LZ Backgrounds and Mitigation

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Liquid Xenon TPC
(Time Projection Chamber)
10 tons xenon

LZ Shielding

TPC Only
Fiducial Mass: 3.8 T

Counts/ton/day
R \^2 (cm\(^2\))
Z (cm)

TPC+Skin+Gd-Scint
Fiducial Mass: 5.6 T

Counts/ton/day
R \^2 (cm\(^2\))
Z (cm)
Event Discrimination

- Detect **WIMPs** via **Nuclear Recoils (NR)**
- Most of our **background events** are **Electron Recoils (ER)**
- These two types of events produce different amounts of light and charge in the detector
  - Characterize charge-to-light ratios (S2 vs S1) and amounts as a function of energy
Background and Signal Calibrations

**Background Events**
- **Electron Recoil (ER)**
- Higher charge-to-light ratio
- Calibrate using high-statistics tritium dataset (LUX)

**Signal Events (WIMP-like)**
- **Nuclear Recoils (NR)**
- Lower charge-to-light ratio
- Calibrate using D-D neutrons (LUX)
  - *In-situ* nuclear recoil (NR) calibration
External Backgrounds

- Mitigated by xenon’s self shielding properties
- Quantified by position reconstruction
Reactive Backgrounds

- Mostly outgassing from detector materials
- Constant gas phase circulation/purification to maintain free electron lifetime
  - Requirement: 670 $\mu$s, already achieved with LUX
- Heated zirconium getter (commercial) removes non-noble impurities
Remaining Backgrounds in The Bulk Xenon
(Luckily these are ER backgrounds…)

• Solar neutrinos
  – Irreducible
  – ~1 event per day in LZ

• Radon
  – Prevent during construction
  – Internal mitigation
  – Goal: 0.67 mBq

• Krypton
  – Present in the air and therefore commercial Xenon
  – Removed in advance
  – Goal: 0.0015 ppt (1/10 of solar neutrino background)
• Radon emanation material screening program underway
• Two components to mitigation: Cold LXe volume vs. warm gas system:
  – LXe volume: 150 μm FEP cable cladding reduces dust and other contamination from steel braiding of the cables
  – Gas system: 8.6 kg charcoal filter added to online gas system, held at 186 K, traps 90% of radon from warm cables & PMT feedthroughs

<table>
<thead>
<tr>
<th>Item</th>
<th>Component</th>
<th>estimated</th>
<th>w/ cladding only</th>
<th>w/ trap only</th>
<th>w/ cladding &amp; trap combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT HV Cables</td>
<td>warm insulation</td>
<td>0.27</td>
<td>0.41</td>
<td>0.027</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>warm braiding</td>
<td>1.88</td>
<td>0.47</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>warm dust</td>
<td>13</td>
<td>0</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cold insulation</td>
<td>2.7 × 10⁻⁴</td>
<td>4.1 × 10⁻⁴</td>
<td>2.7 × 10⁻⁴</td>
<td>4.1 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>cold braiding</td>
<td>1.88</td>
<td>0</td>
<td>1.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cold dust</td>
<td>13</td>
<td>0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>PMT HV Cables</td>
<td>Subtotal</td>
<td>30.0</td>
<td>0.88</td>
<td>16.4</td>
<td>0.09</td>
</tr>
<tr>
<td>Cabling Conduits</td>
<td>warm &amp; cold</td>
<td>0.1</td>
<td>0.1</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>PMT Feedthroughs</td>
<td>warm</td>
<td>7.3</td>
<td>7.3</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>37.4</strong></td>
<td><strong>8.3</strong></td>
<td><strong>17.2</strong></td>
<td><strong>0.87</strong></td>
</tr>
</tbody>
</table>
Kr-85

- Kr-85 is an ER-like background (beta emitter)
  - Present in the atmosphere, half life of 10 years

\[ \sim 10,000 \text{ ppt} \rightarrow 3 \text{ ppt} \rightarrow 0.015 \text{ ppt} \quad (0.300 \text{ ppt}) \]

Commercial Xe & LUX & LZ Goal & (LZ requirement)

- 0.015 ppt corresponds to only a shotglass of air in 10 tons of xenon
- Remove via gas charcoal chromatography (with helium carrier gas)
  - Kr has a faster flow rate through activated charcoal than Xe
Kr Removal R&D System at SLAC

- Upgraded version of LUX Kr removal system (arxiv:1605.03844)
- Run through **Chromatography Loop** to trap Kr
- Then switch to **Recovery Loop** to recover purified xenon into condenser.
Distillation Assay System

- Cold-trap assisted RGA (arXiv:1103.2714)
- Sensitivity at the 0.005 parts per trillion level
- Will be moved to LZ for online purity monitoring
Results of Kr R&D

Commercial Xe: 1,000-100,000 ppt
LUX: 3 ppt
LZ Requirement: 0.3 ppt
LZ Goal: 0.015 ppt
R&D result 0.060 ppt

• Main challenges were cross-contamination and trace impurities in our UHP Helium
• Developed diagnostic tools such as a clean-xenon-backflow to systematically check isolated regions and components of the system
• Left with one more kr source in system which we could not fix
  – ‘Virtual leak’ from the gearbox of our recovery pump into the process space
  – Production system will use a different pump design without this failure mode
Kr Removal Production System

- Process all xenon at SLAC then ship to SURF
- About 1/2 of the LZ Xenon has already arrived and been assayed
- Scale up batch size by factor of 8 and overall processing rate by a factor of 20
  - 2 charcoal columns for continuous running
Conclusion

• Surpassed our Kr-85 requirement of 0.3 ppt by a factor of 5 and expect to reach our 0.015 ppt goal with production system
• Radon emanation screening program underway
• PLR-based analysis allows us to fully exploit ER & NR calibrations and profiling of backgrounds
• LZ is fully funded and construction has begun! Turns on in early 2020
Backup
Neutrino background

- Expect ~900 ER events, mostly from pp fusion chain
- Expect 7 coherent neutrino scattering (NR) events from $^8\text{B}$, plan to fit and subtract
- Expect 0.5 coherent scattering events from atmospheric neutrinos, irreducible, looks like high-mass WIMP
Profile Likelihood Ratio (PLR)

- Compares data to background distribution and signal distributions for different mass models
- Function of $S_1$, $S_2$, radius, and depth
- Fit for systematic parameters (derived from DD data)

i.e. Expected signal distribution for a 33 GeV WIMP
Photos of SLAC R&D System

Kr Trap
Dewar
Source & Accumulator Bottles

Gas Panel
Charcoal Column
Circulation Pumps
Condenser

Kr Trap in LN
Charcoal Column
Condenser (87 K)

Source
Diagnostics: Clean Xenon Backflow

Can make small amounts of <5 ppq Xenon with assay system

- Backflow small amount of xenon into test space
- Can diagnose contamination sources
  - led us to remove certain components from the recovery line and to discover the virtual leak in the recovery pump
## LZ Kr Removal System Scale up From LUX

<table>
<thead>
<tr>
<th>Scaling</th>
<th>LUX</th>
<th>LZ</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Column / slug size</strong></td>
<td>2 kg Xe slug in 60 kg charcoal</td>
<td>16 kg Xe slug in 500 kg charcoal</td>
<td>Saturation: fix M</td>
</tr>
<tr>
<td><strong>Chromatography</strong></td>
<td>120 min: 100 LPM 50 SLPM @ 0.5 bar</td>
<td>120 min: 1000 LPM 500 SLPM @ 0.5 bar up to 2000 SLPM @ 2 bar</td>
<td>Transit time ~ M flow); higher pressure reduces diffusion</td>
</tr>
<tr>
<td><strong>Recovery</strong></td>
<td>180 min: 1500 LPM 15 SLPM He @ 10 mbar 120 SLPM Xe at peak</td>
<td>120 min: 25000 LPM 250 SLPM He @ 10 mbar</td>
<td>Match chromatography time; conservative scaling since 1.5 faster × 8 M volume flow, or 18000 LPM</td>
</tr>
<tr>
<td><strong>Processing rate</strong></td>
<td>2 kg / 5 hours 10 kg/day 50 kg/week, incl. storage</td>
<td>16 kg / 2 hrs 192 kg/day 20T / 120 days (85% uptime)</td>
<td>Continuous processing in LZ - no downtime for storage; 2 passes of 10 T</td>
</tr>
</tbody>
</table>
Materials Screening

• Dedicated gamma counting facilities
  – Primary gamma emitting isotopes: $^{40}$K, $^{137}$Cs, $^{60}$Co, $^{238}$U, $^{235}$U, $^{232}$Th, (U and Th chains also responsible for neutron production)

• Intrinsic radioactivity goals for fixed contamination in detector components: single scatter rate less than 0.4 NR counts and less than $37 \times 10^{-6}$ events/keV/kg/d (37 μdru).

• Direct measurements of radon emanation from construction materials
  – Maximum tolerable activity is 10 mBq throughout LXe, 1 mBq goal for emanation
  – $^{210}$Pb activity on surfaces < 10 mBq/m$^2$, 0.5 for inner TPC surfaces

• Screening programs for cryostat titanium, detector PTFE, PMT bases & components, etc

• Robust cleanliness protocols during assembly

More info in arxiv:1703.09144
# Materials Screening Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Isotopic Sensitivity</th>
<th>Typical Sensitivity Limits</th>
<th>Sample Mass</th>
<th>Sampling Duration</th>
<th>Destructive/Non-destructive and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPGGe</td>
<td>$^{238}$U, $^{235}$U, $^{232}$Th chains, $^{40}$K, $^{60}$Co, $^{137}$Cs any γ-ray emitter</td>
<td>50 ppt U, 100 ppt Th</td>
<td>kg</td>
<td>Up to 2 weeks</td>
<td>Non-destructive, very versatile, not as sensitive as other techniques, large samples</td>
</tr>
<tr>
<td>ICP-MS</td>
<td>$^{238}$U, $^{235}$U, $^{232}$Th (top of chain)</td>
<td>$10^{-12}$ g/g</td>
<td>mg to g</td>
<td>Days</td>
<td>Destructive, requires sample digestion, preparation critical</td>
</tr>
<tr>
<td>NAA</td>
<td>$^{238}$U, $^{235}$U, $^{232}$Th (top of chain), K</td>
<td>$10^{-12}$ g/g to $10^{-14}$ g/g</td>
<td>g</td>
<td>Days to weeks</td>
<td>Destructive, sensitive to some contaminants</td>
</tr>
<tr>
<td>GD-MS</td>
<td>$^{238}$U, $^{235}$U, $^{232}$Th (top of chain)</td>
<td>$10^{-10}$ g/g</td>
<td>mg to g</td>
<td>Days</td>
<td>Destructive, minimal matrix effects, cannot analyze ceramics and other insulators</td>
</tr>
<tr>
<td>Radon Emanation</td>
<td>$^{222}$Rn, $^{220}$Rn</td>
<td>0.1 mBq</td>
<td>kg</td>
<td>1 to 3 weeks</td>
<td>Non-destructive, large samples, limited by size of emanation chamber</td>
</tr>
</tbody>
</table>
Distillation Assay System Signal

Average here to get pressure baseline

Signal integration window
Distillation Assay System Linearity

- Create stock calibration xenon with known Kr content
- Dilute with clean Xenon to map linearity
- Tune impedances of system and cold trap parameters to optimize signal and linearity