Phase Time projection chamber (LXe TPC).
• The TPC produces the main source of data that is used to identify potential WIMPs.
• Gaseous and 5t liquid phase xenon
• When a particle enters the TPC it can scatter off of a Xe atom via electronic or nuclear recoil.
• This interaction will produce two signals called S1 and S2
• The S1 and S2 signals can be used to reconstruct the collision location and energy of the colliding particle.
• Through S1 and S2 signals, as while as other signals from the outer ’shells’ of the detector the collision can be classified as being that of a WIMP particle or not.
• Image courtesy of XENON Collaboration

• In order for the WIMP particle or other interesting particles to be detected background sources need to be reduced

• Particularly problematic background sources are neutrinos, neutrons, $^{222}\text{Rn}$, and $^{85}\text{Kr}$.

• While neutrinos and neutrons can effectively be shielded or vetoed, impurities within the TPC like $^{222}\text{Rn}$, and $^{85}\text{Kr}$ create a more persistent background.

• In order to accurately detect dark matter particles the background from these impurities must be reduced and characterized.
IMix (Impurity Measurement In Liquid Xenon) Goals

• Characterize the evolution of impurities in LXe

• Determine the relative volatilities of different impurities in GXe/LXe

• Understand how different characteristics of the detector affect impurity evolution

• Better understand the backgrounds in LXe TPCs.
Motivations

• Understanding the transport of impurities in large detectors is important because
  □ TPCs uses internal radioactive sources for calibration
  □ Adding these sources is effectively adding impurities and they need to be managed.
  □ Methods to add and remove impurities are needed.

Photo of impurity removal test apparatus from Xclipse
IMix

- Volatility of most species in LXe is unknown and must be determined experimentally.
- Volatility describes the tendency for a species to vaporize.
- Relative volatility is the ratio of vapor pressures of two components.
- Pressure and temperature dependent.
- The iMix experiment will measure the relative volatility of $Ar$, $Kr$, $H_2$, $O_2$, $He$, $CO_2$, and $N_2$.

Figure courtesy of XENON Collaboration
Basic IMix Design
IMix Setup
Construction

• A lot of the project was spent constructing the apparatus
• Leak checking the valves and tubing
• Installing the level meter and temperature sensor.
• Installing sampling tubes
• Installing liquid xenon vessel.
• Closing the system
Heat Flow Calculation

- Liquid xenon needs to be kept at 177K in order to remain in the liquid phase.
- For volatility measurements temperature needs to be held constant.
- Heat added to the vessel will effect how impurities move.
- Want to control amount of heat entering system.
- 2 main sources of heat
  - Radiative heat flow from the vacuum to the multilayer insulation
  - Conductive heat flow

Apparent Thermal Conductivity of MLI: \( k_a = \frac{1}{n/\Delta x} \left[ h_s + \left( \frac{\sigma e T_2^3}{2-e} \right) \left[ 1 + \left( \frac{T_1}{T_2} \right)^2 \right] \left( 1 + \frac{T_1}{T_2} \right) \right] \)

Conductive Heat Flow: \( Q_c = -k_a A \frac{dT}{dx} = 0.0172 \text{ W/m}^2 \)

Radiative Heat Flow: \( Q_R = \sigma A_1 F_A F_E (T_1^4 - T_2^4) = 2.54 \text{ W/m}^2 \)

\( Q_T = 2.55 \text{ W/m}^2 \) which is within the cooling abilities of the refrigerator.
Maximum Tolerable Leak Rate

• Want to know the maximum leak rate from
  • a) outside the vessel
  • b) within the tubes in the vessel, such that we can still resolve $100 \pm 10\text{ppm}$ of impurities

• The maximum tolerable leak rate from outside of the vessel is $Q_L = 9.6 \times 10^{-10}\text{mbar L/s}$

• The maximum tolerable leak rate from the tube fittings inside the vessel in order to maintain impurity resolution from the liquid sample is $Q_L = 9.7 \times 10^{-8}\text{mbar L/s}$
Level Meter Read out

- Inside the LXe vessel there is a capacitor which is used to measure the volume of LXe in the chamber.
- Capacitance: \[
\frac{2\pi\varepsilon_0}{\ln(b/a)} L
\]
- Capacitance of device changes as level changes because the permittivity (\(\varepsilon_0\)) between plates of the capacitor changes.
- Level meter resolution in mm: \[
\frac{\sigma}{8\mu F} = 45\mu m
\]
Residual Gas Analyzer (RGA)

- The device used to determining the composition of gas from the LXe is the Residual Gas Analyzer (RGA).
- Made up of three components
  - Ion source
  - RF Quadrupole
  - Faraday cup and electron multiplier.
- The ion source produces electrons which collide with gas molecules and atoms to create positively charged ions
- The ions are then focused toward the RF Quadrupole
- The RF quadrupole acts as a mass filter, only allowing ions with a specific mass to charge ratio through.
- Measured current is directly proportional to the partial pressures of the gas of a specific species.
RGA

• Understanding the characteristics of the RGA, as while as tuning it to optimal sensitivity are crucial to getting the best resolution of the contents of the samples.

• Reducing the background increases the sensitivity of the RGA.

• Tuning the RGA scan parameters can also increase the sensitivity.

• Interpreting the spectra for different RGA scans can be used to optimize the RGA and to characterize components.
RGA scans and interpretation

- Different molecules and atoms have different Cracking Patterns
- A spectrum taken from a sample with multiple species may have overlapping peaks for ions with the same charge to mass ratio.
- Known gases have known cracking patterns which can be used to tune and RGA and to interpret spectra

Figure from O'Hanlon, John F. *A User's Guide to Vacuum Technology*. Wiley-Interscience, 2003
Commissioning Plan

- Take RGA spectrum of background gases in vacuum. (vary different RGA parameters)
- Take spectrum with sample consisting of a known quantity of Xe + He.
- Determine RGA sensitivity
- Bake the RGA.
- Take background spectrum after baking.
- Close system
- Evacuate system
- Fill system with Xe
- Add known impurities
- Measure relative volatility.
Background Scans in Vacuum

- Scan for the vacuum background at pressure of $2.68 \times 10^{-8}$ mbar
- Composition is mostly water, nitrogen and hydrogen and carbon dioxide.

![Graph showing current vs m/z for background scan]

![Graph showing current vs M/z for Background Scan in Vacuum]
Improving Background through Baking

• The RGA vessel is heated to high temperatures “baked” in order to outgas the system.
• Reduces the amount of background in vacuum.
• Allows for higher sensitivity to impurities
**Xe + He Sampling Scans**

- A sample containing 10% He and 90% Xe was connected to an RGA.
- A small amount enters the RGA via a leak valve, but the system remains at vacuum.
- This sample allows us to characterize and tune the RGA specifically for what the expected samples from the vessel will be.
- Measured spectrum agrees with tabulated isotopic abundance for Xe.
Electron Multiplier (SEM) comparisons

- The SEM is located directly after the Faraday Cup in the RGA
- When turned on it increases the measured current by specified gain factor (G)
Determining RGA sensitivity

• The sensitivity of the RGA can be approximated by adding the peak current for each species and dividing by the total pressure of the RGA vessel.

\[ S = \frac{\sum i_n}{P} \]

• Using the electron multiplier increases sensitivity.
RGA sensitivity to Xe
Partial Pressures

• The partial pressure of a species in the sample is found by dividing the peak ion current of the species by the gain and sensitivity of the RGA for that species if the peaks are separate.

• \[ P_n = \frac{i_n}{G_S n} \]

• The sensitivity factor for multiple different species is can be found in tabulated data, and then corrected for based on the experimentally determined sensitivity of the RGA.
Changing Sample from Xe to air

- In order to take an RGA scan a smaller volume is filled with the sample gas.
- Want to know the size of the smaller volume
- Change composition at a known time and measure how long it takes the RGA to register change.
- Can determine the volume of the sample and the amount of time it takes for the old sample to clear from the RGA.
Exponential pressure growth due to change of samples

\[ y = ae^{t/\tau} + b \]

- Calculate time constant (\( \tau \)) of exponential and determine how long it takes to connect the small volume
- Determine size of the volume
- The Turbopump has a through put of 200L/s
- Pressure of the RGA vessel during sampling is \( 2 \times 10^{-7} \text{ mbar} \)
- Time to pump small volume: \( \tau = 2123.6 \text{ seconds} \)
- Volume: \( V = \left( \frac{200 \text{ L}}{s} \times 2 \times 10^{-7} \text{ mbar} \times s \times \tau \right) = 0.0849 \text{ cm}^3 \)
- It would take a very long time to get rid of the old sample before taking new data
- Need another way to clear the chamber: attach to separate turbo pump and evacuate.
Next Steps

- Cool down system
- Measure/calculate the rate of heat flow
- Fill with LXe and take samples to understand background
- Fill with known impurities
- Determine volatilities of impurities
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