The LZ Krypton Removal Chromatography System

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On behalf of the LZ collaboration
LIDINE 2021
The LUX-Zeplin (LZ) Detector

- Xenon based dark matter direct detection experiment, 7 tonne active volume
- Located at Sanford Underground Research Facility (SURF) in Lead, South Dakota
- Energy depositions result in light (S1) and charge (S2) signals
- 3D position reconstruction using PMTs (x-y) and drift time (z)
- Discriminate nuclear vs electron recoils with S1/S2 ratio
Shielding and background rejection

**Shielding**
- Water tank
- Underground: ~1 mile of rock
- Xenon self-shielding & fiducialization

**Outer detector system**
- Gd-loaded liquid scintillator
- Instrumented Xe “skin”

5.6 tonne Xe fiducial volume
Internal backgrounds

Background contributions for 1000 live days

<table>
<thead>
<tr>
<th>Source</th>
<th>Nuclear recoils</th>
<th>Electron recoils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector components</td>
<td>0.07</td>
<td>9</td>
</tr>
<tr>
<td>Xenon contaminants</td>
<td>0</td>
<td>819</td>
</tr>
<tr>
<td>Laboratory and cosmogenics</td>
<td>0.06</td>
<td>5</td>
</tr>
<tr>
<td>Surface contaminants</td>
<td>0.39</td>
<td>40</td>
</tr>
<tr>
<td>Physics (neutrinos, $^{136}$Xe 2νββ)</td>
<td>0.51</td>
<td>258</td>
</tr>
<tr>
<td><strong>Total (before ER discrimination &amp; NR efficiency)</strong></td>
<td><strong>1.03</strong></td>
<td><strong>1195</strong></td>
</tr>
</tbody>
</table>

**Xe contaminants: radioactive nobles**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>ER cts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn (1.8 μBq/kg)</td>
<td>681</td>
</tr>
<tr>
<td>$^{220}$Rn (0.09 μBq/kg)</td>
<td>111</td>
</tr>
<tr>
<td>$^{nat}$Kr (0.015 ppt g/g)</td>
<td>24.5</td>
</tr>
<tr>
<td>$^{nat}$Ar (0.45 ppb g/g)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Krypton-85 ER backgrounds

\[ ^{85}\text{Kr} \beta \text{ decay} \]

\[ ^{85}\text{Kr} \rightarrow ^{85}\text{Rb} + e^- + \bar{\nu}_e \]

\[ Q = 687.0 \text{ keV} \]

Krypton content

\[ ^{85}\text{Kr}/^{\text{nat}}\text{Kr}: \quad \sim 10 \text{ ppt } ^{85}\text{Kr} (10^{-11}) \]

Research grade Xe: \( \sim 5 \text{ ppb } ^{\text{nat}}\text{Kr} (10^{-9}) \)

LZ Xe goal: \(< 300 \text{ ppq } ^{\text{nat}}\text{Kr} (3 \times 10^{-13}) \)

ER background spectra in the fiducial volume for single scatter events (no cuts)
Gas Charcoal Chromatography

**Chromatography**: separation of a mixture based on differing transit times through a stationary medium

Relative concentration exiting the column vs time

- **Inject Xe w/ ppb Kr t = 0**

- **Constant helium flow**

Charcoal chromatography column at SLAC
Overview of the SLAC Kr removal system

1. **Chromatography:**
   Kr separated and discarded

2. **Recovery:**
   Purified Xe transferred to freezer

3. **Storage:**
   Xe compressed into cylinders for transport
Chromatography loop

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of columns</td>
<td>2</td>
</tr>
<tr>
<td>Charcoal mass per column</td>
<td>400 kg</td>
</tr>
<tr>
<td>Column pressure</td>
<td>1.3-1.4 bar</td>
</tr>
<tr>
<td>He flow rate</td>
<td>500 - 600 SLPM</td>
</tr>
<tr>
<td>Xe processed per cycle</td>
<td>16 kg</td>
</tr>
<tr>
<td>Cycle duration</td>
<td>3h</td>
</tr>
</tbody>
</table>
Detecting the end of chromatography

Rising Xe signal on residual gas analyzer (RGA, top), and binary gas analyzer (BGA, bottom)

BGA trace for one full chromatography cycle, showing Kr peak and rising Xe edge (600 ppm calibration xenon)
## Recovery: Remove purified Xe from column

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column pressure</td>
<td>10 mbar</td>
</tr>
<tr>
<td>Freezer pressure</td>
<td>600 - 800 mbar</td>
</tr>
<tr>
<td>He flow rate</td>
<td>100 - 150 SLPM</td>
</tr>
<tr>
<td>Recovery duration</td>
<td>2.5 - 3 hours</td>
</tr>
<tr>
<td>Freezer capacity</td>
<td>150 - 250 kg</td>
</tr>
</tbody>
</table>

3 stage vacuum pump maintains 10 mbar in columns during recovery circulation for high volume flow to maximize recovery speed.

LN lines (copper) run through collection plates (aluminum) in the freezer interior.
Helium reduction

- Trace He is entrained in Xe ice during recovery freeze-out
- He can damage PMTs -- require < 200 ppb for LZ PMT lifetime
- Pumping on Xe ice leaves O(1ppm) residual
- Solution: liquefy Xe to release entrained He, then refreeze and pump away He
- Result: O(10 ppb) He

Freezer pressure and temperature during warmup and recooling
Xenon storage

Storage compressor during unloading at SLAC

Storage packs being loaded onto a truck for transport to SURF
Impurity analysis

- RGA sensitive to ppm
- Cold trap increases concentration of impurities to measurable levels
- $10^5 - 10^6$ increase in sensitivity: 10s of ppq
- Fully automated with pneumatic raising & lowering of dewars
Automated processing

PLC (Programmable Logic Controller)

- Low level instrument control & readout (e.g. valves, sensors, pumps)
- Processes requiring high reliability & repeatability, e.g. circulation
- Xenon safety or equipment safety -- interlocks

Slow control (Ignition)

- Human interface with PLC
- High-level scripting in Python -- complex and long duration processes
- Alarms for sensors out of normal range
Run control

- High-level Ignition scripting in Python
- Directs PLC operations for long-term continuous unattended processing
- Coordinates parallel operations in both columns
- Interface with sampling system automation
- Tracks location and status of each “slug” of Xe

State-based alarms

- Dynamic alarm levels based on current system status
- Customizable “delays” to avoid transients
Summary

- Large scale gas chromatography purification system designed and built at SLAC purifies 16 kg of Xe every 3 hours, totalling 10 tonnes
- Xe purity is continuously monitored during and after processing
- Automation infrastructure written in Python enables 24/7 operation without human monitoring
- On track to exceed specifications for Kr (< 300 ppq) and He (< 200 ppb)

Purified Xe underground at SURF!
LZ (LUX-ZEPLIN) Collaboration
34 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

Thanks to our sponsors and participating institutions!

https://lz.lbl.gov/
Thanks!
Detailed system diagram
Run control process for a 2-column cycle

**Start:**
One column has clean Xe to be recovered (REC col)
Other column empty (CHR col)

**Reduce REC col pressure to ~10 mbar**
Increase CHR col pressure to ~1.4 bar

Begin circulation in recovery loop to transfer clean Xe to freezer

Take Xe sample from recovery loop for assay

End recovery circulation once clean Xe has been fully recovered

End chromatography circulation when Xe begins to exit CHR col

Begin chromatography circulation, feed source Xe into CHR column

Columns switch roles and a new cycle begins