CEνNS and the Search for Dark Matter in the LZ experiment

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On behalf of LZ Collaboration
Magnificent CEνNS 2021
Physics Reach of LZ

- LZ detector is multi-purpose (Swiss-Army-Knife)
- Projected World-leading Dark Matter Sensitivity
  - Full exposure: 15.3 tonne-year
  - SI WIMP-nucleon sensitivity: $1.4 \times 10^{-48} \, \text{cm}^2$ at 40 GeV
  - SD WIMP-neutron (proton) sensitivity: $2.7 \times 10^{-43} \,(7.1 \times 10^{-42}) \, \text{cm}^2$ at 40 GeV
  - Sub-GeV masses accessible via Migdal effect
- Search of Other DM Candidates:
  - ALPs, hidden photon, mirror DM, etc
- Non-DM Physics
  - Solar axions, supernova neutrinos
  - Neutrino magnetic moment
  - Search of $0\nu\beta\beta$
  - $2\nu\text{ECEC}$ on $^{124}\text{Xe}$
Working Principle of a TPC

Coherent → sees nucleus as a whole
Elastic → no nuclear excitations

Principle of a TPC
- Prompt primary scintillation light at interaction site → S1
- Ionization electrons are drifted to gas pocket where it produces light via electroluminescence → S2
- Drift time → z position at O(mm) precision.
- S2 channel pattern → (x,y) positions at O(cm) precision
- S2/S1 ratio → ER/NR Discrimination:
  ○ S2/S1 ratio depends on dE/dx
  ○ ER produces relatively more charge than NR
Background (ER/NR) to Dark Matter Search:

- **Internal LXe:**
  - $^{222}\text{Rn}$ (target: 2 $\mu$Bq/kg), $^{220}\text{Rn}$, $^{85}\text{Kr}$, $^{136}\text{Xe}$
- **Material $\gamma$-rays:**
  - $^{238}\text{U}$, $^{232}\text{Th}$ chains, $^{60}\text{Co}$, $^{40}\text{K}$
- **Physical:** solar $pp$ neutrinos
- **Detector material:** ($\alpha$,n) & spontaneous fission
- **Cosmogenic neutrons**
- **CEvNS:**
  - Solar $^8\text{B}$, Atmospheric, Diffuse Supernova, Solar hep
- **Surface backgrounds ($\alpha$-decays, recoiling nuclei)**

LXe TPC has powerful discrimination against ER backgrounds
Neutrons are suppressed by shielding & active neutron veto

Three Layers System:
1. A layer of LXe skin in the TPC inner cryostat, monitor by separated PMTs
   a. tagging γ-rays efficiency: >95%
2. Acyclic vessels surrounding TPC cryostat
   a. Gd (0.1% doped) loaded LS (Linear Alkyl Benzene)
   b. Neutron captured on Gd followed by emission of 3-5 γ-rays:
      i. \( n + ^{155}\text{Gd} \rightarrow ^{156}\text{Gd} + 8.5 \text{ MeV (18\%)} \)
      ii. \( n + ^{157}\text{Gd} \rightarrow ^{158}\text{Gd} + 7.9 \text{ MeV (82\%)} \)
   c. neutron veto efficiency > 95%
3. Water Tank as a passive shielding
Photo of the LZ TPC

TPC Assembled

Gate Wire Grid

TPC PMT Array (R11410-20)

TPC as it descends into Ti cryostat
Acyclic Vessels Inside the Water Tank

X. Xiang (2021)
LXe TPC as Neutrino Observatory via CEvNS

- LXe is an excellent target for CEvNS
  - Enhanced cross-section due to $\sim N^2$
  - Sensitive to sub-keV CEvNS (high scintillation and ionization yield)
- LXe TPC is optimized for observing rare NR from WIMPs (same as CEvNS signature)
  - Low background (radiopurity & shielding & veto)
  - $S2/S1$ (ionization to scintillation ratio) discriminates against Electronic Recoils (ER) events
  - Scalable detector

Suitable for observing natural neutrino via CEvNS down to 5 MeV
CEνNS from Natural Neutrinos

All CEνNS recoil spectra that LZ is capable of seeing

- $^8$B spectrum is the same as a 6 GeV WIMP
- Atm. spectrum is the same as WIMPs > 100 GeV

Supernova Neutrino

- LZ is a member experiment of the Supernova Neutrino Early Warning System 2.0 (SNEWS 2.0) network.
- Observed signal is a stream of S2 pulses within 10 seconds
Opportunity: the First $^8$B Observation via CE$\nu$NS

- $^8$B has never been observed in CE$\nu$NS channel. This is exciting!
- Events populate near threshold (purple).
- The expected event rate (FV=5.6e3 kgd) is sensitive to the thresholds (preliminary):
  - LZ threshold (3-fold, $N_{ee} \geq 5$): $(2.7 \pm 0.69^{\text{yield}})$ evt/100 day
  - Lower threshold (2-fold, $N_{ee} \geq 5$): $(12 \pm 2.3^{\text{yield}})$ evt/100 day
- A significant claim is not a matter of if, but a matter of when

NEST Simulation of $^8$B Rate in 100 day (preliminary)
(Assuming efficiency from the right plot)

<table>
<thead>
<tr>
<th>$N_{ee}$ ≥ e^-</th>
<th>3-fold (S1 ≥ 3 phd)</th>
<th>2-fold (S1 ≥ 2 phd)</th>
<th>S2-only (0 or 1 phd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{ee} \geq 8$ e^-</td>
<td>1.39</td>
<td>5.32</td>
<td>23.6</td>
</tr>
<tr>
<td>$N_{ee} \geq 7$ e^-</td>
<td>1.78</td>
<td>7.1</td>
<td>37.8</td>
</tr>
<tr>
<td>$N_{ee} \geq 6$ e^-</td>
<td>2.23</td>
<td>9.42</td>
<td>58.4</td>
</tr>
<tr>
<td>$N_{ee} \geq 5$ e^-</td>
<td><strong>2.73</strong></td>
<td><strong>12.1</strong></td>
<td>91.7</td>
</tr>
<tr>
<td>$N_{ee} \geq 4$ e^-</td>
<td>3.25</td>
<td>15.4</td>
<td>142</td>
</tr>
<tr>
<td>$N_{ee} \geq 3$ e^-</td>
<td>3.73</td>
<td>18.8</td>
<td>217</td>
</tr>
</tbody>
</table>

Arxiv: 1802.06039
An accidental coincidence event occurs when an isolated S1 randomly pile-up with an isolated S2.

**Possible sources of isolated S1:**
- Dark count pile up
- Cherenkov in PMT windows / PTFE wall
- Energy deposition occurs in non-drifting region

**Possible sources of isolated S2:**
- Field electron emission from gate and cathode grids
- Delayed electron emission following S2s (ex. electron trapped at liquid surface or captured by impurity)
- Radiogenic grid emission

**Data-driven Modeling**
- Find isolated S1 events and isolated S2 pulse, and randomly pair them up (top plots)

**Features & Rejection:**
- Asymmetric S2 pulse shape (Machine Learning)
- Drift time is uncorrelated to electron diffusion (Drift time vs S2 width)
- Correlate with PMT that has abnormally high DC rate (PMT tagging)

**BDT technique in LUX** (K. Oliver-Mallory 2020):
- (b): Longitude electron diffusion → S2 pulses from bulk LXe are symmetric (b)
- (d) (e): Non-linear field fringing → S2 pulses from grid surface are asymmetric
The $^8$B Rate Uncertainties

Neutrino Flux
- 4.4% uncertainty [SNO, Broxino]

Cross-section
- Helm’s form factor $\sim 1$ for $^8$B

The best NR calibration data:
- $L_y$: LUX Run4 calibration (Huang 2020)
- $Q_y$: Livermore measurement (Xu 2019)

Ly is the highest source of systematics.

NEST* Yield Model
- Def. # of quanta created per energy deposition
- Light yield ($L_y$)
- Charge yield ($Q_y$)

$(S1, S2)$ Detection Threshold $\rightarrow$ NR Efficiency

Signal Detection Efficiency
- Electron survival probability during the drift (e-life $\sim 850\, \mu s$)
- $g_1$: probability of a photon being detected ($g_1 \sim 0.12$)
- $g_2$: avg. number of electroluminescence photons per electron ($g_2 \sim 80\, \text{phd/e}$)

$$<S_1> = E_r \times L_y \times g_1$$
$$<S_2> = E_r \times Q_y \times g_2$$
The Ly Uncertainty

- The Ly uncertainty for low-energy NRs is studied
  - Uncertainty in 8B Rate (preliminary): ~25% (3-fold) ~18% (2-fold)
  - Ly variation affects both WIMPs and CEvNS (correlated)
- In comparison, Qy uncertainty for N_{ee} > 5 threshold: 6%
- The effect on the proj. sensitivity is investigated:
  - Earlier saturation at high exposure
  - Short-term (<100 days) effect is subdominant to Poisson fluctuation
- Low-energy NR calibration requirement is quantified.
Mitigation Strategy - DD Calibration

**Direct DD Mode:**
- Monoenergetic 2.45 MeV neutrons from the deuterium-deuterium (DD) fusion in the generator
- Neutron production pulsed width of **12 us** (HWHM)

**D-Reflector Mode:**
- Backward-scattering from deuterated scintillator (EJ315) generates **350±40 keV** neutron KE peak (HWHM)
- Time-of-flight (ToF) tag between D-reflector scintillator and TPC permits per-neutron KE reconstruction
- Delivers ~**600 “golden” single-scatter** events /keV/day in 1-10.6 keV<sub>nr</sub> recoil energy with per-event ToF-tagged neutron KE.

**H-Reflector Mode:**
- Forward-scattering near 90 degrees off hydrogenous scintillator (EJ200) generates **10-160 keV** neutron KE range.
- Time-of-flight (ToF) between H-reflector scintillator and TPC permits per-neutron KE reconstruction
- Delivers ~**700 “golden” single-scatter** events /keV/day in 0.3-4.8 keV<sub>nr</sub> recoil energy with per-event ToF-tagged neutron KE.
Mitigation Strategy - Photoneutron Calibration

- $(\gamma, n)$ reaction
  - Match $\gamma$ energy to Q-value $\rightarrow$ low-energy $n$
  - Small cross-section $\rightarrow$ $10^4:1$ $\gamma$-n yield $\rightarrow$ Tungsten shielding
- $^{88}$Y-Be source:
  - $3.7$ MBq $^{88}$Y MeV-scale $\gamma$-rays
  - $E_n \sim E_\gamma + Q \rightarrow \sim470$ n/s, $E_n\sim153$ keV
  - Single-scatter NR endpoint: $4.6$ keV
- For more info, see: A. Biekert (APS April 2019)

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Atm. Neutrino Uncertainty:

- Current 20% ($E_{\nu} < 100$ MeV), 15% ($E_{\nu} < 1$ GeV) u/c comes from calculation [Honda 2011]. No direct experimental measurement for sub-GeV atm.

- Future experimental constraint (not necessarily a completed list):
  - DUNE [K. J. Kelly 2019]: 0.1 - 1 GeV range
  - Hyper-Kamiokande [Z. Li 2017], 100 MeV - 10 TeV
  - JUNO [G. Settanta 2019], 0.1 GeV - 10 GeV range, projected u/c: 10% to 25%
Atmospheric Neutrino and the Neutrino Floor (Fog)

Atm. Neutrino Flux Uncertainty:
- Current 20% \((E_\nu,<100 \text{ MeV})\), 15% \((E_\nu,<1 \text{ GeV})\) u/c from calculation [Honda 2011]. No direct experimental measurement for sub-GeV.
- Future experimental constraint (not necessarily a completed list):
  - DUNE [K. J. Kelly 2019]: 0.1 - 1 GeV range
  - Hyper-Kamiokande [Z. Li 2017], 100 MeV - 10 TeV
  - JUNO [G. Settanta 2019], 0.1 GeV - 10 GeV range, projected u/c: 10% to 25%

Effect on WIMP Sensitivity (neutrino floor/fog)
- An generic LXe detector simulated by NEST
  - NR efficiency curve is similar to LZ (slide 10, black curve)
  - Total ER leakage: \(10^{-4}\) below NR median
- Backgrounds considered (Rn is ignored):
  - Atmospheric neutrino (20% u/c)
  - pp neutrinos
  - \(^{136}\text{Xe} \, 2\nu\beta\beta\) (N.A., \(T_{1/2} = 2.11 \times 10^{21} \text{ yr}\) [EXO-200])
- PLR Setting:
  - Two-sided, Frequentist, \(\mu>0, \ldots\) [arxiv: 2105.00599]
Summary

- Ton-scale LXe detector is sensitive to MeV-scale natural neutrinos via CEvNS
- Opportunity for LZ to make the first detection of 8B in CEvNS channel
- CEvNS presents challenges for WIMP searches
  - Above 100 GeV: hard neutrino floor (fog) due to atm. uncertainty
  - 4-10 GeV: neutrino floor (fog) due to $^8$B uncertainties (light yield)
    - Short-term impact is subdominant to Poisson fluctuation.
    - Long-term impact on sensitivity → improvement in light yield measurement is crucial
  - 10 GeV - 100 GeV: soft neutrino floor (fog) due to different spectrum shape between WIMP and atm neutrinos
- Next Generation Liquid Xenon experiment may (aside from WIMP search) measure:
  - solar $pp$ ($Weinberg's$ $angle$ $sin^2 \theta_W$) via electron scattering
  - $^8B$ (NC NSI) via CEvNS
  - CNO (Solar metallicity) via Charge Current
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US  UK  Portugal  Korea

34 Institutions: 250 scientists, engineers, and technical staff

LZ Collaboration Meeting – September 8–11, 2021

Thanks to our sponsors and participating institutions!

U.S. Department of Energy
Office of Science

https://lz.lbl.gov/
Backup
Livermore (2020) measurement significantly brings down the Qy uncertainty, comparing to Ly.

The expected $^8$B rate varies ~6% due to Qy variation.
Background Energy Spectra

![Energy Spectra Graphs](image-url)

- **Electronic recoil energy [keV]**: The left graph shows the energy spectra for various isotopes and sources, including $^{136}\text{Xe}$, $^{222}\text{Rn}$, Solar $\nu$ (free electron) (RRPA), $^{220}\text{Rn}$, $^{85}\text{Kr}$, and Det. + Sur. + Env. The graph is on a logarithmic scale, ranging from $10^{-6}$ to $10^{-4}$ counts/kg/day/keV.
- **Nuclear recoil energy [keV]**: The right graph displays the energy spectra for $^{8B}$, Det. + Sur. + Env., DSN, and Atm, with rates ranging from $10^{-11}$ to $10^{-3}$ counts/kg/day/keV.
PMT Arrays

PATRIC @ Brown

Me Looking Tired