Light only Liquid Xenon experiment (LoLX)

Physics goals and Nitrogen Gas Commissioning

Austin de St. Croix
Queen’s PhD Student at TRIUMF

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LoLX Collaboration:

TRIUMF

Thomas Brunner, Soud Al Kharusi, Thomas McElroy, Christopher Chambers, Xiao Shang, Eamon Egan

McGill

Carleton University

Simon Viel, Bindiya Chana, Damian Goeldi

SNO+LAB

Pietro Giampa

INFN Pisa

Luca Galli
Marco Francesconi
Simone Stracka

Università di Pisa

Marc-André Tétrault
Julien Roy-Sabourin
LoLux Overview and Phases

Detector

- Single phase LXe, zero applied field
- silicon photomultipliers (SiPMs) for light collection
- design focus is high speed timing

Main Physics Goals

- measure Cherenkov and scintillation yields
- study prompt light characteristics
- external cross-talk in SiPMs

LoLux prototype detector body, black pieces for cable routing (McGill)
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Experimental Phases
Phase 1: Separation using optical filters, slow digitizer, Hamamatsu SiPMs
- few ns resolution
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Experimental Phases
Phase 1: Separation using optical filters, slow digitizer, Hamamatsu SiPMs
   ~ few ns resolution

Phase 2: upgrade to GHz digitizer (from MEG2 experiment)
   ~ 100ps resolution?

Phase 3: Digital SiPMs, temporal separation of Cherenkov and scintillation light
   ~ 10ps resolution?
The Detector (Phase 1)

Optical filters

- separate Cherenkov and scintillation light

24 Hamamatsu VUV4 SiPMs

- efficiency ~15% at 175 nm (see ref [5])
  (LXe scintillation wavelength)
- 1.5cm x 1.5cm

Radioactive sources placed on needle tip, 370 Bq

- Sr-90 beta (0.55 MeV) → Y-90 beta (2.28 MeV)
- Po-210 alpha (5.4 MeV)
  - not installed
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Body is hexagonal prism
- 3D printed body, ‘Formlabs SLA 3D Durable Resin’
- ~ 60% photo coverage
SiPM Layout

24 Silicon Photomultipliers

- Each SiPM has 4 readouts
  - 96 outputs

results in lots of cables!
**SiPM Layout**

**24 Silicon Photomultipliers**
- Each SiPM has 4 readouts
  - 96 outputs

**22 Cherenkov SiPMs:** Longpass optical filter
  - Blocks scintillation light

**1 Scintillation SiPM:** UV bandpass filter
  - Allows only scintillation light

**1 bare SiPM**
  - View scintillation and Cherenkov light
  - Emit cross-talk photons
SiPM Layout

24 Silicon Photomultipliers
- Each SiPM has 4 readouts
  ➔ 96 outputs

22 Cherenkov SiPMs: Longpass optical filter
- blocks scintillation light
  4ch summing → +22 digitized channels

1 Scintillation SiPM: UV bandpass filter
- allows only scintillation light
  no summing → +4 channels

1 bare SiPM
- view scintillation and Cherenkov light
- emit cross-talk photons
  no summing → +4 channels

\[8 + 22 = 30\] digitized channels
Simulation

- detector simulated in GEANT4
- preliminary optical data used for detector
- separation between alpha and beta events

Filtered vs. Bare Channels

- $^{90}\text{Sr}$ source
- $^{210}\text{Po}$ source

$^{90}\text{Sr} - Q = 2.28$ MeV
$^{210}\text{Po} - Q = 5.4$ MeV
Cryostat at McGill

Detector held upside-down in vacuum Flange
System Installed!

DAQ System Installed!
**Motivation A: nEXO**

nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in $\sim 4.5$ m$^2$ of SiPMs
- requires $\sim1\%$ ΔE for background rejection

| gamma from $^{238}\text{U}$, $^{232}\text{Th}$ near $Q_{0\nu\beta\beta}$

Diagram of a $\beta\beta$ event in nEXO detector (adapted from [4])

Cylinder walls lined with SiPMs
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↓ energy resolution driven by light collection efficiency (see ref [4])

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LoLX is complementary to nEXO:

- validate photon transport simulations

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\[ \downarrow \text{energy resolution driven by light collection efficiency (see ref [4])} \]

LoLX is complementary to nEXO:

- validate photon transport simulations
- gain experience operating many SiPMs in LXe
  - stability of photo-detection efficiency
  - monitor SiPMs using IV curves

In situ IV curves of 48/96 SiPMs in LoLX (at room temperature)
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- validate photon transport simulations
- gain experience operating many SiPMs in LXe
  - stability of photo-detection efficiency
  - monitor SiPMs using IV curves
- study **external cross-talk (eXT)** between SiPMs
  - charge avalanches produce IR photons, trigger other SiPMs
    - see talk by Joe McLaughlin, Thursday, Photodetectors Session
    - “External Cross-talk characterization from dark avalanches in SiPMs”
  - relevant for other experiments such as **Darkside-20k, DUNE** (large area SiPMs facing one another)
Motivation B: Study Cherenkov Light

Cherenkov light in LXe:
- broadband (~150 nm to IR)
- extremely prompt (~ few ps)
- slight directionality in LXe (scattering)
- low yield
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Applications of Cherenkov light:
Future LXe $0\nu\beta\beta$ experiments (not nEXO!)
- discrimination against single-scatter gammas: (see ref [1], [7])

Analytic Cherenkov yields for electrons in LXe
(calculated using NIST-eStar data, LXe refractive index from ref [8])
Motivation B: Study Cherenkov Light

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  (see ref [1], [7])

Timing Resolution
- **Time-Of-Flight** in nuclear medical imaging:
  - 10ps resolution (see ref [2], [3])
- higher energy gammas (1-100MeV)
  - TOF calorimetry?

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Analytic Cherenkov Spectra

- Calculated using NIST-eStar data, LXe refractive index from ref [8]
Motivation C: Scintillation Signal

scintillation signal has 4 contributions:
excitation / ionization  singlet (~2ns) / triplet (~20ns)

- Energy deposited
  - excitation
    - \( \tau \sim 2\text{ns} \)
    - \( \tau \sim 20\text{ns} \)
  - ionization
    - \( e^- + \text{ion recombination!} \)
    - \( \tau \sim 2\text{ns} \)
    - \( \tau \sim 20\text{ns} \)
- UV photon
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Energy deposited

- excitation
  - $\tau \sim 2\text{ns}$
- ionization
  - $\tau \sim 20\text{ns}$
  - $e^- + \text{ion recombination!}$

UV photon

Prompt light!
- alphas or nuclear recoils: fast recombination
- Electron Recoils: slow recombination
Motivation C: Scintillation Signal

Prompt scintillation signal:
- **alphas or nuclear recoils**: *fast* recombination
- **Electron Recoils**: *slow* recombination

prompt signal → timing resolution
discrimination → high mass DM search, other applications

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- excitation / ionization  
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Toy model showing recombination contribution to prompt light
Motivation C: Scintillation Signal

Prompt scintillation signal:
- alphas or nuclear recoils: fast recombination
- Electron Recoils: slow recombination

Prompt signal → timing resolution
discrimination → high mass DM search, other applications

Other studies:
- IR light production
- recombination vs Cherenkov yield
  - ionization fluctuations

scintillation signal has 4 contributions:
excitation / ionization singlet (~2ns) / triplet (~20ns)

Qualitative Photon Intensity

Toy model showing recombination contribution to prompt light
Commissioning: Gaseous Nitrogen

Data taken during summer 2020
- filled with **Nitrogen gas** to cool entire detector
  - operating between -90C to -110C

**Goals for GN\textsubscript{2} run:**
- commission electronics
- study **external cross-talk** between SiPMs
  - LoLX sensitive to **variety of geometries**
  - (primarily generated by dark noise)
Commissioning: Gaseous Nitrogen

Signal Quality/Commissioning

- great SPE resolution
- consistent breakdown voltages

Example Waveforms from cold GN2 data

Charge histogram for summed channel (4 inputs)

QPE histogram, channel 16

- 1PE
- 2PE
- 4PE
Commissioning: Gaseous Nitrogen

**BUT** $^{90}$Sr source still installed!

- Nitrogen gas scintillates
- literature reports low LY (24 ph/MeV) ref [9]
  - room temperature, field of ~250 V/cm

**Variables**

**NPE** - total photons

**Nhit** - occupancy (channels with > 0.5PE)
Commissioning: Gaseous Nitrogen

**BUT** $^{90}\text{Sr}$ source still installed!

- Nitrogen gas scintillates
- literature reports low LY (24 ph/MeV) ref [9]
  - room temperature, field of ~250 V/cm
- see LOTS of light!
  - distributed across detector

**Variables**

- **NPE** - total photons
- **Nhit** - occupancy (channels with > 0.5PE)

investigate Nhit = 2
External Cross-Talk (eXT)
What does it look like?

- prompt pulse pairs across channels
- geometric effect (emitted light refracted ‘down’)

Gaseous Nitrogen Data
External Cross-Talk (eXT)
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- prompt pulse pairs across channels
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Gaseous Nitrogen Data

LoLX Detector Unfolded

eXT expectation: channel 25 will be coincident with ‘close’ SiPMs
Gaseous Nitrogen Data

SiPM hits Coincident with SiPM 25

- **red**: Nhit = 2, prompt (4ns)
- **green**: Nhit = 2, late
- **blue**: Nhit > 10, prompt (4ns)
- **pink**: Nhit > 10, late

LoLX Detector Unfolded

eXT expectation: channel 25 will be coincident with ‘close’ SiPMs
Gaseous Nitrogen Data

Not so conclusive...

- SiPM 25 shows qualitative evidence for eXT
  - other channels **do not** show similar
    'step structure' 😞
Investigate in time domain

- time between pulses on different channels
- eXT contribute a large peak around zero
- preserves exponential decay from scintillation
  - everything looks the same!

Conclusion: other fast processes dominate
Gaseous Nitrogen Data

What fast processes?

- $\text{N}_2$ scintillation with 2.5 ns lifetime (see ref [9])
  - data taken at room temperature, E field

- Cherenkov/Fluorescence in glass!
  - $\beta$ hit wall due to detector size
  - light in filter/quartz **backscatters** into detector

---

Diagram beta hitting window
Gaseous Nitrogen Data

new variable

- **Fgap** - charge ratio of two brightest channels

  example: \( F_{\text{gap}} = 2 \)

- Pure scintillation \( \rightarrow \) low Fgap
- Window event \( \rightarrow \) high Fgap
Gaseous Nitrogen Data

Data for all channels

new variable

\( \text{Fgap} = \) charge ratio of two brightest channels

\( \text{NPE} = \) total photons
Gaseous Nitrogen Data

Data for all channels

new variable

$F_{gap} = \text{charge ratio of two brightest channels}$

NPE - total photons
Gaseous Nitrogen Data

Window dominated events are **not isotropic**!
- dominant in SiPMs centered on 7
- source **anisotropy**
  - useful for **Cherenkov** study in LXe!
Outlook for LoLX

**Commissioning in cold N\(_2\) gas**
- some evidence for eXT ...
- other prompt processes make it difficult to extract eXT signal
  - N\(_2\) scintillation, window cherenkov/fluorescence
- source directionality!
- bigger fish to fry → LXe runs

**Future outlook**
- LXe cooldowns commencing in June!
- use bare SiPM at varying voltage as ‘source’ of eXT photons
- Cherenkov measurement incoming
- other scintillation physics!
- WaveDAQ digitizer prepared for shipping
  phase 2 coming soon!
References

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[5] - Characterization of the Hamamatsu VUV4 MPPCs for nEXO  
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[7] - G. Signorelli, S. Dussoni. “Possible usage of Cherenkov photons to reduce the background in a 136Xe neutrino-less double-beta decay experiment”  
https://doi.org/10.1016/j.nima.2015.11.099

https://doi.org/10.1103/PhysRevA.15.2538

[9] - G. Lehaut et al. “Scintillation properties of N2 and CF4 and performances of a scintillating ionization chamber”  
https://doi.org/10.1016/j.nima.2015.05.050
24 SiPMs x 4 = 96 output cables

Next upgrade is to WAVEDAQ digitizer
GHz sampling rate!
16ch input amplifier
- in situ IV curves!

RF amp
DC to 2GHz BW

op-amp
optional 4ch summing

CAEN DT1740
Digitizer
62.5MHz sampling
(16ns, slow)

Cryostat at McGill

Cherenkov SiPMs are summed → 22 channels
Bare and bandpass SiPMs unsummed → 8 channels
Extras: Deposition time

Inverting and integrating range as a function of energy, we can find the time for the particle to slow down. This sets the lower limit on the scintillation rise time.
Toy MC: Overview

Variables:
NPE = number of photons per event
\( \tau_1, \tau_2 \) = lifetimes
\( \rho = \frac{N_{\text{fast}}}{N_{\text{slow}}} \)
P = probability of eXT occurring
res = timing resolution (spread of eXT photons)

1. generate scintillation photon times (NPE)
   \( \beta = \frac{\rho}{1 + \rho} \)
   store in vector<float> timesPure

2. generate all TTNP combinations using nested forloops, store in vector<float> gapsPure
3. add eXT induced times for each photon
   loop on photons
   \( t_0 \) //photon time
   if rand() < p_{ext}
     timesPure.push_back\((t_0 + \text{rand::gaus}(0, \text{res}))\)
4. calculate TTNP times again
5. repeat for certain ‘number of runs’ → NPE = 10, run x 1000 is not the same as NPE = 1000, run x10
Toy MC: only slow scint, eXT = 10%, NPE = 10

Slow time constant

<table>
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<tr>
<th>gapPureA</th>
<th>Entries</th>
<th>450000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>2.612</td>
</tr>
<tr>
<td></td>
<td>Std Dev</td>
<td>8.827</td>
</tr>
</tbody>
</table>

- green: pure wfn
- red: pure TTNP
- pink: eXT waveform
- blue: eXT TTNP

NPE = 10, runs = 10000
- ts = 15.0 ns, tt = 15.0 ns, \( p = 0.5 \)
- eXT: \( p = 10.0\% \), \( \sigma = 1.0 \)
Toy MC: adding fast scint, eXT = 5%, NPE = 2

Again: do better with lower NPE.
Cryostat: Feedthrough

Feedthrough Challenges

- PCB potted feedthrough using STYCAST 2850FT epoxy Black
  - developed a leak
- switched to new strategy using multiple smaller feedthroughs

Cryostat at McGill

96 cables from SiPMs
Extras: Single PE resolution (Oscilloscope)

Histogram charge from many waveforms

1PE waveforms

Total events = 3326
50 events shown

dark noise charge histogram

PE_hist
Entries  10001
Mean    134.1
Std Dev 16.72

1PE peak
2PE peak

Single PE resolution is given by
1PE charge vs gaussian width
Extras: Single PE resolution (Oscilloscope)

Charge resolution is good (with scope)

*no horizontal error bars, which represent uncertainty in breakdown voltage due to temperature uncertainty
Extras: Cerenkov helping 0νBB Experiments

Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cerenkov Light

Jason Philip Brodsky\textsuperscript{a}, Samuele Sangiorgio\textsuperscript{a}, Michael Heffner\textsuperscript{a}, Tyana Stiegler\textsuperscript{a}

\textsuperscript{a}Lawrence Livermore National Laboratory

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Sensitivity improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
<td>1.43</td>
</tr>
<tr>
<td>2</td>
<td>Compton Scatters included</td>
<td>1.11</td>
</tr>
<tr>
<td>3</td>
<td>Perfect background rejection</td>
<td>7.61</td>
</tr>
<tr>
<td>4</td>
<td>Back-to-back evenly-split 0νββ</td>
<td>1.96</td>
</tr>
<tr>
<td>5</td>
<td>Back-to-back, even split 0νββ and straighter tracks</td>
<td>5.53</td>
</tr>
<tr>
<td>6</td>
<td>Truth-value Cerenkov ID</td>
<td>1.40</td>
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<tr>
<td>7</td>
<td>100% detection efficiency</td>
<td>1.59</td>
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<tr>
<td>8</td>
<td>10% detection efficiency</td>
<td>1.20</td>
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<tr>
<td>9</td>
<td>No directional information</td>
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