Far-Field Monitoring of Reactor Antineutrinos for Non-Proliferation

Gary Smith

On Behalf of the AIT-WATCHMAN collaboration
Demonstrate nuclear reactor monitoring for non-proliferation purposes through antineutrino detection using a large, scalable technology (Gadolinium-loaded water).
Advanced Instrumentation Testbed

• Situated at Boulby Underground Laboratory (N.Yorks., UK)
• Located 26 km from two 1.5 GWth advanced gas-cooled reactors (Hartlepool)
• Test novel methods for the discovery of reactor cores

Water Cherenkov Monitor of Anti-Neutrinos

• Investigate signal efficiency and radioactive backgrounds
• Operational status recognition (on/off cycles of two reactors)
• Sensitivity for discovery of one reactor in the presence of another
The WATCHMAN Collaboration

19 institutions from US and UK
91 collaborators

Co-spokespersons
Adam Bernstein
Mark Vagins
Anti-Neutrino Production and Detection

Produced in nuclear reactors
- $\beta$-decay of fission fragments
- $2 \times 10^{20}$ anti-neutrinos per GWth
- isotropic emission

Detectable via Inverse Beta Decay
- low cross-section $\sim 10^{-42}$ cm$^2$
- impossible to shield

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

E$_{\nu}$ (MeV)

(arbitrary units)

Emitted spectrum
Cross-section
Detected spectrum

arXiv:1101.2663 [hep-ex]
Anti-Neutrino Based Reactor Monitoring

Close Proximity (up to 200 m)
- estimate fissile content and relative thermal power
- high statistics operation validation

Mid- to Far-Field (200 m – 100+ km)
- low statistics regime
- remote monitoring
- reactor discovery / absence
- large area coverage

Numerous experimental efforts

Very few Far-Field detectors

Advanced Instrumentation Testbed!
Load water with gadolinium sulphate

- Gd has 49,000 b neutron capture cross-section (c.f. hydrogen 0.3 b)
- Capture produces 8 MeV γ-ray cascade (4-5 MeV visible)
- Thermalisation takes ~30 µs

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

Achieve ~50% detection efficiency for antineutrinos interacting in fiducial volume

**Anti-neutrino heartbeat**
Inverse beta decay is detectable via two flashes of light occurring within a short time interval (~100 µs) and in close proximity.
Working polysulphate mine
Second deepest mine in Europe (1.4 km)

Site choice motivation
• A 30-year record of safe science at Boulby
• longstanding cooperation with AWE
• strong University partnership
• $10^6$ reduction in cosmic ray flux vs. surface
• two-reactor site gives a stringent nonproliferation test for the new technology
AIT-WATCHMAN
Baseline Design

- 6000 m³ tank
- Veto region between tank and PMTs (suppress cosmics & natural radioactivity backgrounds)
- Steel PMT support frame 3 m inside tank
  - 3600-4400 photomultiplier tubes (PMTs)
  - Low radioactivity 10” PMTs
  - 20-25% photo coverage
- 1.5 m between PMTs and fiducial volume (suppress radioactivity from PMTs & support structure)
- Kiloton fiducial volume (virtual)
Antineutrino Interaction Rate

- Flux information for Boulby based on the online geoneutrino map project (https://geoneutrinos.org)

See arXiv:1611.01575 Steve Dye

- Hartlepool provides ~83.4% of total antineutrino flux
- This translates to around 500 interactions/year
The table on the left shows the expected detection rates for one detector configuration.

The effect of varying photo-coverage and volume sizes on event rates is under investigation.

Analyses can include (unblind) or ignore (blind) prior knowledge of the operation of either or both reactor/s.

### Event Rate Breakdown

<table>
<thead>
<tr>
<th>Signal / Background Source</th>
<th>Events per week (20% photo-coverage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 1</td>
<td>4.2</td>
</tr>
<tr>
<td>Core 2</td>
<td>4.2</td>
</tr>
<tr>
<td>World reactors</td>
<td>1.3</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.9</td>
</tr>
<tr>
<td>Fast neutrons*</td>
<td>0.6</td>
</tr>
<tr>
<td>Radionuclides</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Signal</td>
<td>8.4</td>
</tr>
<tr>
<td>Total Background</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Total Estimated</strong></td>
<td><strong>11.3</strong></td>
</tr>
</tbody>
</table>

* Fast neutron study with FLUKA underway
The WATCHMAN detector can be used to test several non-proliferation related observations!

**Example Observation Scenarios**

- **Scenario 1**: With known backgrounds, how long to detect the presence of a reactor? *one week*
- **Scenario 2**: How long to detect a second core with knowledge of the first core? *one month*
- **Scenario 3**: How long to confirm the status of both reactor cycles with prior knowledge? *one year*
### AIT beyond WATCHMAN

**Future Studies**

<table>
<thead>
<tr>
<th><strong>Directionality</strong></th>
<th>Detection of reactors at the longest ranges necessitates the addition of directionality information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supernovae trigger</strong></td>
<td>A dedicated trigger for recording supernovae neutrino events is under study</td>
</tr>
<tr>
<td><strong>Fast Timing Detectors (e.g. LAPPD)</strong></td>
<td>AIT will provide a future platform in which to test fast timing detectors such as Large Area Picosecond Photon Detectors</td>
</tr>
<tr>
<td><strong>Water-based Liquid Scintillator (WbLS)</strong></td>
<td>A water soluble mixture with fast timing, good spectral response, tunable light yield</td>
</tr>
</tbody>
</table>
AIT-WATCHMAN
Project Timeline

DRAFT TIMELINE - SUBJECT TO CHANGE
Far-Field Monitoring of Reactor Antineutrinos for Non-Proliferation

Summary

- **WATCHMAN** will detect anti-neutrinos from a remote reactor using a tank of Gd-loaded water in Boulby Underground Laboratory.
- The primary goal is to monitor two nuclear reactor cores at 26 km standoff to prove the concept of a scalable monitoring system for non-proliferation.
- The Advanced Instrument Testbed (**AIT**) aims to increase sensitivity beyond **WATCHMAN**.
- Design and construction are underway.
Thanks for your attention!

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