Light collection and simulation in nEXO

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Yale University
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Neutrinoless double beta decay (0νββ)
Finding 0νββ implies physics beyond the Standard Model

1. Lepton number violation

2. New class of elementary particles

3. Implications for matter-antimatter asymmetry

4. Insight into neutrino mass

- Leptons & Anti-leptons
- Only leptons

Image: APS/ Alan Stonebraker

See-saw mechanism

Possible new mass giving mechanism

\[ (T_{1/2})^{-1} \sim |m_{\beta\beta}|^2 \]

Double beta decay

Neutrinoless double beta decay

Neutrinos are Majorana particles

\[ \nu = \bar{\nu} \]
Planned $0\nu\beta\beta$ detector

Builds off success of EXO-200
1st observation of $2\nu\beta\beta$ in $^{136}\text{Xe}$

Single phase TPC
400 V/cm drift field, $\sim$1.2 m drift length

5,000 kg of LXe enriched to 90% $^{136}\text{Xe}$
High Q-value of 2458 keV

Detector size exceeds gamma ray absorption length
Self shielding, Scalability

Scintillation light
- Time stamp of interaction time
- Independent measurement of charge and light is instrumental for energy resolution requirement of $\leq 1.1\%$ and our energy resolution goal of $\leq 0.8\%$

Energy resolution

EXO-200 Th-228 source calibration data

Energy spectra of Th-228 events

Rotated energy resolution is dominated by light collection efficiency

Light collection efficiency ($\mathcal{E}$)

$$\mathcal{E} = PTE \times DAP = PTE \times \frac{PDE}{1-R}$$

Photon detection efficiency

Photon transport efficiency

Device avalanche probability

Reflection at normal incidence in vacuum
Light Collection
**Photon detection system**

**Silicon Photo-Multipliers (SiPMs)**
- Individual SiPMs
- Grouped in 6 cm² sub-arrays → readout channels

**Tile Modules**
- 16 sub-arrays to tile w/ smaller daughterboard & integrated ASIC
- 20 tile modules arrayed to form stave

**Staves**
- 24 staves surround barrel, behind field shaping rings
- Electroformed copper

**Geometry**
- Square cylinder
- Decreases the number of reflections before hitting a photodetector

**Photocoverage**
- 4.6 m²
- 7,680 channels

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Light Collection and Simulation in nEXO | Molly Watts

CPAD 2023
VUV-sensitive SiPMs in nEXO

2 candidate manufacturers
Fondazione Bruno Kessler (FBK)
Hamamatsu Photonics (HPK)

Tested 3 devices (6x6mm²)

- FBK VUVHD3
- HPK VUV4-50 Quad
- HPK VUV4-Q-50 Quad

Replaces previous generation: FBK VUVHD1


<table>
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<th>nEXO requirements to meet ≤1.1% energy resolution</th>
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<td>Photon detection efficiency (PDE)</td>
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<td>Dark count rate at -100°C</td>
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<tr>
<td>Fluctuations in correlated avalanches (CAF) per pulse in 100μs at -100°C</td>
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Photon detection efficiency (PDE)

175 nm PDE as function of over voltage
Requirement: ≥ 15% for ~175 nm photons

Light collection efficiency ($\varepsilon$):
$$\varepsilon = \frac{PTE \cdot PDE}{1 - R}$$

G. Gallina, nEXO collaboration.
Correlated avalanche fluctuations (CAF)

\[ CAF = \frac{\sigma_{\Lambda}}{1 + \langle \Lambda \rangle} \]

- RMS error of CA charge per photoelectron (PE)
- Mean charge in CA per primary PE

Devices meet nEXO requirement at optimal over voltage

**nEXO energy resolution with candidate SiPMs**

Estimated energy resolution as a function of applied over voltage

![Graph showing energy resolution vs over voltage for HPK VUV4-Q-50/VUV4-50, FBK VUVHD3, and nEXO requirement and goal.]

- **Energy resolution**
  - nEXO requirement ≤1.1%
  - nEXO goal ≤0.8%

**Devices meet our requirements!**

Note: Yet to account for external cross talk. Might produce slightly steeper rise but shouldn’t impact reaching goal.

Papers from TRIUMF & IHEP out soon!

Contribution to light channel to total energy resolution neglecting recombination fluctuations

Optical Simulations
Chroma

GPU-accelerated ray tracing package
- Up to 300x faster than Geant4
- Can work with detailed geometry

Light collection efficiency ($\varepsilon$):
$$\varepsilon = \frac{PDE}{1 - R} \times PTE$$

Photon transport efficiency (PTE)

Most detailed light response of nEXO
Contains ~1 trillion photons!


Lightmap from nEXO sensitivity paper
Improving discrimination for Bi-Po tagging

**Backgrounds**

Bi-214 is a dominant background with a gamma close to our 2.5 MeV Q-value.

In the volume, we can reject this background with perfect efficiency by tagging Po-214 $\alpha$.

$$T_{1/2}^\alpha = 160 \mu s$$

**Radon 222 decay chain**

- Radon 222
- Polonium 218
  - $\alpha$ 3.1 m
- Bismuth 214
  - $\beta$ 27 m
- Lead 214
- Polonium 214
  - $\alpha$ 160 $\mu$s
- Lead 210
Improving discrimination for Bi-Po tagging

Backgrounds

Bi-214 is a dominant background with a gamma close to our 2.5 MeV Q-value

Rn-222 ionized daughters can plate out on cathode

At edges like this, it is more difficult to tag Bi-Po events…
Improving discrimination for Bi-Po tagging

• Current sensitivity projection assumes no tagging based on spatial light discrimination
Alpha particle tagging above cathode

In the volume, we can reject this background with perfect efficiency by tagging Po-214 α

\[ T_{1/2}^{\alpha} = 160 \, \mu s \]

Under cathode, current sensitivity projection assumes NO tagging
**Alpha particle tagging below cathode**

Hit pattern of Po-214 alpha decay below surface of cathode

In the volume, we can reject this background with perfect efficiency by tagging Po-214 α. $T_{1/2}^{\alpha} = 160 \mu s$

Under cathode, current sensitivity projection assumes NO tagging.

We can tag these alphas based on spatial light discrimination!
Topological discrimination with hit patterns

Hit pattern of Bi-214 beta decay above surface of cathode

Current work: Exploring clustering algorithm to discriminate between background and signal

Future work: Employ Convolutional Neural Network
Summary

**Light detection**
Have devices from two manufacturers that meet nEXO requirements!!

- Good agreement amongst multiple institutions
- More measurements than shown today

arXiv:2209.07765

**Optical simulations**
Provide better background rejections and better modeling for energy resolution

- Ongoing discrimination work to better characterize events
Thank you!! Questions?

International collaboration involving 10 countries, 36 institutions, ~200 collaborators

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship.
Back-up slides
Multiparameter analysis

Energy: Signal like

Standoff:

Topology:

Sensitivity and discovery potential

- Projected half-life: $1.35 \times 10^{28}$ years at 90% confidence level
- Design goal $\leq 1\%$ energy resolution at Q-value of 2458 keV
Hardware setups
SiPM characterization - combined effort of multiple institutions

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>TRIUMF</th>
<th>McGill University</th>
<th>Yale University</th>
<th>University of Massachusetts, Amherst</th>
<th>Brookhaven National Laboratory [28]</th>
<th>Institute of High Energy Physics</th>
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<tr>
<td>DAQ I-V</td>
<td>Keithley 6487 Keysight B2985A</td>
<td>Keysight B2987</td>
<td>Keithley 6487</td>
<td>Keithley 6482</td>
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<td>LXE/GXE</td>
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<td>SiPM PDE</td>
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<td>No</td>
<td>No</td>
<td>No</td>
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Dark count rate (DCR)
Geiger mode avalanche in absence of a photon

Requirement at 163 K ≤ 10 Hz/mm²

Requirement met for all devices in the entire range of over voltages!


Correlated avalanches (CA)

FBK VUVHD3

Avg extra charge produced by CA \((\Lambda)\) as a function of applied over voltage

\[
CAF = \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}
\]

RMS error of CA charge per photoelectron (PE)

Mean charge in CA per primary PE

Grey points are FBK VUVHD1*

New VUVHD3 are an improvement!


Correlated avalanches (CA)

HPK VUV4s

Avg extra charge produced by CA ($\lambda$) as a function of applied over voltage

$$CAF = \frac{\sigma_{\lambda}}{1 + \langle \lambda \rangle}$$

RMS error of CA charge per photoelectron (PE)

Mean charge in CA per primary PE

RMS error ($\sigma_{\lambda}$) as function of over voltage

Grey points are older test

HPK VUV4 has almost no correlated avalanches!