LArCADe: lowering thresholds in LArTPC detectors

Magnificent CEvNS – UChicago – November 3rd, 2018

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LDRD project @ Fermilab started in spring ‘18

Investigate feasibility of obtaining stable $e^-$ charge amplification in LAr.

→ past attempts, non-conclusive.

With the goal of trying to further expand the physics reach of large-scale LArTPCs

This talk:
1) Project overview + CEvNS as physics motivation.
2) Results in gas + future plans for LAr.
Few attempts at obtaining charge amplification in liquid argon. Electron amplification has been observed but unstable.

Challenges: amplification gain / bubble formation / $e^-$ vs $Ar^+$ drift.

Advantages: single-phase / scalable / position resolution / complementary to scintillation light.

Our goal is to explore in more detail the feasibility of obtaining stable, proportional charge amplification in liquid argon.
Challenges for e\textsuperscript{-} signature

Significant quenching of charge (80-90%) due to ion recombination.

Significant variation in models.

“detectable” electrons

\[ N_e = L_{\text{eff}} \frac{E_{\text{dep}}}{W} \frac{1 - R}{1 + \alpha} \]

amplification @ \( \sim 10^6 \) V/cm

NR e- signature:
arXiv:1707.05630 [DarkSide]

Ar xsec:
Phys Rev A, V65, 042713
What is required to detect ionization charge from Ar recoil?

1) wire-readout single-phase LArTPCs have noise @ 400 e\(^{-}\) level, using cold electronics.
2) signature of 10s of MeV CEvNS \(\rightarrow\) 10s – 100 e\(^{-}\).

Factor of x100 amplification brings S:N close to that of MIP signatures for current LArTPCs.

https://github.com/bradkav/CEvNS

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LArCAdE Project
LArCADe Setup

~5cm drift purity monitor operated @ Fermilab’s PAB facility.

gold-plated photocathode

optical fiber
LArCADe Setup

Collect charge @ anode on small tips
Intense field in tip proximity

Simulation

COMSOL simulation tool to model electric field in detector geometry and simulate electron drift.

Rely on literature to extract expected amplification for gas in function of local field and pressure.

\[
\frac{\alpha}{\beta} = A e^{-\frac{BP}{E}} \quad M = \exp \left[ \int_{x_1}^{x_2} \alpha(x) \, dx \right].
\]

(24)

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Data Analysis

Anode signal provides a reference of original electron cloud.

Comparison with anode used to study possible amplification.
Data Analysis [ gas runs ]

Stable drift, no amplification

transparency effect @ anode

amplification @ anode

Stable drift, no amplification
Data Analysis [ gas runs ]

Stable drift, no amplification

amplification @ anode

transparency effect @ anode

500 V @ Anode

Anode
Cathode

1000 V @ Anode

Anode
Cathode

1500 V @ Anode

Anode
Cathode
Data Analysis [ liquid argon ]

No sign of amplification
[not unexpected at these fields]

Decreased signal strength in liquid

getting close to $10^6$ V/cm
Next Steps

Move from 1 μm to tips of 100 and 10 nm.

Study impact of tip / grid geometry on absolute gain determination.

Investigate possibility of moving to using micro-strip arrays for a scalable device.
Challenges for Amplification

High E-field can induce gas bubbles in the vicinity of tips.

Induce undesired and unstable gas amplification.

Investigate bubble formation with a raspberryPi camera

Amplification occurs in tip’s proximity → space charge effect of e⁻ / Ar⁺

Observe in gas slow drift, possibly caused by Ar⁺ ions.

Would be problematic in liquid.
Summary

1. Single-phase LArTPCs currently limited to O(1 MeV) energy thresholds by noise levels.
   [for wire/pixel detectors reading out drift e⁻ charge]

2. Amplification in liquid could expand physics reach to nuclear recoils & CEvNS.

3. LArCADe program aims to explore the feasibility of obtaining stable amplification in LAr.
   1) Gained understanding of setup performance in gas.
   2) Moving to measurements in liquid with different tip configurations.
   3) Aiming to investigate effects impacting the feasibility stable amplification.
Backup
Signal Processing

- **Anode Drift**
- **Cathode Drift**

![Graph showing anode and cathode drift](image1)

- **Noise Spectrum**

![Graph showing signal and background FFT](image2)
Electronics Noise in LArTPCs

Pressure Dependence in Gas

Observe different regimes of amplification.

Pressure dependence significantly impacted by tip geometry.

Higher field, more amplification in denser environment.

Lower threshold → multiplication sustained for longer distance.
Project Overview

- Measure gain amplification factor in gas when running with FNAL-produced tips.

Two-steps:

1) Simulate E-field and e- trajectory in COMSOL.

2) Calculate amplification factor from analytic expression.

\[ M = \exp \left( \int_{x_1}^{x_2} \alpha(x) \, dx \right) . \]

\[ \frac{\alpha}{\beta} = A e^{-\beta P/E} \]

\( \alpha = \text{Townsend coeff.} \rightarrow \text{Inverse of ionization mean free path, or, number of ions produced per unit distance.} \)

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Amplification Calculation

$M$ represents the multiplication factor. In the general case of a non-uniform electric field, $\alpha = \alpha(x)$, Eq. (23) has to be modified in the following way:

$$M = \exp \left[ \int_{x_1}^{x_2} \alpha(x) \, dx \right].$$

$$\frac{\alpha}{\bar{p}} = A e^{-BP/E} \quad (24)$$

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What to expect based on this model.

**Fig. 44** First Townsend coefficient as a function of the reduced electric field, for noble gases$^{22})$

- Generally good agreement
- Poor agreement. Also less significant [no amplification]
Impact of Anode / Tip geometry

V = 550 V, 7 psi

Amplification Factor

Starting point [mm]

disk of simulated drifting e⁻
$e^-$ scatter / ionization in LAr

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Ar xsec:

- Phys Rev A, V65, 042713
FIG. 14. $L_{\text{eff}}$ dependence on NR energy as measured by this work and compared with other data sets [14–16] and models [18, 19].