Update on NuLat: A Compact, Segmented, Mobile Anti-neutrino Detector

John Learned
for the NuLat Collaboration:

J. Blackmon\textsuperscript{3}, R. Dorrill\textsuperscript{7}, M. Duvall\textsuperscript{7}, C. Lane\textsuperscript{1}, J. G. Learned\textsuperscript{7}, V. Li\textsuperscript{7}, D. Markoff\textsuperscript{5}, J. Maricic\textsuperscript{7}, S. Matsuno\textsuperscript{7}, R. Milincic\textsuperscript{6}, H. P. Mumm\textsuperscript{4}, S. Negrashov\textsuperscript{7}, M. L. Pitt\textsuperscript{8}, C. Rasco\textsuperscript{9}, G. Varner\textsuperscript{7}, R. B. Vogelaar\textsuperscript{8}, T. Wright\textsuperscript{8}


And a number of others who have helped along the way.
NuLat Motivation

• **Demonstrate reactor monitoring capabilities**
  – Security monitoring
  – Commercial burn-up monitoring

• **Investigate fast neutron directionality capabilities**
  – Detection of special nuclear material

• **Probe reactor anomalies**
  – Sterile neutrino search
  – Precision $\nu_e$ energy spectrum measurement

• **Exceptional background rejection**
  – **full 3D precision** segmentation (256 cubic centimeters)
  – complete event ‘topology’ (dE,x,y,z,t)
  – exceptional light collection (600 pe/MeV)
  – sub-nanosecond timing
# NuLat Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Rational</th>
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</thead>
<tbody>
<tr>
<td>Excellent Energy Resolution</td>
<td>Precision Spectral Analysis – Distortions from prediction</td>
</tr>
<tr>
<td>Unique Start Signal</td>
<td>separate positrons from gammas, neutrons, and electrons</td>
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<tr>
<td>Unique Stop Signal</td>
<td>separate n-capture from backgrounds</td>
</tr>
<tr>
<td>Short Time Delay</td>
<td>improves real/random</td>
</tr>
<tr>
<td>Fine Segmentation</td>
<td>smaller improves real/random</td>
</tr>
<tr>
<td>E, x, y, x, t complete event topology</td>
<td>best method to remove residual backgrounds</td>
</tr>
<tr>
<td>Minimal Wall Material</td>
<td>improves systematics and signal degradation</td>
</tr>
<tr>
<td>Fast Timing (Sub Nanosecond)</td>
<td>time-ordering of energy deposits</td>
</tr>
<tr>
<td>Minimal Fiducial Cut Required</td>
<td>minimizes shielding size</td>
</tr>
<tr>
<td>Strong neutrino source</td>
<td>L/E easier at shorter distances, better S/B</td>
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<tr>
<td>Movable</td>
<td>Vary L without E, multiple sources and uses</td>
</tr>
</tbody>
</table>
Classical $\bar{\nu}_e$ Signature

\[
\bar{\nu}_e + p \rightarrow e^+ + n \\
\tau \sim 7\mu s \\
n + ^6Li \rightarrow \alpha + ^3H
\]

\[
(n + ^6Li \rightarrow ^4He + ^3H + 4.8\ MeV)
\]

localized 400 keV\textsubscript{ee}

$\bar{\nu}_e$ (Inverse Beta Decay)

Prompt ($e^+$)  

Delayed ($n$)  

11 Oct 2018  

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Raghavan Optical Lattice

- light channeling via total internal reflection
- full 3D light collection along principle axes
  - Breaks degeneracies present in other detection schemes
Segmentation

proven technique: micro-LENS
  operational liquid scintillator ROL detector
  located at KURF
  Cell size = (3.25”)³
  thin Teflon walls (0.002”)
  partial light channeling (n=1.34 and 1.49)

• NuLat Demonstrator (solid scintillator)
  – 5x5x5 cubes
    • effectively 125 individual detectors
  – 2.5 inch polished plastic scintillator cubes
  – 0.5% $^6$Li by wt. loading (Eljen)
  – VM2000 reflective film ‘dots’ to maintain air-gap
  – Total light channeling (n=1 and 1.54)
  – Easily scalable to larger mass
  – True zero-mass wall – no energy loss

* Change to Liquid Base
Due to sold plastic inadequate optical properties, slow development and escalated cost.
Segmentation

- The amount of light detected in the plane that is not directly facing the cell with the energy deposit is at the level of < 5%
- This pattern is seen in all 3 projections
- The cube containing the energy deposit is identified uniquely by amplitude alone
- Detected light may further be identified by signal timing, permitted location (such as the gammas from positron annihilation must be on average in opposite directions)

Log plot of light output on the (X-Y) face of a mirrored NuLat design via deposition of 2 MeV in the central cell
Unique Start Signal

- Positron plus annihilation gammas
  - large single cell (or two), small halo (0.1-1.0 MeV total), in that time order
  - rejects most gammas (primary reduction via passive shielding when close to reactor)
    - single Compton within detector with no halo
    - multiple Compton within detector with too large a halo
    - single P.E. effect with no halo
  - rejects most cosmogenic backgrounds
    - pulse-shape discrimination rejects fast neutrons
    - $^9$Li, $^8$He are $\beta$- emitters with no annihilation
  - pair production reduced by primary shielding
Event Topology

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\tau \sim 10\mu s \quad n + ^6Li \rightarrow \alpha + ^3H$$

Reconstruction of a typical 2 MeV positron event.

Note: 3D allows digital separation of events along channel.

Average single-cell prompt response to a uniform 3.8 MeV anti-neutrino flux.

No fiducial cut.

4%/600 p.e. /MeV)

Single cell position (< 3 cm w timing)

Effectively 15³ individual high-resolution detectors giving complete event topology.
Changes in Primary Design

Plastic scintillator on hold

Revert to LENS liquid design

Li loaded production delayed ~2yrs

Use available Li loaded scintillator

Optical properties not as needed (transmission, pulse shape ID)

Change from Teflon film to acrylic hollow windows

Cost much escalated

fill/drain & calibrate through small vertical tubes

May go back later – easy change

Assembly underway now.

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Hollow clear plastic windows

Bruce Vogelaar invention and implementation
Now using laser cutter, and will try laser welding
Prototype in Lab
Electronics Improvement

We utilize digitizers made at UH for miniTimeCube

First triggering utilized simple multiplicity

Upgrade almost ready, employing trigger specific to one cube in lattice (or with neighbors)
ROL $5^3$ Antineutrino Detector

- Design Re- Finalized
- All major material in hand
- Construction to be completed ~late 2018
- Deployment:
  - Ready in Early 2019
  - Venue(s) TBD... various alternatives
Conclusion

• NuLat design:
  – Precision topology capabilities $E(x,y,z,t)$
  – Short mean time for coincident signal
  – Pulse shape discrimination for both start and stop signals
  – Several methods of evaluating systematics

• NuLat addresses
  – Reactor neutrino physics
  – Reactor monitoring
  – Special nuclear material safeguards
Questions?
PSD in $^6$Li Plastic

Eljen LLNL based EJ-200 $^6$Li PSD characterization as measured at Virginia Tech

Better energy resolution results in better background rejection.

$FOM = \frac{d}{FWHM_\gamma + FWHM_n}$

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Energy Resolution

→ $E_\nu = E_{e^+} + 1.8$ MeV
→ full positron energy in one cell or at most two (vertex cell)
→ minimal contamination by annihilation gammas in vertex cell
→ allows excellent neutrino energy resolution throughout the complete detector

unique to NuLat

available to all integrating small detectors
Unique Stop Signal

- Lithium-6 PVT
  - 7 $\mu$s time correlation
  - 0.5% by wt. $^6$Li PVT
  - mono-energetic $\sim$400 keV$_{ee}$
  - single cell stop tag
  - n/gamma PSD separation
  - 23% n capture in same cell as positron
  - 60% n capture in same cell as positron plus the six facing cells
  - 940 barns

![Neutron Capture Time in $^6$Li PVT Scintillator](chart.png)
NIST Background Studies

- Gamma spectrum surveyed via germanium detector (red)
- Germanium detector response to gamma model developed (blue)
- Gamma model allows for detailed simulation studies inside mTC Cave
222Rn Internal Calibration

- 226Ra 222Rn-Generator
- Fill airgaps with 222Rn rich gas
- Same/adjacent cell

214Bi $\rightarrow$ $\beta^-$ + 214Po
followed by ($\tau = 164\mu s$)

214Po $\rightarrow$ $\alpha$ + 210Pb

- Close temporal and spatial structure to that of an antineutrino capture
- Provides PSD stop tag
- Mean $\beta^-$ E = 642keV
- Mean $\alpha$ E $\sim$ 700keVee
- Characterize surface scintillation affects

Prompt ($\beta^-$)  Delayed ($\alpha$)  time
Sterile ν Search Performance

- $S/B = 3$
- Time is calendar time at NIST
- NuLat is expected to have better $S/B$, even in higher-flux environments (10/1)

\[ \Delta m^2 = 1.770 \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.025 \]

\[ \Delta m^2 = 0.85 \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.025 \]

Live-time
reactor power

\[ \Delta m_{41}^2 \text{ [eV}^2] \]
\[ \sin^2 2\theta_{41} \]

Gallium Anomaly, 95% CL
Reactor Anomaly, 95% CL
All $\nu_e$ Disappearance, 95% CL
$5^3$, 1 year, $1\sigma$ CL
$10^3$, 5 years, $3\sigma$ CL
$15^3$, 5 years, $3\sigma$ CL

arXiv:1212.2182
arXiv:1501.06935
IRS: Custom Digitizers

- SCROD - board stack with IRS3d chips similar to those used in Belle – 100 ps timing resolution
- Separate Data and triggering paths
- 16 chips per board stack -> seen at right
- 192 chips per cube (1536 chan)
- 8 channels per chip, 2-4 Gigasamples / s
- 32,768 sample analog storage
- (per channel)
Additional System Electronics

- Clock and Triggering Board
  - Provides a low-jitter clock to front-end modules ($\sigma_t < 2$ ps)
  - Issues system triggers to all boardstacks based on parameters set by the user
  - Can distribute pulses for testing and calibration
- Weiner HV power supply
- Dell server and other computers for storing data, remote operation
- Laser calibration system

The clock and trigger board, designed by Serge Negrashov here at UH