Status and Results from the LUX-ZEPLIN Experiment

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On behalf of the LZ Collaboration
Lake Louise Winter Institute 2024
The LZ Collaboration

**LUX-ZEPLIN (LZ) is...**

- 250 scientists, engineers, and technical staff
- 37 institutions
- 5 countries (US, UK, Portugal, Korea, Australia)

- Follow us! @lzdarkmatter
- Our website: [https://lz.lbl.gov/](https://lz.lbl.gov/)
The LZ Experiment

1 mile under the Black Hills of South Dakota

Davis Cavern

Sanford Underground Research Facility
The LZ Experiment

**Dual-phase liquid xenon (LXe) time projection chamber (TPC)**

- 10 tonnes total mass
- 7 tonnes active mass
- 5.5 tonnes fiducial mass

![Image of the LXe TPC with dimensions 1.46 m]
Dual-phase liquid xenon (LXe) time projection chamber (TPC)

- 10 tonnes total mass
- 7 tonnes active mass
- 5.5 tonnes fiducial mass

Mesh wire grid electrodes

GXe extraction region between gate and anode—7.3 kV/cm
LXe drift region between cathode and gate—193 V/cm
Dual-phase liquid xenon (LXe) time projection chamber (TPC)
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Mesh wire grid electrodes
- GXe extraction region between gate and anode—7.3 kV/cm
- LXe drift region between cathode and gate—193 V/cm

Instrumented with 494 Hamamatsu R11410-22 3” PMTs
- 253 PMTs in top array
- 241 PMTs in bottom array
Event Reconstruction

A typical signal

Time [µs]
Event Reconstruction

A typical signal

S1

S2

Time [µs]
Event Reconstruction

A typical signal

\begin{itemize}
  \item Hit pattern gives radial position
  \item \(\Delta t\) gives vertical position
\end{itemize}

3D Position Reconstruction
Event Reconstruction

**A typical signal**

![A typical signal diagram](image)

**Energy Reconstruction**

\[ E = 13.5 \text{ eV} \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]

- \( g_1 \equiv \) S1 photons detected (phd) per scintillation photon
- \( g_2 \equiv \) S2 phd per ionization electron
A typical signal

Particle Identification
- Electronic Recoils (ERs) have exciton:ion ratio $\sim 0.06$  
  $\Rightarrow$ Favours ionization
- Nuclear Recoils (NRs) have exciton:ion ratio $\sim 1$  
  $\Rightarrow$ Favours scintillation
Outside the TPC

Anti-Coincidence Veto System

- **17 tonnes** Gd-loaded scintillator in OD
- High thermal neutron capture cross-section
- Release of ~8 MeV $\gamma$-rays from neutron capture

**LXe Skin** detector 78±5% efficient at tagging $\gamma$-rays from internal TPC decays
Outside the TPC

**Anti-Coincidence Veto System**

- Simulations show anti-coincidence veto reduces NR backgrounds in 1000 day run by factor of 10

6-30 keV nuclear recoils **before anti-coincidence veto**

- 10.4 events in fiducial mass

6-30 keV nuclear recoils **after anti-coincidence veto**

- 1.03 events in fiducial mass
First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

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The LUX-ZEPLIN experiment is a dark matter detector centered on a dual-phase xenon time projection chamber operating at the Sanford Underground Research Facility in Lead, South Dakota, USA. This Letter reports results from LUX-ZEPLIN’s first search for weakly interacting massive particles (WIMPs) with an exposure of 60 live days using a fiducial mass of 5.5 t. A profile-likelihood ratio analysis shows the data to be consistent with a background-only hypothesis, setting new limits on spin-independent WIMP-nucleon, spin-dependent WIMP-neutron, and spin-dependent WIMP-proton cross sections for WIMP masses above 9 GeV/c². The most stringent limit is set for spin-independent scattering at 36 GeV/c², rejecting cross sections above $9.2 \times 10^{-48}$ cm² at the 90% confidence level.

DOI: 10.1103/PhysRevLett.131.041002
**SR1 Calibration**

**Tritiated methane** \((CH_3T)\) used to calibrate ER band
- spatially homogenous
- \(\beta\) spectrum with 18 keV endpoint energy

**DD fusion neutrons** used to calibrate NR band
- Monoenergetic neutron source; 2.45 MeV

**ER and NR bands** fit using NESTv2.3.7
- [GitHub link](#)

99.9% of ER events fall above NR band mean

\[
g_1 = 0.114 \pm 0.002\text{ phd}/\gamma \\
g_2 = 47.1 \pm 1.1\text{ phd}/e^- 
\]
**ER Band Backgrounds**

Total expected ER counts in ROI in first run: **276 + [0, 291] from $^{37}$Ar**

Total expected NR counts in ROI in first run: **0.15**

Dissolved $\beta$-emitters:
- $^{214}$Pb ($^{222}$Rn daughter)
- $^{212}$Pb ($^{220}$Rn daughter)
- $^{85}$Kr
- $^{136}$Xe ($2\nu\beta\beta$)

Includes $\gamma$-emitters in detector materials:
- $^{238}$U chain, $^{232}$Th chain, $^{40}$K, $^{60}$Co

ER backgrounds
- Dominated by $^{214}$Pb and $^{37}$Ar

Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- $^{37}$Ar
- $^{127}$Xe
- $^{124}$Xe (double e-capture)

Solar neutrinos (ER):
- $pp + ^7$Be $+ ^{13}$N

NR backgrounds:
- Neutron emission from spontaneous fission and ($\alpha$,n)
- $^8$B solar neutrinos

Accidental coincidence backgrounds:
- 1.2 events expected

**Accidental Coincidence Background**

- **Unrelated S1s & S2s** can accidentally combine to produce single scatter events.

- **Rate**: population of definite accidental events with drift time >1 ms

- **Distribution**: fake events constructed from lone S1 & S2 pulse waveforms

- Analysis cuts developed to combat observed pulse/event pathologies
  - >99.5% efficiency in removing accidentals
  - SR1 WIMP search counts: 1.2 ± 0.3
SR1 Results

- 335 events remaining after analysis cuts
- Statistical inference with Profile Likelihood Ratio (PLR) method
**SR1 Results**

**Data**

- **Total Observed Events**: 335

**World leading sensitivity**

- WIMP masses > 9 GeV
- Highest sensitivity at 36 GeV
- Power constrained at $-1\sigma$

### Table: Expected Events vs Fit Result

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Events</th>
<th>Fit Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ decays + Det ER</td>
<td>215 ± 36</td>
<td>222 ± 16</td>
</tr>
<tr>
<td>$\nu$ ER</td>
<td>27.1 ± 1.6</td>
<td>27.2 ± 1.6</td>
</tr>
<tr>
<td>$^{127}$Xe</td>
<td>9.2 ± 0.8</td>
<td>9.3 ± 0.8</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>5.0 ± 1.4</td>
<td>5.2 ± 1.4</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>15.1 ± 2.4</td>
<td>15.2 ± 2.4</td>
</tr>
<tr>
<td>$^8$B CEνNS</td>
<td>0.14 ± 0.01</td>
<td>0.15 ± 0.01</td>
</tr>
<tr>
<td>Accidental</td>
<td>1.2 ± 0.3</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>273 ± 36</td>
<td>280 ± 16</td>
</tr>
<tr>
<td>$^{37}$Ar</td>
<td>[0, 288]</td>
<td>52.5 ± 0.8</td>
</tr>
<tr>
<td>Detector neutrons</td>
<td>0.0+0.2</td>
<td>0.0+0.2</td>
</tr>
<tr>
<td>30 GeV/c$^2$ WIMP</td>
<td>...</td>
<td>0.0+0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>...</td>
<td>333 ± 17</td>
</tr>
</tbody>
</table>

**Total Observed Events**: 335

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**Data are consistent with background-only hypothesis**

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[Image of a graph showing the observed and expected limits for WIMP detection.]
A search for new physics in low-energy electron recoils from the first LZ exposure


(Received 28 July 2023; accepted 12 September 2023; published 9 October 2023)

The LUX-ZEPLIN (LZ) experiment is a dark matter detector centered on a dual-phase xenon time projection chamber. We report searches for new physics appearing through few-keV-scale electron recoils, using the experiment’s first exposure of 60 live days and a fiducial mass of 5.5 t. The data are found to be consistent with a background-only hypothesis, and limits are set on models for new physics including solar axion electron coupling, solar neutrino magnetic moment and millicharge, and electron couplings to galactic axionlike particles and hidden photons. Similar limits are set on weakly interacting massive particle (WIMP) dark matter producing signals through ionized atomic states from the Migdal effect.

DOI: 10.1103/PhysRevD.108.072006
Low Energy ERs

Anything interesting happening here?
Low Energy ERs

Neutrino Electromagnetic Moments

$\mu_\nu$ (neutrino magnetic moment)

$q_\nu$ (neutrino millicurrent)

$$\frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_\nu^2 \mathcal{O}(E_r^{-1}) + q_\nu^2 \mathcal{O}(E_r^{-2})$$
Low Energy ERs

Neutrino Electromagnetic Moments

\[ \frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_L^2 \mathcal{O}(E_r^{-1}) + q_L^2 \mathcal{O}(E_r^{-2}) \]

Solar axions/ALPs

Hidden photons

[Diagram showing various energy levels and decay processes related to neutrino electromagnetic moments and solar axions/ALPs.]
Low Energy ERs

- Solar axions/ALPs
- Hidden photons
- Migdal Effect

Neutrino Electromagnetic Moments

\[ \frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_\nu^2 \mathcal{O}(E_r^{-1}) + q_\nu^2 \mathcal{O}(E_r^{-2}) \]
Low Energy ERs

Neutrino magnetic moment most stringently constrained by astrophysical observations

LZ upper limit: \(1.36 \times 10^{-11} \mu_B\)

\[
\frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_L^2 \mathcal{O}(E_r^{-1}) + q_L^2 \mathcal{O}(E_r^{-2})
\]

Neutrino electromagnetic moments

Neutrino magnetic moment \(\mu_L\) (neutrino magnetic moment)

Neutrino millicharge \(q_L\) (neutrino millicharge)

Leading neutrino millicharge observed

LZ upper limit: \(2.24 \times 10^{-13} e_0\)

\(e_0 \equiv \text{electron charge}\)

\(\mu_B \equiv \text{Bohr magneton}\)
Low Energy ERs

- Solar axions/ALPs
- Hidden photons

**Graphs:**
- ALP Mass, $M_{ALP}$ vs. Axio-Electric Coupling, $g_{ae}$
- Hidden Photon Mass, $M_{HP}$ vs. Kinetic Mixing Parameter, $\kappa$
- Solar Axion Mass, $m_A$ vs. Axio-Electric Coupling, $g_{ae}$

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Low Energy ERs

Migdal Effect
In Summary

LZ first results set world-leading upper limits for WIMPs
Competitive searches for physics in low energy ERs
Continuing to take data for future WIMP searches

In the pipeline

Nonrelativistic Effective Field Theory
See Sam Eriksen’s talk next!
Ultra Heavy Dark Matter Search
Radon Tagging Veto
Muon Flux Measurements
Thank you!
Backup Slides
Atoms in the track of a recoiling nucleus become excitons or ions.
Excitons form excited dimers (excimers) with ground-state atoms
Excimers decay to ground and emit VUV photons: **S1 signal**
Ions form charged dimers, can recombine to become excimers.

Excimers decay to ground and emit VUV photons: **S1 signal**.
Electrons drift from liquid into gaseous extraction region.

**DRIFT REGION**
\[ \overrightarrow{E} \sim 100 \text{ V/cm} \]

**EXTRACTION REGION**
\[ \overrightarrow{E} \sim \text{kV/cm} \]
Electroluminescence makes secondary VUV photons in gas phase: **S2 signal**

Electrons drift from liquid into gaseous extraction region

$\vec{E} \sim \text{kV/cm}$

$\vec{E} \sim 100 \text{ V/cm}$