Light detection with SiPMs for the nEXO experiment

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for the nEXO photodetector group
Overview
Search for $0\nu\beta\beta$ Decay

- $Q_{\beta\beta}$ of $2458.07 \pm 0.31$ keV
- Target energy resolution: $\sigma/Q_{\beta\beta}$ of 1% for the $0\nu\beta\beta$ decay of $^{136}$Xe at $Q_{\beta\beta}$
- Half Life is $10^{25}$ times longer than the estimated age of the universe (Projected half life limit of this decay greater than $10^{25}$ years)

ArXiv:1906.02723
nEXO Design

nEXO is a proposed ~5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of $\sim 10^{28}$ yrs.

- 90% enrichment in $^{136}$Xe
- Drift height $\sim 120$ cm
- Modular anode tiles on top
- Electric drift field $\sim 400$ V/cm
- **4.5 m$^2$ covered with VUV-sensitive SiPMs**
- 600 m$^3$ water tank as veto and shield
SiPM technology
SiPMs technology

Main Characteristics:
- SPADs connected in parallel
- Operated in reverse bias mode
- Incoming photon triggers charge avalanche
- Single pixel is discharged

Advantages:
- High gain at low bias voltage
- Single photon detection resolution
- High radio purity possible
- Suitable at cryogenic temperature
Noise Sources in SiPMs

**Uncorrelated Avalanche Noise**
- Dark Noise (DN)

**Correlated Avalanche Noise**
- extra charge realised per avalanche
  - Afterpulse (AP)
- Cross talk (CT)
# nEXO SiPM Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-detection efficiency (PDE) at 175-178 nm in liquid Xenon (PDE)</td>
<td>( \geq 15% )</td>
</tr>
<tr>
<td>Radio purity: contribution of photo-detectors on the overall background</td>
<td>(&lt; 1% )</td>
</tr>
<tr>
<td>Dark noise rate at -110 °C</td>
<td>( \leq 50 \text{ Hz/mm}^2 )</td>
</tr>
<tr>
<td>Relative Fluctuation of the mean number of Correlated Avalanches (CA) at -110°C within 1μs</td>
<td>( \leq 0.4 )</td>
</tr>
<tr>
<td>Single photo-detector active area</td>
<td>( \geq 1\text{cm}^2 )</td>
</tr>
<tr>
<td>Capacitance per area</td>
<td>(&lt; 50 \text{ pF/mm}^2 )</td>
</tr>
<tr>
<td>Equivalent noise charge</td>
<td>(&lt; 0.1 \text{ PE r.m.s} )</td>
</tr>
</tbody>
</table>

Three SiPMs considered for nEXO: Hamamatsu VUV4 MPPC and FBK VUVHD1/VUVHD3 SiPM
nEXO Test Setups

- Several setups and test facilities currently testing prototype devices:
  
  **BNL:**
  - Testing in vacuum at LXe temps
  - CW VUV light source (with monochromometer)
  - Upgrades to record temperature and eliminate dead time in scope acquisition

  **TRIUMF:**
  - Testing in vacuum at LXe temps
  - CW VUV light source (with monochromometer)
  - Improvements in pumping/baking to eliminate residual water films

  **IHEP:**
  - Testing in vacuum at room temp to -50°C
  - CW VUV light source (with monochromometer)
  - Back online and measurements of new devices (HD3, VUV4) in progress

  **McGill:**
  - Testing in vacuum at LXe temp
  - Several different light sources, including scanning laser
  - Multiplexer able to acquire IV curves for many devices

+ UMass, Stanford, UofA setups used for previous measurements
Dark Noise Rate at 163 [K]

Extrapolated from time distribution between pulses

nEXO Requirement is outside this plot

nEXO Requirement: DN < 50 Hz/mm²

All the devices tested have a Dark Noise Rate that is well below the nEXO spec. at 163 [K]
Great Improvement of new FBK devices if compared with previous generation

- VUV4 can be operated up to 3.5 V.
- FBK VUV HD 1 can be operated up to 2.5 V.
- FBK HD 3 has 1 OV improvement compared to previous generation.

FBK VUV HD 3 has triple-doping technology to suppress After Pulse.

Correlated Avalanche Noise (CA) in 1 us at 163 [K]

nEXO Requirement: Ratio < 0.4 with Ratio ≡ \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}

Mean Number of CA: \langle \Lambda \rangle  +  STD Number of CA: \sigma_\Lambda
• PDE is within nEXO Spec.
• Hamamatsu VUV4 SiPM seems showing a correlation between VUV exposure and PDE loss even for extremely small light fluxes (e.g. MEG 2).
• This last aspect is under investigation.
Photon detection efficiency (PDE)

- PDE is within nEXO Spec.
- Hamamatsu VUV4 SiPM seems showing a correlation between VUV exposure and PDE loss even for extremely small light fluxes (e.g. MEG 2).
- This last aspect is under investigation.

Why these measurements are important?
nEXO Energy Resolution

\[ n = \text{number of quanta produced by the original } 0\nu\beta\beta \text{ energy deposition} \]

\[ \frac{\sigma_n}{\langle n \rangle} = \sqrt{\left( \frac{(1 - \varepsilon_p)n_p}{\varepsilon_p} \right) + \left( \frac{\varepsilon_p n_p \sigma^2\Lambda}{\varepsilon_p (1 + \langle \Lambda \rangle)^2} \right) + \left( \frac{(1 - \varepsilon_q)n_q}{\varepsilon_q} + \frac{\sigma^2_{q, noise}}{\varepsilon_q^2} \right)} \]

nEXO Requirement: \( \frac{\sigma_n}{\langle n \rangle} \leq 1\% \)

- Fluctuation due to number of photons detected
- Fluctuation Due to Correlate Avalanche Noise
- Fluctuation due to number of charges detected
- Fluctuation due to electronics in charge channel
## Summary

Next steps:

- Understand CA in detail, publish paper with consistent results from all groups showing devices meeting specs (target summer 2021)
- Test upcoming prototypes (HPK and FBK 1cm² devices, eventually with TSVs)
- Understand device uniformity and performance over time, including in LXe

<table>
<thead>
<tr>
<th>Requirement:</th>
<th>Hamamatsu VUV4</th>
<th>FBK HD3</th>
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<tbody>
<tr>
<td></td>
<td>BNL</td>
<td>TRIUMF</td>
</tr>
<tr>
<td>PDE (&gt;15%):</td>
<td>21%</td>
<td>19 ± 3%</td>
</tr>
<tr>
<td>CA (&lt;0.2* at &gt;3V OV):</td>
<td>0.15@3V</td>
<td>0.42@4V</td>
</tr>
<tr>
<td>Dark counts (&lt;50 Hz/mm²):</td>
<td>0.8 Hz/mm²@4V</td>
<td>0.2 Hz/mm²@4V</td>
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</table>
Backup
Correlated Delayed Avalanche Noise and Additional Prompt Avalanches 163 [K]

Triple Doping technology suppresses After Pulse

CDA = Correlate Delayed Avalanches i.e. Afterpulse
After Pulse is strongly suppressed

APA = Additional Prompt Avalanches i.e. Direct Crosstalk
Cross Talk is the same of the previous generation
Correlated Avalanche Noise (CA) in 1 us at 163 [K]

Some disagreement between BNL and TRIUMF measurements of CA (HD3 higher, VUV4 lower)
• Device to device variations? Measurement techniques?