Characterization of Delayed Ionization Backgrounds in the LZ Experiment

Eli Mizrachi (they/them)
On Behalf of the LZ Collaboration

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Introduction

What are Electron Trains?
What do we know about them?
Electron Trains (AKA “e-trains”)

- “Electron trains” are a form of background noise in dual-phase TPCs
- Spurious single electrons (SEs) observed for at least a second after S2s
  - 30% livetime loss vetoing electron/photon-trains in LZ Science Run 1 (SR1) (Linehan [1])
  - $\Delta t_{S2} < t_{drift} \to$ dominated by electrons from photoionization of TPC liquid & grids
  - $\Delta t_{S2} > t_{drift} \to$ dominated by electrons captured & released by impurities in drift path?

Single scatter S2 followed by SEs for at least 40ms (GIF)

Top PMT array, left, showing position-correlated SEs (GIF)
Electron Train Hypotheses

• Top: “Drift” liquid events generate electron trains, not photoionization in gas or below cathode

• E-train rates are [2] [3]:
  ▪ Bottom: correlated with electron lifetime
    ○ ▶️ ⭐ ➝ increasing time since S2
  ▪ Anti-correlated with drift time of progenitor (shown later)

• ➝ Liquid bulk origin, not liquid surface
  ▪ Unclear physics; electrons captured and released by impurities in drift path?

![Graph 1: Electron trains in XENON1T](2)

![Graph 2: E-train electron lifetime dependence in LUX](3)
Electron Trains in LZ

$r \approx 40\text{cm}$

$t_{\text{drift}} \approx 1\text{ms}$
Position Dependence of SEs after “Progenitor” S2s

- Prog $r < 55\text{cm}$, area $> 1\times10^4$ phd ($\sim 200$ SE)
  - Skip if $< 200\text{ms}$ after any pulse $> 5\times10^3$ phd
- $[\text{Hz/cm}^2]$ because larger $\Delta r \implies$ larger area in XY $\implies$ more child pulses
- Define position-correlated and uncorrelated child pulses
  - p-corr: $\Delta r < 10\text{cm}$
  - p-uncorr: $20\text{cm} < \Delta r < 30\text{cm}$
- Position-correlated region captures power law (next slide), position-uncorrelated avoids power law and walls
- Prog drift time within fiducial volume

SE Rate vs. radial distance $\Delta r$ between progenitor and child
SE Rates vs. Time Since S2

- **Top:** P-corr flux is more intense and appears to follow a power law
- **Bottom:** Fit power law $\alpha t^{-\beta}$ to p-corr rates
  - $\beta$ consistent with LUX [3], XENON1T [2]
- Dip in rates prior to 1ms is known artifact of pulse pile-up from photoionization
Drift Time and Progenitor Area

- **Top:** SE Rate vs. progenitor area
  - \( SE_R \): Progenitor size in electrons extracted

- **Bottom:** SE Rate vs. progenitor drift time
  - Normalize by \( SE_I = SE_S \exp(t_{\text{drift}}/\tau_{e^-}) \)
  - \( SE_S \rightarrow SE_R \), corrected for extraction efficiency

- \( \Delta t \) [s]: (0.003, 0.3) avoids photoionization in p-uncorr rates

- P-uncorr pulses show virtually no correlation for either prog area or drift time
  - Favors explanation of uncorrelated pulses coming from previous e-trains (XENON1T [2])
Electron Lifetime

- Rates in SR1 exhibit dependence on electron lifetime up to 8ms
Electron Loss Normalization

Advancing the Liquid Bulk Hypothesis
Electron Lifetime and Drift Time

- Electron lifetime and drift time dependence hint at liquid bulk origin
- Normalizing by $SE_I$ does not cancel out dependence
Electron Loss Normalization

- Normalizing by $e_{\text{loss}} = SE_I - SE_S$ unifies drift time and electron lifetime
- Clear indication that power law originates with liquid bulk impurities
- Also shows (again) lack of correlation for uncorrelated backgrounds
“Drift” Field Dependence
Two TPCs for the Price of One

- Distinguish between extraction liquid (EXL) and drift liquid (DRL) single scatters with drift time
- Use top-bottom asymmetry to exclude gas events
- EXL: a second TPC where the gate is a “cathode” i.e. $E_{\text{drift}} = E_{\text{extract}}$
- Vary extraction field, compare EXL and DRL e-trains
- Isolate “drift” field dependence with otherwise identical detector conditions!

- **Right:** Drift time does *not* affect exponent
- Correct for extraction efficiency and increased charge yield in EXL with $SE_S$ normalization

Fits to power law at different drift time bands show exponent does not depend on drift time
\( \Delta V_{\text{Extract}} \) 7, 8kV - EXL Events

- E-trains from extraction liquid have much weaker delayed correlated pulses
- Try subtracting flux from uncorrelated pulses for slightly cleaner power law
- Liquid field \( \approx 3400, 3900 \) V/cm for 7, 8kV respectively; radial field variation \( \sim \) few %
$\Delta V_{\text{Extract}}$ 7, 8kV - Uncorrelated Subtraction

- Exponent is steeper than typical ~1.0-1.1 from drift liquid events (~0.5-1 sigma difference)
- Gate grid at 2.5us drift time; no change in exponents with drift time cut at 2us
$\Delta V_{Extract}$ 7, 8kV - DRL Events

- Rate curves shown here from same datasets, different drift time cut
- Appears compatible with “weak” extraction field dependence reported by XENON1T [2]
- $\longrightarrow$ Field in drift path could influence a time constant in power law exponent
Conclusions
Summary of General Characterization

- Power law observed for rate of single electron pulses following S2s in drift region
- P-uncorr pulses also uncorrelated w/other progenitor characteristics e.g. area and drift time
- **Bottom:** $e_{\text{loss}}$ normalization appears to unify electron lifetime and drift time dependence
  - Strong evidence for liquid bulk impurities as dominant factor in power law

![Graph showing correlated and uncorrelated positions with child area and drift time data points]
Summary of Possible “Drift” Field Dependence

- Simultaneous analysis of e-trains in extraction liquid (EXL) and drift liquid (DRL)
- Steeper exponent at field > 3 kV/cm?
  - Apparent agreement with result from Akimov et al. [4]
- Exponent in DRL at field \( \approx 180 \text{ V/cm} \) matches literature
- Studies of this effect are worth pursuing to gain a better understanding of e-train physics and modeling!

Note: value for study conducted by Kopec et al. [5] was reported for 500 V/cm and “unchanged” for other fields
Acknowledgements 👏

Thank you to our sponsors and 37 participating institutions!
References


Backup
# Normalization Reference

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$SE_R = S_{2phd}/n_{phd}/SE$</td>
<td>“Raw” (extracted) S2 area in units of single electrons</td>
</tr>
<tr>
<td>$SE_S = SE_R/e_{eee}$</td>
<td>“Surface” S2 area, i.e. $SE_R$ corrected for extraction efficiency</td>
</tr>
<tr>
<td>$SE_I = SE_S \exp(t_{drift}/\tau_e)$</td>
<td>“Initial” S2 area, i.e. $SE_S$ corrected for drift losses</td>
</tr>
<tr>
<td>$e_{loss} = SE_I - SE_S$</td>
<td>Number of electrons lost while drifting</td>
</tr>
<tr>
<td>$cm^2$</td>
<td>Area of liquid surface subtended by radial selection of pulses</td>
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</tbody>
</table>
Electron Trains in TPC Regions

[Graph showing rate distribution for TPC regions GAS, EXL, and DRL.]

- TPC Region: GAS
- TPC Region: EXL
- TPC Region: DRL

Extraction dV [kV]: 8
Drift dV [kV]: 28
Position:
- Correlated
- Uncorrelated
$E_{\text{drift}}$ Sweep - DRL Events

Position: Correlated
Extraction dV [kV]: 8
TPC Region:

- DRL
- EXL
$E_{\text{drift}}$ Sweep - “Background” Subtraction in DRL Events

Drift dV [kV]: 16
$\alpha_0 = (6.36+/-0.64)e-07$
$\beta_0 = -1.03+/-0.02$

Drift dV [kV]: 28
$\alpha_0 = (8.41+/-0.63)e-07$
$\beta_0 = -1.10+/-0.02$

Drift dV [kV]: 35
$\alpha_0 = (1.30+/-0.12)e-06$
$\beta_0 = -1.01+/-0.02$

Position: Correlated
Extraction dV [kV]: 8
TPC Region: DRL
BigDEB Main Algorithm

- Livetime between windows is not counted unless trigger efficiency of pulse is ~100%

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Livetime

Wall Time

Event Start  Event End  Event Trigger  E-train Start  E-train End  Trigger Holdoff