Low-energy Event Detection in a Liquid Xenon Proportional Scintillation Counter

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An R&D Program towards a Low Background Electron Counting Apparatus

➢ R&D program supported by DOE (2018-2020)
  ➢ Investigate single-and-few e- background in liquid xenon detectors
  ➢ Dedicated setups to test various ideas to mitigate the electron background
  ➢ Accurate calculations and modeling of expected low energy signals
➢ Following the R&D program, propose/build a liquid xenon detector with much reduced single e- background for Light DM Search
Motivation

- Coherent Elastic Neutrino Nucleus Scattering (CEνNS) at a nuclear reactor
  - High flux
  - Sub-keV nuclear recoils in Xe (mostly S2-only events)

- Next generation of LXe dark matter searches for:
  - WIMPs (if ER/NR discrimination is comparable)
  - Light dark matter (if S2 only background can be reduced)

Integrated reactor CEνNS rate on different noble elements (K. Ni et. Al. universe7030054)
➢ Single-electrons up to 1 second after a large S2 pulse
➢ Seen in dual-phase LXe TPCs (LUX, XENON1T)
➢ Major background for low-energy ionization-only searches
➢ Origins are unclear:
  ➢ Could be related to the liquid-gas interface
  ➢ Could be related to impurities
  ➢ Or a mix of both

XENON1T, arXiv:2112.12116 (PRD 2022)
Principle of a single phase liquid Xenon (LXe) detector (Qing Lin *JINST* 16 P08011)

- Produces S2 directly in liquid:
  - 100% extraction efficiency
  - Simplifies detector design (no need to maintain a gas-gap)
  - Potential to investigate the origin of the single-electron background after a large S2

- Needs > 425 kV/cm to produce S2s in LXe (E. Aprile et. al.: *JINST* 9 P11012 (2014))
Previous results:
- 10 µm anode wire, arXiv:2301.12296 (JINST 2023)

Recently changed wire to 18 µm
- Smaller maximum field
- Larger electroluminescence region

Modified from a design by Dr. Yuehuan Wei
Evidence of S2 pulse induced single electron emission from cathode wires
Measured $g_2$ of $1.8 \pm 0.3$ PE/e-
More details at arXiv:2301.12296
EL gain consistent with Aprile et al. (JINST 9 P11012 (2014)) after correcting for the wire shadow effect

Low Energy ER from tritium decays observed

More details at arXiv:2301.12296
Larger anode diameter (18 μm) ⇒ larger electroluminescence region
  • Higher electric field in the bulk
  • Anode: 4.5 kV, Cathode: -650 V

252Cf calibration:
  • 129mXe and 131mXe activated lines (236 keV and 164 keV gammas, respectively)
  • Nuclear recoil band

Xe activated lines:
  • High statistics (made possible with new triggerless digitizers!)
  • Cuts in drift time (i.e. electric field) for Doke-plot

Tritium:
  • Gives us a measurement of ER-leakage for small g2
Electric Field

Field simulation is consistent with analytic field (near the center in z and r)

➢ Charge insensitive volumes (CIV) near the top and bottom
  ➢ Next iteration will have field shaping rings
  ➢ Current experiment has ~17% CIV

➢ CIV may cause charge loss (i.e. smaller S2s)
Activated Xenon Lines

- Clear $^{131m}\text{Xe}$ and $^{129m}\text{Xe}$ lines (164 and 236 keV respectively)
- Larger drift times $\rightarrow$ larger event radius $\rightarrow$ smaller electric field
- Drift time slices correspond to electric field slices
- Single-electron gain is the same regardless of drift time slice
- $g_2$ measured to be $\sim$3.5 PE/e$^-$ (before electron lifetime effects)
- $g_1 \approx$ 0.14 PE/photon (photosensor coverage: 29%)
Cuts applied:
- z-cut
- Diffusion cut (drift time vs S2 width)
- Multiple scatter
- Noise cuts

Light emissions: main limitation

NR Band from $^{252}$Cf
ER (Tritium)/NR Discrimination

- $1\sigma$ regions seem well separated
- However: a “shower” of leakage events for both ER and NR
  - Could be due to imperfect charge collection (charge insensitive volume)
- Two methods to calculate leakage:
  - Counting
  - Gaussian fitting
ER (Tritium)/NR Discrimination: Leakage by counting

- Find NR median, count tritium events below NR median
- NR Acceptance ~47.5% (after data-quality cuts + NR events below median)
- Some bins have leakage < 0.01, but most have leakage > 0.01
- Investigation of leakage events is still ongoing
ER (Tritium)/NR Discrimination: Leakage by fitting

- Motivation: To estimate the ideal-case leakage
  - Ideal case: no CIV, no reconstruction effects, only tritium events
- Fit tritium events’ Log10(S2/S1) in each S1 slice with gaussian
- Find fitted proportion below the NR median

Most bins have leakage < 0.01
Future Steps

➢ NUXE-3: A 3 kg prototype
➢ Gate to separate drift region from electroluminescence region
➢ Dense SiPM array on the outside for more coverage
➢ Field shaping rings for a more uniform field and lower charge insensitive volume
Further into the future: NUXE-100 as LBECA

If LXePSC is successful in reducing single electron background: Scale up!

- **NUXE** is a planned reactor neutrino CEvNS experiment using ~100 kg LXe (or Xe-doped LAr) single-phase PSC
- The same detector system can be moved underground for light dark matter search after demonstrating the detection of reactor neutrinos.
Regardless, results of this talk suggest ER/NR discrimination can still be maintained in the single-phase
- Strip-coated electrodes on a quartz window
- No need to maintain liquid level and worry about extraction efficiency
Summary

- Obtained a $g_2$ of 3.5 PE/e$^-$ while maintaining sensitivity to low-energy (O(1keV)) events
- Obtained an energy calibration (doke plot) by slicing the data in radial slices
- First observation of nuclear-recoil events in a single-phase liquid Xenon detector using both light and proportional scintillation signals
- First estimation of ER-leakage for such a detector
- **Main limitation:** Higher rates of spurious light emission, low $g_2$ (might not be an issue for higher-energy NR)