LBECA: a Low Background Electron Counting Apparatus for sub-GeV Dark Matter Detection

Kaixuan Ni (University of California San Diego)
For the LBECA Collaboration

TAUP 2019, Sep 9-13, 2019, Toyama, Japan
Two-phase xenon time projection chamber (XeTPC) is the current & future leading technology for heavy dark matter searches

- The three best limits for heavy WIMPs are all obtained by the two-phase xenon TPCs (LUX, PandaX-II, XENON1T)
- The upcoming (XENONnT, LZ, PandaX-4T) and future (DARWIN) experiments with Xe TPCs will further improve the sensitivity for both SI and SD interactions
- The other complimentary technology for heavy WIMPs include liquid argon (DarkSide-20k) for SI, and bubble chamber (PICO) for SD-proton interactions

![Graphs showing WIMP-nucleon cross-section and discovery limits](image)

arXiv:1805.12562
PRL 121, 111302 (2018)

arXiv:1902.03234
PRL 122, 141301 (2019)
Two-phase xenon detector for dark matter search

- Low threshold: keV (set by S1)
- Large target mass (currently 1-10 tons)
- Ultra-low background
  - 3D fiducilization
  - ER/NR discrimination with S2/S1

With both S1 and S2 signals (TPC mode):

- Ultra-low threshold: 10-100 eV (set by S2)
- Background control a challenge:
  - No ER/NR discrimination
  - Only XY position determined, no Z
  - Known/unknown source of single/few electrons

With S2 only signal (EC - Electron Counting mode):

- Ultra-low threshold: 10-100 eV (set by S2)
- Background control a challenge:
  - No ER/NR discrimination
  - Only XY position determined, no Z
  - Known/unknown source of single/few electrons
LXe detector is the pioneering technique to search for light dark matter & dark photons interacting with electrons

Essig et al., arXiv:1206.2644

An et al., arXiv:1412.8378
XENON1T S2-only search set strong limits for low-mass (GeV) and light (sub-GeV) dark matter

- Threshold: $\sim 200$ eVee ($4\sim 5$ e-)
- Exposure: 22 tonne-days (60 kg-year)
- Background: $\sim 1$ event/keVee/tonne/d (>400 eVee)
- Below threshold: 1000 events/keVee/tonne/d
Challenges for sub-GeV Light Dark Matter search with LXe

- Signals contain single or a few electrons
- NO ER rejection
- NO Z position information
- Background below threshold not fully understood

**XENON1T, arXiv:1907.11485**

**Possible sources of single-and-a-few electrons:**

- Photoionization of metal surfaces
- Photoionization of electronegative impurities in the bulk
- Delayed extraction of ionized electrons:
  - Trapped at liquid-gas interface
  - Attached on electronegative impurities
Single and a few electrons observed

- Amplified single electron signals observed as S2
  - Typical width: ~μs
  - Typical size: 10~100 PE

- But they still show up after several hundreds of milliseconds after a large energy deposit
Single and a few electron rate in the LXe bulk

**XENON10, arXiv:1206.2644**

- 15 kg-day
- Rate: 0.1~10/kg/day at 2~3 e-
- 10~100/kg/day at single e-

**XENON100, arXiv:1605.06262**

- 11,000 kg-day
- Rate: 0.1/kg/day at ~4 e-

**XENON1T, arXiv:1907.11485**

- 22,000 kg-day
- Rate: 0.01~1/kg/day at 3~4 e-

- Background at a few electron level is not always going down with increasing target mass.
- We now understood much better the sources of these background electrons.
Photo-ionization of metal surfaces and impurities in the bulk LXe

Observation and applications of single-electron charge signals in the XENON100 experiment

Mitigation solutions:

- reduce metal components directly contacting the LXe target in the TPC
- significantly improve the purity of LXe target
Delayed extraction of electrons trapped at the liquid-gas interface

P. Sorensen, arXiv:1702.04805

Theoretical investigation

- the Shottky barrier model: an electron approaches a dielectric boundary held at a constant potential feels a force due to its image charge (energy barrier)
- the $n$-th chance model: electron fails to escape the barrier at the initial attempt will continue to scatter
- The electron emission coefficient depends on the liquid emission field (approaching 100% at 7 kV/cm)

Mitigation solutions:

- Apply strong emission field: at least 7 kV/cm in the liquid
- Implement a fast (~us) high voltage switching: push the electrons back to the gate electrode
- Stimulate the electron emission using IR photons
LBECA: a Light Dark Matter Search experiment using LXe with significantly reduced single/few electron background

- **100-kg LXe detector** with ~60 kg active target
- Two-phase operation using primarily **S2 only** signals
- **Strong emission field:**
  - 7-10 kV/cm (liquid)
  - Extra: HV switching
- IR light to **stimulate electron emission**
- **Sealed Chamber** with fused silica body:
  - Less outgassing (fused silica vs. Teflon)
  - External outgassing prevented entering easily into the target
  - Improve purification speed (clean LXe fed directly into the target)
- SiPM Array on top: high XY position resolution
- Extra: alternative electrode material
  (graphene, gold or platinum coating, etc.)
Members: P. Sorensen (LBNL); A. Bernstein, J. Xu. S. Pereverzev (LLNL); R. Lang, M. Clark, A. Kopec (Purdue); R. Essig, M. Fernandez-Serra, C. Zhen (Stony Brook); K. Ni, J. Qi, J. Ye (UCSD)

Experience from XENON/LUX/PandaX/DarkSide experiments + theory

R&D program supported by DOE (2018-2020)
  - Dedicated setups to test various ideas to mitigate the electron background
  - Accurate calculations and modeling of expected low energy signals

Full development proposal submitted to DOE (2019-2022)
  - Implement the ideas in one prototype detector
  - Design the 100-kg scale LBECa detector based on the test performance

Detector deployment and data taking (2022-2025)
R&D: high emission field for full electron extraction (LLNL)

Full electron extraction requires 7.5 kV/cm or higher field.

Very high gain (~72 p.e./e-) for single electrons obtained.

J. Xu et al., arXiv:1904.02885
IR light increases extracted electron signals of alpha events, although the effect is small. More powerful IR light to be implemented.
R&D: Sealed TPC to improve purification efficiency (UCSD)

~500 us electron lifetime achieved with <1 day of circulation at 5 SLPM
LBECA Goals and Sensitivity Reach

- **100 kg-year exposure** down to single or two e- threshold
- Background goal: $\sim 10/100$ kg-year at 2 e- threshold
  - 3 orders of magnitude lower than XENON10/100/1T
  - $\sim 10\%$ of the expected $^8$B solar neutrino coherent-scattering rate
- Discovery potential for **sub-GeV dark matter**:
  - probe parameter space for “freeze-in” DM abundance with a very light mediator
  - probe region with other DM production mechanisms (AsymDM, ELDER/SIMP)
- Bonus: $5\sigma$ detection of coherent-scattering of $^8$B solar neutrinos (1801.10159)