The Light only Liquid Xenon experiment (LoLX)

Physics goals and analog electronics

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for LoLX Collaboration

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LIDINE 2019
LoLX Overview + Plan

Light only Liquid Xenon experiment

- Single phase LXe, zero applied field
- silicon photomultipliers for light collection
- measure Cerenkov and scintillation light
LoLX Overview + Plan

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Physics goals
Phase 1: Cerenkov and scintillation yields, optical filters
  ~ 16ns resolution

Phase 2: upgrade electronics, FBK SiPMs, study scintillation timing
  ~ 100ps resolution

Phase 3: 3D SiPMs, temporal separation of Cerenkov and scintillation light
  ~ 10ps resolution
  Possible application to TOF-PET medical scanners (ref [2], [3])
Motivation for LoLX

LoLX is a nEXO R&D project

- SiPM operation in LXe with many channels
- fully characterize reflectivity/transmission of detector materials → validate photon transport in simulations
- nEXO requires ~1% ΔE
  ↳ limited by light collection efficiency [4]
- Cerenkov light can help discriminate against single-scatter gamma backgrounds

See [1] “Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light”

$0\nu\beta\beta$ spectrum: average decay shares $E, p$ equally between electrons. Taken from [1]
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  See [1] “Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light”

Independent of nEXO

- Further characterize scintillation timing structure
- Particle ID with scintillation rise time (NOT PSD)

\[0\nu\beta\beta\] spectrum: average decay shares E, p equally between electrons. Taken from [1]
The Detector (Phase 1)

Optical filters
- separate Cerenkov and scintillation light

24 Hamamatsu VUV4 SiPMs
- PDE ~13% at 189nm
- 1.5cm x 1.5cm
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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)
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- Sr-90 beta (0.55 MeV) → Y-90 beta (2.28 MeV)
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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 quadrant has 4 readouts $\rightarrow$ 96 outputs
SiPM Layout

24 Silicon Photomultipliers

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22 Cerenkov SiPMs: Lowpass optical filter

- blocks scintillation light

Filter Properties

Longpass filter transmittance and arbitrary Cerenkov spectrum
SiPM Layout

24 Silicon Photomultipliers
   ▪ Each quadrant has 4 readouts → 96 outputs

22 Cerenkov SiPMs: Lowpass optical filter
   ▪ blocks scintillation light

1 Scintillation SiPM: UV bandpass filter
   ▪ allows only scintillation light
   ▪ blocks cross-talk photons

Filter Properties

Longpass and VUV filter transmittance
SiPM Layout

24 Silicon Photomultipliers
- Each quadrant has 4 readouts → 96 outputs

22 Cerenkov SiPMs: Lowpass optical filter
- blocks scintillation light

1 Scintillation SiPM: UV bandpass filter
- allows only scintillation light
- blocks cross-talk photons

1 bare SiPM
- views scintillation and Cerenkov light
- Also sensitive to cross-talk photons
Electronics: Goals and constraints

Nanosecond timing resolution
- Low jitter (sub ns)
- Equal time delay across channels

Single photon counting
- Requires good single PE charge/noise ratio
- Still retain full dynamic range for ‘bright’ events
- Require well characterized dark noise
  as Cerenkov signal is weak
Electronics Layout: Feedthrough

96 cables from SiPMs

Cryostat at Carleton (or McGill)

Custom PCB potted feedthrough
Sealing with electrically insulating, cryogenic and vacuum rated epoxy

- STYCAST 2850FT epoxy Black
- Currently being tested at McGill
Electronics Layout: Cables

96 cables from SiPMs

Using kapton insulated coaxial cables
- No appreciable rise time change or signal attenuation compared to standard MCX terminated coax
- No soldering: crimped to SiPM leads

Cryostat at Carleton (or McGill)
Electronics Layout: Amp

Stage 1
RF amp
DC to 2GHz BW
Voltage gain ~12

96 cables from SiPMs

Cryostat at Carleton (or McGill)

CAEN DT1740 Digitizer
Electronics Layout: Amp

Cryostat at Carleton (or McGill)

Stage 1
RF amp
DC to 2GHz BW
Voltage gain ~12

Stage 2
4ch summing
Operational amp
Voltage gain ~4.5

Cerenkov SiPMs are summed → 22 channels

96 cables from SiPMs

CAEN DT1740 Digitizer
Electronics Layout: Digitizer

Stage 1
RF amp
DC to 2GHz BW
Voltage gain ~12

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96 cables from SiPMs

CAEN DT1740
Digitizer

2Vpp dynamic range
12 bits
62.5MHz sampling
(16ns, slow)

Cerenkov SiPMs are summed → 22 channels

Cryostat at Carleton (or McGill)
Scintillation SiPMs are not summed $\rightarrow 22 + 8 = 30$ channels

Cryostat at Carleton (or McGill)

Stage 1
RF amp
DC to 2GHz BW
Voltage gain ~12

Stage 2
4ch summing
Operational amp
Voltage gain ~4.5

CAEN DT1740
Digitizer
2Vpp dynamic range
12 bits
62.5MHz sampling
(16ns, slow)
**Target SiPM Overvoltage**

**Cherenkov** SiPMs, $V_{over} = 4V$
- Above 4V correlated avalanche probability increases above 0.2 (nEXO requirement for required energy resolution)

**Bare SiPM**
- depends on dynamic range (aiming for 4V as well)

Correlated Avalanches in 1us vs overvoltage. See ref [5]
Single Photon Resolution

Example of 1PE SiPM signal with 16ns digitizer

Induced noise affects 1PE resolution

Dark noise 1PE pulses, $V_{\text{over}} = 4\text{V}$
Single Photon Resolution

Example of 1PE SiPM signal with 16ns digitizer

Induced noise affects 1PE resolution

Small overlap from 1PE peak and induced noise

1PE peak = 20 ADC = 10mV
2Vpp Threshold ~ 188 PE (baseline ≠ 0)

Many options to handle this:
- Noise is periodic (veto it)
- McGill/Carleton setup may be ‘cleaner’
- Run at higher overvoltage

Histogram of pulse heights, $V_{\text{over}} = 4V$
data taken with attenuated 444 nm laser
Simulation: Photon Transport

Using **Geant4** and **LUT Davis** package

- Handles reflection/transmittance of optical photons
- Added additional process in *BoundaryProcess.cc* to absorb photons in optical filters

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**Longpass Filter Properties**

`\text{Rand} < T(\lambda, \theta)`

`T < \text{Rand} < T+R`

`\text{Rand} > T+R`

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Transmittance  | 0  |
Absorbance     | T   |
Reflection      | 1   |

Longpass filter data, including reflectivity and absorption

Hybrid data - Measurements stitched with manufacturer’s
Simulation: Optical Measurements

Vacuum UV Transmissometer at TRIUMF → perform optical measurements of detector materials

- Deuterium lamp + monochromator (Δλ ~ 0.14nm)
- Sample and PMT can rotate 0-360 independently
- Measure specular and diffuse reflectivity
Simulation: Optical Measurements

Cryoarm

- Can replace sample holder with LN$_2$ cooled, PCB mounted cryodoor
- Measure PDE and reflectivity of SiPMs as function of $\lambda, \theta$
Simulation: Preliminary Results

Y-axis: Cerenkov channels

X-axis: 1 naked SiPM
Simulation: Preliminary Results

Y-axis: Cerenkov channels
X-axis: 1 naked SiPM

Some leakage ‘cerenkov’ photons for alpha event
Simulation: Preliminary Results

Y-axis: Cerenkov channels

X-axis: 1 naked SiPM

90Sr
0.546 MeV
2.28MeV Yttrium daughter

Filtered Non-Filtered

<table>
<thead>
<tr>
<th></th>
<th>Filtered</th>
<th>Non-Filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Mean x</td>
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<tr>
<td>Mean y</td>
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<tr>
<td>Std Dev x</td>
<td>58.31</td>
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<tr>
<td>Std Dev y</td>
<td>6.278</td>
<td>6.278</td>
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</tbody>
</table>
Outlook for LoLX

- Can perform single photon counting
- Current simulations show sufficient dynamic range for alpha events
- Optimistic goal is to take data by end of September
  → Depending on slow control electronics and cryostat availability

Phase 1 of LoLX

- Novel measurement of Cerenkov yield in LXe
- SiPM external crosstalk

Future Phases (Fast timing resolution)

- Detailed timing studies, energy resolution, etc

Argon sister experiment LoLA planned for future phases

- Precision timing measurements with no wavelength shifter

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Fabrice Retière, Pietro Giampa, Austin de St. Croix, Peter Margetak

(Pisa): Luca Galli, Giovanni Signorelli, Simone Stracka

Marc-André Tétrault (Banting Fellow)
References

[1] - Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light
   https://arxiv.org/abs/1812.05694v1


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.
Extras: Cryostats

Partially assembled cryostat at McGill

Innards of Carleton Cryostat, designed by Sébastien Claude Delaquis
Check for unwanted timing effects or signal attenuation

Tested Cables
- MCX terminated coaxial cable (reference)
- MCX with vacuum feedthrough junction
- Kapton insulated coax

Tested with RC circuit pulser and waveform generator

<table>
<thead>
<tr>
<th>Cable type</th>
<th>Jitter (ps)</th>
<th>amplitude (mV)</th>
<th>rise time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>std dev</td>
<td>mean</td>
</tr>
<tr>
<td>small signal (2mV VPP)</td>
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<td></td>
<td></td>
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<tr>
<td>ref cable (mcx)</td>
<td>178</td>
<td>63</td>
<td>3.2</td>
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<tr>
<td>kapton</td>
<td>185</td>
<td>60.2</td>
<td>3.3</td>
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<tr>
<td>mcx + FT + mcx</td>
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<td>61.6</td>
<td>3.5</td>
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<td>large signal (50mV VPP)</td>
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<td>ref cable (mcx)</td>
<td>24.5</td>
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<td>2.62</td>
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<tr>
<td>kapton</td>
<td>24.4</td>
<td>2998.7</td>
<td>2.63</td>
</tr>
<tr>
<td>mcx + FT + mcx</td>
<td>24.8</td>
<td>2999.2</td>
<td>2.63</td>
</tr>
</tbody>
</table>

Kapton coated coaxial cable

Constrained by waveform generator rise time
Extras: Varying Overvoltage

Overlap increases drastically for lower overvoltage (3V, right)
Histogram charge from many waveforms

1PE waveforms

Total events = 3326
50 events shown

dark noise charge histogram

1PE peak
2PE peak

Single PE resolution is given by
1PE charge vs gaussian width
Charge resolution is good (with scope)

*no horizontal error bars, which represent uncertainty in breakdown voltage due to temperature uncertainty

Extras: Single PE resolution (Oscilloscope)
### Extras: Cerenkov helping nEXO

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

Jason Philip Brodsky*, Sanna Sanjorgio*, Michael Heffner*, Tyana Stiegler*

*Lawrence Livermore National Laboratory

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**Case** | **Description** | **Sensitivity improvement**
--- | --- | ---
1 | Baseline | 1.43
2 | Compton Scatters included | 1.11
3 | Perfect background rejection | 7.61
4 | Back-to-back evenly-split $0\nu\beta\beta$ | 1.96
5 | Back-to-back, even split $0\nu\beta\beta$ and straighter tracks | 5.53
6 | Truth-value Cerenkov ID | 1.40
7 | 100% detection efficiency | 1.59
8 | 10% detection efficiency | 1.20
9 | No directional information | 1.34

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Digitizer: Single PE resolution

Two distinct sources of noise
Digitizer: Single PE resolution

Two distinct sources of noise

- Intrinsic
- induced

(local electronics or cyclotron?)
Two distinct sources of noise
- Intrinsic
- Induced
  (local electronics or cyclotron?)

Can see clearly in histogram of ADC values

amp noise, FWHM = 5.63 adc
Induced noise, FWHM = 12.24 adc