Purification Methds in Time Projection Chambers

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Introduction

1. Time Projection Chambers and Experiments
2. Importance of Purity
3. Measuring Purity
4. Purification Methods

Time Projection Chambers

- Time Projection Chambers were created at LBL to study particle tracks [1].
- Particle interactions produce ionization and primary scintillation(S1)
- Electrons drifted through electric field up to wire grid to give radial and axial coordinate
- Drift time gives the z-coordinate

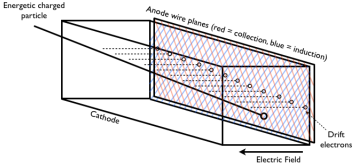

Figure: Time Projection Chamber (wikipedia.org)

Dual-phase Time Projection Chambers

- Uses both gas and liquid phases for operation.
- Near the anode, the electrons are extracted through the gas phase using another electric field.
- Extraction produces scintillation (S2), proportional to the extraction field.
- Allows for the study of ionization and scintillation simultaneously[3]

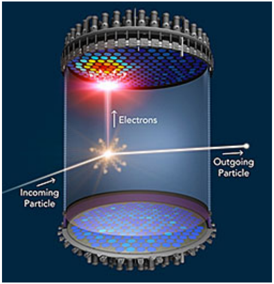

Figure: Lux-Zepplin (SLAC)

Choice of detector medium

Requirements for TPC medium

- Scintillates; transparent to scintillation frequency
- Dense: more targets for incoming particles
- Chemically inert: ionization doesn't cause chemical reactions
- Manageable boiling point: so it can be boiled and liquified easily

Xenon checklist

- Noble gas
- Boils at 161 K (For reference, LN_2 is 77K)
- Liquid phase density: 3.1 g/cm^3 (For reference: granite is 2.75 g/cm^3)
- Xenon Scintillation light: 178 nm[4]. Xenon has no strong arbsorption lines at that wavelength[3].

Figure: Xenon bulb (images-of-elements.com)

The Need for Purity

- Xenon is good for TPCs, so why don't we just buy a bunch of it?
- Radioactive impurities will create events which cause problems for rare event searches.
- Electronegative impurities will absorb ionization signal
- Impurities will absorb scintillation signal

Rare Events

- Current Limits on dark matter: $10^{-45} cm^2$ for 10 GeV WIMP(LUX 2016)[5]
- Current limits on $0\nu\beta\beta$ decay: 2.1×10^{25} years (GERDA 2016)[6]
- Current limits on $Br(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$ [8].
- Need to eliminate backgrounds and other obstacles to observing these events.

Obtaining Xenon

- Xenon is manufactured using cryogenic fractional distillation[7].
- Air is passed through filters, then liquified.
- Volatile gases are boiled off, then less volatile liquids are condensed until relatively pure liquids are produced.
- Xenon is commercially available at impurities of 50 ppm[8].

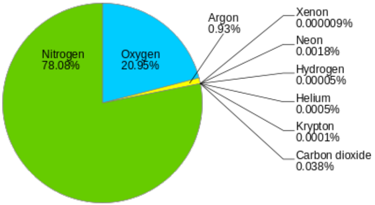

Figure: Composition of the atmosphere (wikipedia.org)

Radioactive Impurities

- Radioactive impurities will cause the detector to trigger
- Particularly bad: inert, long half-life, low energy emitters
- Main emitters inside the Xenon are radioactive isotopes, Radon, and Krypton
- Ultimately we want these impurities to be removed, and then to be able to estimate how much remains.

Xenon Isotopes

- Longest lived Xe isotope: ^{127}Xe with $\tau_{1/2} = 36$ days [9].
- Dark matter experiments generally wait for activated Xe to decay, then look for the 35 keV γ from ^{127}Xe decay path to estimate contamination.
- The Enriched Xenon Observatory centrifuge natural Xe until ^{136}Xe is enriched [10].

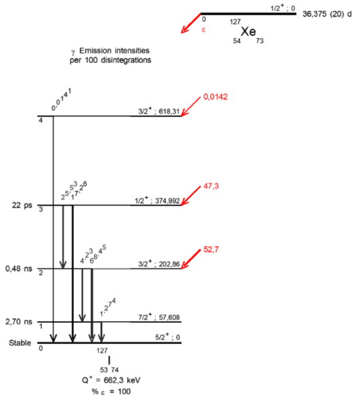

Figure: Xenon decay channel [11]

Centrifugal Enrichment

- Why isn't centrifugal enrichment used all the time?
- Expensive: both in terms of time and money
- Waste: you end up with depleted Xenon
- Xenon decays quickly as it is
- Will end up being activated unless it is taken underground immediately

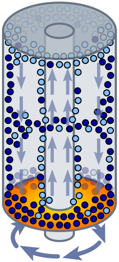

Figure: Gas Centrifuge (wikipedia.org)

Radon

- Noble gas, hard to remove
- ^{222}Rn Decay chain relatively fast, easily identified by 7 MeV α emission from ^{214}Po decay.
- Nothing in particular is done to remove Radon from Xenon in most TPC experiments.
- Most experiments are worried about sources of Radon, i.e. from the detector materials.

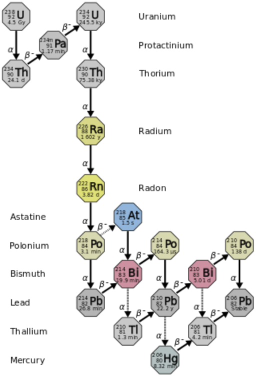

Figure: Radon decay chain

^{85}Kr

- ^{85}Kr has $\tau_{1/2} = 11$ years.
- LUX and XENON removed Krypton with a charcoal distillation column.
- Xe was passed through a column of charcoal, where Xe and Kr adsorbed at different rates.
- LUX reported ^{nat}Kr levels of 4 ppt, and 3.6 low energy backgrounds in 90 days.
- Decays into an unstable ^{85}Kr state, so the "double bang" signal can be used to estimate contamination.

Figure: Charcoal (instructables.org)

Electronegative Impurities

- Why do electronegative impurities matter?
- Absorption of scintillation light
- Quenching of scintillation light
- Absorption of electrons
- Electronegative impurities include O_2, H_2O, N_2, and essentially any organic molecule.
- The effects of the impurities may be used to estimate their contamination level

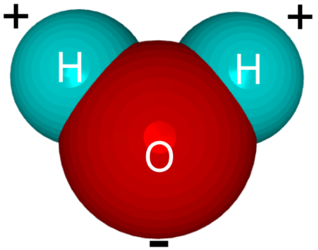

Figure: Water molecule (wordpress.com)

Estimating Impurities - Scintillation Quenching

- Xenon/ Argon scintillation mechanism [12]

$$\begin{aligned} \mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^* + \mathrm{Xe} \qquad & \mathrm{Ar}^* + \mathrm{Ar} + \mathrm{Ar} &\rightarrow \mathrm{Ar}_2^* + \mathrm{Ar} \\ \mathrm{Xe}_2^* &\rightarrow 2\mathrm{Xe} + \gamma & \mathrm{Ar}_2^* &\rightarrow 2\mathrm{Ar} + \gamma \end{aligned}$$

- Both Xe and Ar excited states (eximers) have triplet and singlet states, all with different lifetimes.

$$\begin{aligned} \tau(\mathrm{Xe}_T) &= 21ns \qquad & \tau(\mathrm{Xe}_S) &= 4.1ns \\ \tau(\mathrm{Ar}_T) &= 1.1 - 1.6\mu s & \tau(\mathrm{Ar}_S) &= 4 - 6ns \end{aligned}$$

- Process may be quenched in the presence of Oxygen

$$\mathrm{Ar}_2^* + \mathrm{O}_2 \rightarrow 2\mathrm{Ar} + \mathrm{O}_2$$

- Which leads to a reduction in the Argon triplet lifetime, which may be used to measure the impurity level. [13]

$$\frac{1}{\tau'_T} = \frac{1}{\tau_T} + k_Q[O_2]$$

Estimating Impurities - Ionization Electron Absorption

- Electrons will attach to Oxygen molecules

$$e_2 + O_2 \rightarrow O_2^-$$

- In the limit that electron concentration is much less than the oxygen concentration, the ionization electron lifetime can be estimated by

$$\frac{1}{\tau_e} = k_e[O_2]$$

Where k_e is the drift-field dependent rate constant, equal to 1.9 ppm^{-1} μs $^{-1}$ at 1 kV/cm.

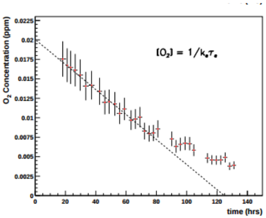

Figure 2. Time evolution of τ_e [Top] and O_2 concentration [Bottom] in the WArP 2.3 lt chamber during Argon purification process. The O_2 concentration values are inferred assuming the k_e value as known, 1.9 ppm$^{-1}\mu$s^{-1} $\pm$ 25 %.

Figure: Cavanna et al. 2010

Estimating Impurities - Scintillation Light Absorption

- Even though Ar and Xe are transparent to their own scintillation, impurities may absorb well in the VUV range.
- Probability of absorption per path length is k_A, the mean free path is l_A:

$$\frac{1}{l_A} = k_A[O_2] = \sigma_A(\lambda)n(O_2)[O_2]$$

- This gives an expression for photon survival rate as a function of distance :

$$T_A(x, \lambda, [O_2]) = e^{-xk_A[O_2]}$$

- In the Argon scintillation region, relevant process is Oxygen dissociation into triplet and singlet states

Electroluminescence

- An additional consideration of the purity is that near the electrodes, breakdown occasionally occurs[17].
- Breakdown causes flashes, which in the time projection chamber gets picked up by the photomultiplier tube.
- At the high voltages that are experienced in TPCs, this electroluminescence will cause problems for rare event searches.
- This electroluminescence is thought to be at least partially caused by the impurities within the medium (whether that be Argon or Xenon).

Electropositive purifications

- So how do we get rid of electronegative impurities?
- Logical guess: react them with metals (which oxidize easily)
- Desire compounds that absorb a large amount of a wide variety of impurities for a given weight of material.
- Titanium fits these requirements, as it burns in Nitrogen.
- Zirconium is also good for these purposes as one can heat it to remove the reacted layers.

Figure: Titanium (images-of-elements.org)

Getters

- Getters are coatings applied to chambers which react with certain gases.
- Frequently used to maintain vaccuums, but they can also be used to purify inert gases.
- LUX used a Zirconium getter for continuous purification of its Xenon.
- Commercially available getters perform well enough for this purpose
- LUX's getter allowed for a drift length of 1.34 m, which is almost 3x the height of the active region (this is field dependent but is roughly in the ppt range)[15]

Figure: Getter Pills (saesgetters.com)

Heat Exchangers

- Disadvantage of getters are that they can only be used in the gas phase
- Detection medium must be pumped out, evaporated, gettered, then condensed and reintroduced into the detector.
- Process is made more efficient by having the outgoing liquid cool the incoming, purified gas.
- LUX used two heat exchangers to accomplish this, and achieved a $>$ 94% heat exchange efficiency [15]

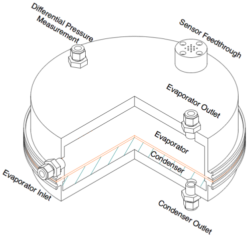

Figure: LUX Heat exhanger (arXiv:1207.3665.)

Titanium Sponges

- Pourous first stages of titanium manufacture
- Can be heated in vaccuum to remove oxide layer
- High surface area allows for a large fraction of its mass to react with the electronegative impurities.
- Has the potential to be used in situ and periodically replaced.

Figure: Titanium Sponge (images-of-elements.com)

Molecular Sieve

- Frequently used in either initial or continuous purification
- Liquid or gas phase is pumped through holes, which only absorb molecules below a certain size.
- The MEG experiment tested a centrifugal pump and a 13 $\AA$ sieve, which brings the impurities down from 250 ppb to 40 ppb [8].

Figure: Molecular sieve beads (hengyeusa.com)

Spark Gap Purification

- XENON proposal includes the use of a spark purifier [16].
- Titanium plates have a voltage put across them, causing an arc
- Bits of the plates are chipped off, which then reacts with the impurities.
- Has the advantage of being able to be used in the liquid phase.

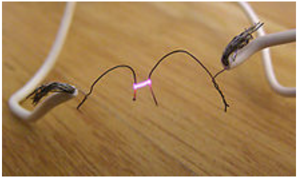

Figure: Example of arcing between conductors (wikipedia.org)

Conclusion:

- Impurities within the TPC scintillator will cause issues during rare event searches
- Radioactive impurities are removed either by waiting for them to decay, or removal through a distillation column
- Electronegative impurities are removed in a variety of ways, commonly a getter, molecular sieve, or spark discharge purifier.
- Impurity levels can be measured by either looking for distinct signals, or taking a measurement of electron/triplet lifetime.

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