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

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Abstract. Here we present NuLat (the Neutrino Lattice), a new detector designed to study electron anti-neutrinos a few meters from a nuclear reactor. NuLat features a Raghavan Optical Lattice (ROL) and consists of 3375 boron or $^6\text{Li}$ loaded plastic scintillator cubical cells boundaries have a 0.127 mm (0.005) air gap, resulting in total internal reflection guiding most of the light down the 3 cardinal directions. NuLat gives excellent spatial and energy resolution, allowing for in-depth event topology studies. These features allow us to discern inverse beta decay (IBD) signals and oscillation patterns, even in the presence of other backgrounds. We discuss here motivation, efficiency, sensitivity and project status.

1. Introduction
Since their discovery by Cowan and Reines in 1956, neutrinos have continued to provide new and exiting insights into physics. Their small reaction cross-section allows them to pass through materials nearly unimpeded, giving us windows into processes in the cosmos as well as inside terrestrial experiments. It has long been a goal of the neutrino-detection community to build compact, mobile anti-neutrino detectors and many such devices are now in the works. Key features of these detectors include relative portability and practicality of use. Though their neutrino capture rates are limited by their small volumes, these detectors have the advantage of running in close proximity to commercial reactors and being moved and redeployed during the course of their active lifetimes.

2. NuLat Motivations
There are several key motivations for constructing a detector like NuLat. As mentioned above, the small size and portability allows deployment in or near reactor sites. This compensates for loss of flux due to volume constraints while also allowing short-baseline studies of neutrinos closer to reactor cores. Commercial reactor monitoring is highly desired, both for security purposes and observation of fuel-burnup. Further, NuLat’s neutron detection capabilities allow for directional detection and monitoring of special nuclear materials.

3. NuLat Features
NuLat features an array of $^6\text{Li}$ loaded plastic scintillator cubical cells with a 0.127 mm (0.005) air gap. This allows for total internal reflection of scintillation light, aiding in energy reconstruction. The channeling of light three dimensions allows for vertex reconstruction both in space and time.
NuLat’s scintillator, in addition to having an excellent capture time for neutrons, allows for pulse
shape discrimination, further enhancing background rejection. More details on these features
are provided in table 1, below.

| Features                               | Rationale                                      |
|----------------------------------------|------------------------------------------------|
| Excellent Energy Resolution            | Precision spectral analysis distortions from prediction |
| Unique Start Signal                    | Separate positrons from gammas, neutrons, and electrons |
| Unique Stop Signal                     | Separate n-capture from backgrounds             |
| Short Time Delay                       | Improves real/random event ratio                |
| Fine Segmentation                      | Smaller improves real/random                    |
| E,x,y,x,t event topology               | Best method to remove residual backgrounds      |
| Minimal Wall Material                  | Improves systematics and signal degradation     |
| Fast Timing (Sub Nanosecond)           | Time-ordering of energy deposits                |
| Minimal Fiducial Cut Required          | Minimizes shielding size                        |
| Strong neutrino source                 | L/E easier at shorter distances, better signal to background |
| Movable                                | Vary L without E, multiple sources and uses     |

4. Detector Design

NuLat’s design comprises a 15 by 15 by 15 cubic array having 3375 cubes of EJ-254 6Li-loaded plastic scintillator 2.5” (6.35 cm) on a side, and spaced 0.01” apart. The base plastic for these is polyvinyl toluene (PVT), which has an index of refraction = 1.58. A gap index between 1.12 and 1.29 would be optimal. For simplicity in construction the nominal design will use air gaps (39 critical angle). Thus, a cell inside NuLat will have the vast majority of the light going to the six PMTs that view it, with some light trapping and no unchanneled light. The outer cells will be instrumented with 2” photomultiplier tubes connected to a short (1.5” long) square channel to round photo-cathode light guide (LG) that will each view a single-lattice channel. The LGs serve as an efficient means to couple the square cross section of the lattice channels to the circular photo-cathode. The full instrumentation will require a total of 1350 PMTs and LGs[1]. Readout will be accomplished with a stack of IRS-3d fast-readout electronics, design at UH Manoa and previously used in the miniTimeCube detector[2].

5. Inverse Beta Decay in NuLat

NuLat detects electron anti-neutrinos through the process of inverse beta decay (IBD): a neutrino interacts with a proton, emitting a positron and a neutron via the reaction shown below.

\[ \nu_e + p \rightarrow p^+ + n \]  

(1)

For reactor sources of IBD events, the positron will almost always deposit its energy in one
scintillator cell, occasionally two cells, and very rarely in more than two cells. The annihilation
Figure 2. Log plot of the light output on one face (X-Y) of a mirrored NuLat design due to the deposition of 2 MeV in the central cell.

gammas will typically scatter around the detector, and deposit their energy in a few cells around the vertex. This allows for the positrons kinetic energy to be reconstructed separately from the total energy of the prompt signal (i.e. the vertex cell contains mostly the energy from the positron with little contamination from the annihilation gammas). This feature is unique to NuLat. The neutron-tag topology in NuLat is fairly simple since the IBD neutron will likely be captured near the vertex cell with a mean time of a few microseconds. Neutron capture on $^6$Li produces a 2.05 MeV alpha and a 2.73 MeV triton which will produce signal in the capture cell of about 483 keVee making it well localized.[1].

6. Conclusion
NuLat has the potential to offer short base observations of neutrinos from nuclear reactors, allowing further understanding of the neutrino oscillation spectrum. It also has applications for special nuclear material monitoring and background observations near reactors. It’s design has the benefit of precision event topology reconstruction as well as pulse shape discrimination and fast-timing for background rejection.

References
[1] C. Lane, S. Usman, J. Blackmon, et al. 2015 NuLat:A new type of neutrino detector for sterile neutrino search at nuclear reactors and nuclear nonproliferation applications. arXiv:1501.06935
[2] V. Li, R. Dorrill, M. Duvall, et al. 2016 *Invited Article: miniTimeCube*. Rev. Sci. Instruments 87. arXiv:1501.06935