Analyzing Gas Diffusion in LXe-TPCs for Upcoming Hydrogen Doping Studies

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Introduction

Liquid xenon time projection chambers (LXe-TPCs) currently lead the direct-detection search for dark matter (DM) in the form of weakly interacting massive particles (WIMPs). However, sensitivity is currently limited to DM with masses above 5 GeV/c^2. Hydrogen doping in LXe-TPCs would allow for better kinematic matching between light DM particles and target nuclei, expanding sensitivity to DM masses down to 200 MeV/c^2. Additionally, this method would introduce sensitivity to spin-dependent DM. So far, no major experiments have explored this parameter space [1].

Plans are underway to dope an existing small-scale LXe-TPC (XELDA) with H_2 to study behavior and mixing properties in LXe. This will include measuring the Henry coefficient and characterizing the charge-to-light spectrum of H_2 recoils in LXe. Prior to this, it is important to determine an expected time scale of H_2 diffusion and saturation in our TPC.

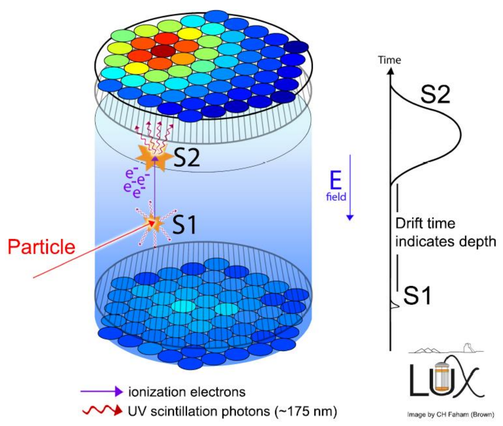

Fig 1. Diagram of an LXe-TPC. A WIMP interacts with a Xe nucleus, producing scintillation light (S1) and ionized electrons. An electric field drifts the charges to a liquid-gas interface, where they are extracted and produce a secondary scintillation signal (S2).

Methodology

Tritiated methane (CH3T) is a radioactive gas with mixing properties similar to H_2. In this project, CH3T is used to understand diffusion and equilibration of non-condensable gases in the XELDA detector.

Detector Operations

- Injected CH3T into source panel, then switched detector into forced circulation mode to encourage Xe-CH3T mixing.
- Returned to data acquisition after four hours of circulation and collected 12 ten-minute data sets.

Fig 2. The XELDA LXe-TPC.

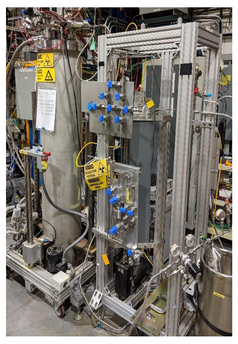

Fig 3. The full XELDA detector setup.

Data Analysis

- Processed and analyzed raw data using ROOT.
- Calculated overall trigger rate for each ten-minute data set to track CH3T activity in the LXe.
- Used S1 pulse area to discriminate between tritium beta decay and ‘other’ events, then analyzed rate trends separately.

Rate Analysis Results

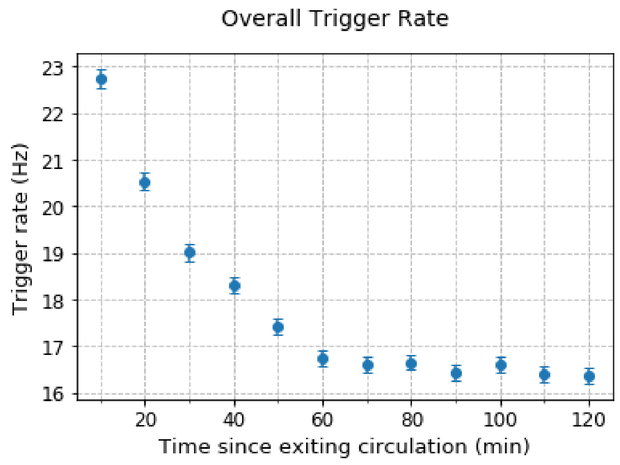

Fig 4. Overall trigger rate following four hours of circulation. The rate falls from 22.7 Hz to 16.4 Hz over a two-hour period, with stabilization beginning appx. one hour after exiting circulation.

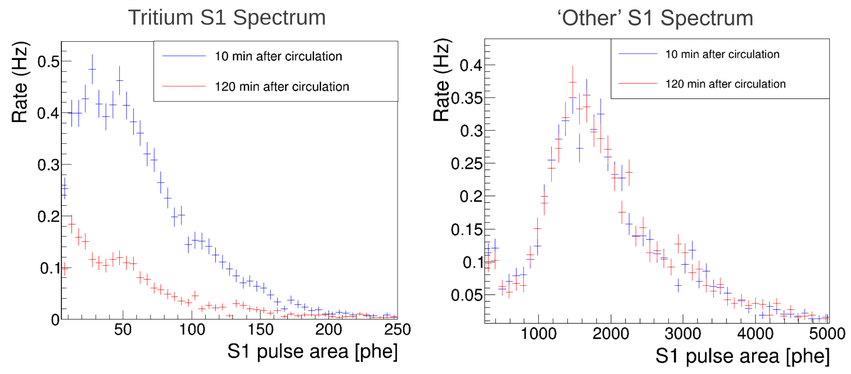

Fig 5. Comparison of rate-normalized S1 spectrums for tritium beta decay events (left) and all other events (right) before and after trigger rate stabilization. Two hours after circulation, the tritium rate fell significantly, whereas the rate of all other events remained constant. This confirms the trend in overall trigger rate was due to a decrease in CH3T concentration in the LXe.

The CH3T over-saturated the LXe during the four-hour circulation period and came into equilibrium approximately one hour after exiting circulation mode. Tritium decay events are still observed after rate stabilization, indicating that a measurable amount of CH3T remained in solution after equilibration.

H_2 Afterpulsing Calculation

Light gases can permeate PMT window materials over time, causing detrimental afterpulsing effects. This is illustrated by the results of an ET Enterprises study, which found that exposure to He at 1 atm causes significant afterpulsing after 17 min and PMT failure after 3 hours in a model 9266B PMT [2].

The pressure inside a PMT at time t is given by Eqs. (1) and (2). To find the permeability K, the data sets in Fig. 6 were extrapolated to T = 194 K. P_{int} was then calculated for XELDA’s top 1” PMTs (HM R850) at T = 194 K and P_{ext} = 1 atm.

$$P_{int} = C\ t\ P_{ext} / (1 + C\ t) \quad (1)$$

$$C = R\ T\ K\ A / (V\ d) \quad (2)$$

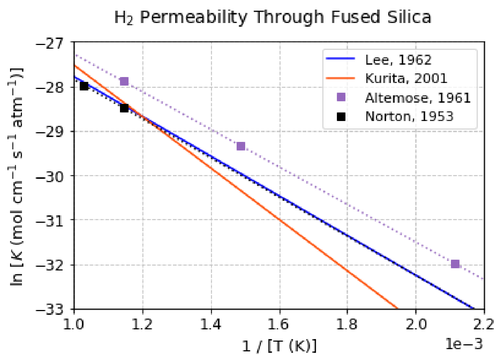

Fig 6. Fits to experimental data from Lee et al. [3], Kurita et al. [4], Altemose, and Norton [5], for K_{H2} in fused silica glass (1000 K < T < 455 K).

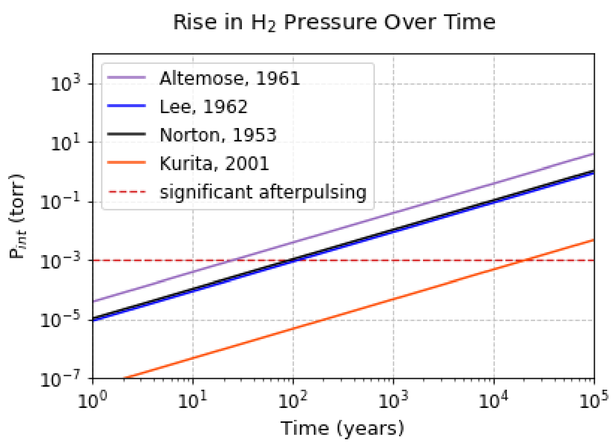

Fig 7. H_2 P_{int} over time at T = 194 K and P_{ext} = 1 atm. Our PMTs are projected to reach the significant afterpulsing threshold (10^{-3} torr) after appx. 26 yrs, 94 yrs, 115 yrs, and 19,000 yrs using permeability data from Altemose, Norton, Lee, and Kurita, respectively.

Conclusions

- Using our circulation methods, the CH3T saturated the LXe on a reasonable experimental time scale and remained in solution after circulation. We expect H_2 to display similar mixing behavior, presenting encouraging results for future operations.
- It is projected that H_2 will not cause significant afterpulsing in our PMTs until at least 26 years of exposure. Based on this analysis, it is unlikely that detrimental effects will occur within the time frame of our hydrogen operations.

References

[1] D. Temples, Low-mass dark matter reach in LXe-TPCs using hydrogen,” (2018).

[2] ET Enterprises Limited, “The effect of exposure to helium on photomultiplier performance and lifetime,” R/P101 Issue 1 (2012).

[3] R.W. Lee *et al*. “Diffusion of Hydrogen and Deuterium in Fused Quartz,” J. Chem. Phys. **36**, 1062 (1962).

[4] N. Kurita *et al*. “Measurements of hydrogen permeation through fused silica and borosilicate glass by electrochemical pumping using oxide protonic conductors,“ Solid State Ionics **146,** no. 1-2, (2002): 101-111.

[5] V. O. Altemose, “Helium Diffusion through Glass,” Journal of Applied Physics **32**, 1309 (1961).

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