HydroX: Hydrogen Doped LXe

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**Concept**

**G2 Xe TPCs:** LZ, XENONnT, PandaX-4T
- S2/S1 discrimination between NR/ER
- $m_\chi > 8$ GeV/c$^2$ (4 GeV/c$^2$ S2-only)
- Self-shielding (1 MeV $\gamma$, 6 cm; 1 keV n, 9 cm)

**Hydrogen dissolved in Xe:**
- LXe is excellent solvent for light gases
- Example: 2.6% mol fraction, ~2 kg H2 in LZ
- Better kinematic matching to low mass DM
Detection Techniques

- Dissolve H2 in LXe

- DM-H2 interactions:
  - DM scatters on H2 (proton)
  - Proton transfers energy to Xe ($m_H << m_{Xe}$)
  - Little energy lost to elastic scatters on Xe, more interactions with Xe e-s: ~5x signal boost
  - Signals read out like any normal Xe TPC

- PMTs are safe: H2 less problematic than He

- Unclear whether H-recoils will have S2/S1 that is ER/NR/in-between-like

- Presence of H2 in the gas phase will negatively affect S2 gain, but allows higher extraction fields before breakdown
  - Garfield sims suggest 40 ph/e- achievable at 120% of the nominal LZ extraction field
Sensitivity

Assumptions:

• H2 in LZ environment

• H2 mol fraction of 2.6%, 2.2 kg

• S2/S1 is ER-like (no discrimination)

• 250 live-day exposure
Proposed R&D

Will it work at all?

If it works, how do we calibrate it?

If it works and we calibrate it, can we make it work in a G2 Xe TPC?
Proposed R&D

Will it work at all? (XELDA test chamber at Fermilab)
  • Measure Henry’s coefficient, $H^{xp} \propto x/p$
  • Quantify effect of H2 concentration on S1 & S2 yield, S2 gain, and anode breakdown voltage
  • Preliminary Xe response to proton recoils

Calibration? Development of a low energy neutron source (UCSB/NU)
  • keV Iron Neutron (keVIN)
  • $^{124}$Sb-$^9$Be source of 24 keV $n$, iron for $\gamma$ attenuation and $n$ E-selection, scandium conduit gives 1-2.5 keV $n$

Can it work in a G2 Xe TPC? (cryogenic systems testing, Penn State)
  • Alternative purification (can’t use Zi getters)
  • Measure H2 diffusion in Xe. Requires forced convection?
  • Can we efficiently remove H2 from Xe?

Follow up with larger scale circulation testing + low energy proton recoil calibration at SLAC
Future Prospects

• H-doping gives new capabilities to existing Xe TPC (LZ, XENON, PandaX)

• Take advantage of existing operations infrastructure

• Xe self-shielding, not available in a conventional low mass experiment

• Detector response and backgrounds will be *well understood* before H-run even starts!

• Probe 100 MeV/c^2 – 5 GeV/c^2 DM masses, with SI and SD sensitivity
Backups
Deuterium

- Only stable $p$-odd AND $n$-odd nuclide

- Substitution of deuterium for H2 (with the same assumptions) shifts SI sensitivities down $\times 4$ and to the right by $\sqrt{2}$

- Provides sensitivity to SD DM-neutron interactions, sensitivity comparable to H2 SD interactions with a shift to the right by $\sqrt{2}$

- Plan to do deuterium measurements in parallel with H2
Dissolving H2 in LXe

• Henry’s law: solute (H2) concentration in liquid (Xe) is proportional to partial pressure in the gas phase.

• Increased solubility of a gas in liquid is correlated with a deeper minimum in the Van der Waals potential (H2 is 3x that of He).

• Xe is an efficient solvent because of its deeper VdW potential.

• Solubilities increase as a function of temperature.

• Extrapolation of existing measurements suggests 5% (2.6% conservative) H2 fraction is achievable.
Iron/Scandium Transmission

5 inches: Scandium, Iron

$^{124}\text{Sb}(1691 \text{ MeV } \gamma)$
$^9\text{Be}(\gamma, n)^{10}\text{Be}$

neutron energy range
XELDA

FNAL Test Chamber
$^{127}$Xe, 300 V/cm

Charge-to-light Spectrum
G1: 0.3
G2 (top): 20

Single Electron Spectrum
Single Electron Mean Size: 93.41 $\pm$ 0.06 phe
Single Electron Width: 17.32 $\pm$ 0.05 phe
Double Electron Width: 31.13 $\pm$ 0.21 phe
**XELDA**

- MCNPX-Polimi simulation
- Left: thermal neutrons
- Right: simplified keVIN source

- Due to XELDA's size, can get mono-energetic source of 1.3 keV deuterium recoils from neutron capture on protons (gamma escapes)

- Xe capture happens at higher rate, but has very low energy recoil

- Endpoints 1 and 2 correspond to maximum energy recoils for SbBe: 24 keV (98%), 379 keV (2%)
Timeline

• Jun 2020 – Operate Xe TPC with dissolved H2
• Mar 2021 – Measure >1 keV proton recoil yields
• Dec 2021 – Demonstrate efficient injection/removal of H2 from Xe
• Jan 2023 – Operation of H2-doped ~30 kg LXe TPC @ SLAC
• Dec 2023 – Development of project plan and design report
• 2025 – Tentative end of LZ science run