Noble gas purification for LZ and other rare event searches

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LRT – Jaca, Spain
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Z position from S1 – S2 timing
X-Y positions from light pattern

Reject gammas by S2/S1 ratio
Expect > 99.5% rejection
LUX-ZEPLIN (LZ) detector

7.0 T active LXe
5.6T fiducial

Instrumented Xe skin detector

50 kV cathode high voltage

17 tonnes Gd-LS Outer Detector

LXe supply & return

Backgrounds uniform in LXe

- Solar neutrinos
- Contamination of the xenon by:
  - Non-noble gases, eg $^3\text{H}$
  - Long-lived noble gases, eg $^{85}\text{Kr}$, $^{39}\text{Ar}$
  - Short-lived noble gases, eg $^{222}\text{Rn}$
Backgrounds uniform in LXe

- Solar neutrinos
- Contamination of the xenon by:
  - Non-noble gases, eg $^3$H
    Removed by Getter
  - Long-lived noble gases, eg $^{85}$Kr, $^{39}$Ar
    Removed before experiment start
  - Short-lived noble gases, eg $^{222}$Rn
    Mitigated by materials screening
    Removed while experiment is running
LZ Circulation

Liquid Xenon Tower
- Sub Cooler
- Cryovalves
- Reservoir
- 2 Phase HX

Compressors

Getter

Radon Removal

Storage and Recovery

Cable Breakout

LXe-TPC
- Weir
- TPC PTFE Walls
- LXe Skin

Weir Drain Pipe

Cable Stand Pipe

Xe Vapor

LXe Skin

Vacuum

Cathode High Voltage

Water Tank

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Circulation Getter

- LZ’s full 10 tonnes purified every 2.3 days
- Saes hot zirconium getter removes electronegative impurities
  - O$_2$, N$_2$, etc.
  - Critical for detector performance
- Getter also removes $^3$H
  - Eliminates this background
LZ – Radon Control

- Radon emanates from materials in contact with Xe
- Screening
  - Around 100 materials/components screened for LZ
  - Warm end of PMT cables potentially significant
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- In-line removal system
  - Impractical to purify 500 SLPM circulation
  - Practical to purify problematic areas
LZ – Radon Control

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• Screening
  • Around 100 materials/components screened for LZ
  • Warm end of PMT cables potentially significant

• In-line removal system
  • Impractical to purify 500 SLPM circulation
  • Practical to purify problematic areas

• Projected Rn level:
  • <2 μBq/kg
LZ Circulation
LZ – In-line radon removal

• Remove radon from subset of circulation flow
  • 0.1% of Xe flow, but significant Rn contribution

• Strategy: charcoal chromatography
  • Radon passes through charcoal slower than xenon
  • Design system to trap radon for many half-lives (3.8 days)

• Radon Removal system in development at the University of Michigan:
LZ – In-line radon removal

- Critical that charcoal remove more radon than it produces!
- Identify low-emanation; high adsorption charcoal

<table>
<thead>
<tr>
<th>Charcoal</th>
<th>Density (g/cm³)</th>
<th>Surface area (m²/g)</th>
<th>Spec. activity (mBq/kg)</th>
<th>Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shirasagi</td>
<td>0.45</td>
<td>1,240</td>
<td>101 ± 8</td>
<td>27</td>
</tr>
<tr>
<td>CarboAct</td>
<td>0.28</td>
<td>1,000</td>
<td>0.23 ± 0.19</td>
<td>15,000</td>
</tr>
<tr>
<td>Saratech</td>
<td>0.60</td>
<td>1,340</td>
<td>1.71 ± 0.20</td>
<td>35</td>
</tr>
<tr>
<td>Saratach (HNO₃)</td>
<td>0.60</td>
<td>1,340</td>
<td>0.51 ± 0.09</td>
<td>135</td>
</tr>
</tbody>
</table>
Any worry about cosmic-ray activation of xenon?

- Cosmic ray interactions produce radioactive byproducts in xenon cylinders at the Earth’s surface
- Many of these are solids, and will not enter experiment
- $^3$H will be removed by getter
- $^{127}\text{Xe}$
  - 36-day half-life reduces impact
  - Production rate too low to be significant background
- $^{133}\text{Xe}$
  - 5.2 day half-life reduces impact

- **We have the luxury of purifying Xe at the surface**

Kr Removal with Chromatography

- Remove via gas charcoal chromatography (with helium carrier gas)
  - Kr has a faster flow rate through activated charcoal than Xe
LZ Kr Removal - Chromatography

- 400 kg Charcoal Column
- Vacuum Pump
- Storage Compressor
- Bottles of Xenon
- Freezer
- Cold Charcoal Trap
- Circulation Pump
- Clean He
- Xenon with ppb Kr
LZ Kr Removal - Recovery

Cold Charcoal Trap
Circulation Pump
400 kg Charcoal Column
Vacuum Pump
Clean He
Freezer
Storage Compressor
Bottles of Xenon
LZ Kr Removal - Storage

Cold Charcoal Trap

Circulation Pump

400 kg Charcoal Column

Vacuum Pump

Freezer

Ultrapure Xe

Storage Compressor

Bottles of Ultrapure Xenon
LZ – Krypton Removal

• Employ 2 columns to clean xenon twice as fast!
• LZ system to process 16 kg slugs every two hours
• Plan to purify 10 tonnes over 6 months
• R&D system reduced Kr content to 0.06 ppt
• LZ system designed to achieve 0.015 ppt (15 ppq)
  • Subdominant to solar neutrinos
  • LZ requires < 0.3 ppt
  • Currently commissioning system
Centrifuge Purification - EXO

- Enriched Xenon Observatory (EXO-200) searched for neutrinoless double-beta decay in $^{136}$Xe
- Centrifuges used to enrich heavy isotopes of Xe
  - $^{136}$Xe fraction increased from 8.9% to 80.6%
- Other lighter elements also removed by this process
  - Including $^{85}$Kr and $^{39}$Ar
- Kr concentration reduced to $16.3 \pm 1.9$ ppt

The EXO-200 detector, part I: detector design and construction, EXO Collaboration. Journal of Instrumentation 7 (05), P05010, 2012
Cryogenic Distillation: Krypton

- Employed by XMASS, XENON100, XENON1T, PANDAX...
- Distillation tower for XENON1T
- Operates at -98 C;
- Vapor pressure of Kr is 10.8x greater than of Xe
- High-Kr gas extracted from the top
- Low-Kr liquid extracted from bottom

- Achieved lowest reported Kr level: < 17 ppq

Cryogenic Distillation: Radon

- Demonstrated on XENON100
  - Installed in series with circulation system
- Operates at -96 C;
- Low-Rn gas extracted from the top
- Rn decays in liquid at bottom

See also talk by Hardy Simgen later this session!

## Kr purity achieved

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technique</th>
<th>Purity Achieved (ppt g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panda X</td>
<td>Distillation</td>
<td>&lt;30</td>
</tr>
<tr>
<td>XENON1T</td>
<td>Distillation</td>
<td>&lt;0.017</td>
</tr>
<tr>
<td>XMASS</td>
<td>Distillation</td>
<td>2.1 ± 0.7</td>
</tr>
<tr>
<td>EXO-200</td>
<td>Centrifuge</td>
<td>16.3 ± 1.9</td>
</tr>
<tr>
<td>LUX</td>
<td>Chromatography</td>
<td>3.5</td>
</tr>
<tr>
<td>LZ R&amp;D</td>
<td>Chromatography</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Thanks for listening!
WIMP backgrounds summary

5.6 tonnes x 1000 days; ~1.5 to ~6.5 keV

<table>
<thead>
<tr>
<th>Background Source</th>
<th>ER (cts)</th>
<th>NR (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Components</td>
<td>9</td>
<td>0.07</td>
</tr>
<tr>
<td>Surface Contamination</td>
<td>40</td>
<td>0.39</td>
</tr>
<tr>
<td>Laboratory and Cosmogenics</td>
<td>5</td>
<td>0.06</td>
</tr>
<tr>
<td>Xenon Contaminants</td>
<td>819</td>
<td>0</td>
</tr>
<tr>
<td>222Rn</td>
<td>681</td>
<td>0</td>
</tr>
<tr>
<td>220Rn</td>
<td>111</td>
<td>0</td>
</tr>
<tr>
<td>natKr (0.015 ppt g/g)</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>natAr (0.45 ppb g/g)</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Physics</td>
<td>322</td>
<td>0.51</td>
</tr>
<tr>
<td>136Xe 2νββ</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td>Solar neutrinos (pp+7Be+13N)</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>Diffuse supernova neutrinos</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>0</td>
<td>0.46</td>
</tr>
<tr>
<td>Total</td>
<td>1195</td>
<td>1.03</td>
</tr>
<tr>
<td>with 99.5% ER discrim., 50% NR eff.</td>
<td>5.97</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Projected WIMP Sensitivity of the LUX-ZEPLIN (LZ)
Dark Matter Experiment, LZ Collaboration,
arXiv:1802.06039, 2018

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