Monitoring nuclear reactor (anti-)neutrinos with AIT-WATCHMAN

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On behalf of the AIT-WATCHMAN collaboration

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What is AIT-WATCHMAN?

- Non-proliferation remote monitoring demonstrator of a single reactor site
- Specifically: “To verify, to 3 sigma confidence, the presence of a nuclear reactor (if one exists) within 30 days”
- A 1kTon scale Gd-loaded water-based anti-neutrino detector for the remote monitoring of small fission reactors
- Project goal is to observe reactor on/off at ~30 km standoff from the reactor
- Rationale is to develop a medium sized detector that can be scaled to MTon masses – required for smaller reactors and/or larger standoff distances
- AIT = Advanced Instrumentation Testbed
- Physics goals include directional supernova detection, geoneutrinos, solar neutrinos, etc.
- Also provides an R&D test bench for future technologies (WbLS, LAPPDs …)
AIT-WATCHMAN collaboration

- Collaboration
  - 21 universities (UK: Sheffield, Edinburgh, Liverpool)
  - 3 US laboratories
  - 2 UK laboratories (AWE, Boulby)
  - ~90 collaborators
AIT-WATCHMAN location

- Hartlepool Nuclear Reactor
- Boulby Underground Science Lab

Distance:
- 25 km
Hartlepool Nuclear Reactor

- Dual-core reactor complex
- Advanced gas-cooled reactors (AGR), 1575 MWth per reactor core
- Look for flux difference between 1-core and 2-core operation
- Scope for future complementary work with near-field detection
Boulby Underground Lab

- STFC-operated science facility 1100 m underground
- 2800 m.w.e.
- Cosmic ray flux attenuation ~ $10^6$
- Working potash/polyhalide mine
- AIT-WATCHMAN will be constructed and commissioned in a completely new cavern ~25m (h) x 25m (d)
Anti-neutrino fluxes at WATCHMAN site

- Flux information taken from online tool (see Antineutrino Global Map project)
- (Ref: Steve Dye, Reactor Anti-neutrinos at Morton and Boulby, nucl-ex:1611.01575)
- Note: reactor signal is no more than 10 events per day!
The world in anti-neutrinos …

see www.geoneutrinos.org for more information
AIT-WATCHMAN: an anti-neutrino detector

- The basic principle of the WATCHMAN detector is that of a water Cerenkov detector.

- However, by loading the water with Gd (in the form of Gd sulphate) anti-neutrino interactions can be identified.

- Anti-neutrinos undergo inverse beta decay to give a neutron and a positron.

- Signal is positron annihilation followed by ~8 MeV gamma cascade (4-5 MeV of visible energy) from Gd de-excitation ~30 μs later.

- ~70% detection efficiency.

- The experimental signature is thus:
  - exactly 2 Cerenkov flashes ...
  - .. which occur within 100 μs ...
  - ... and within a voxel of 1m³.
Why Gadolinium?

- Cross-section for neutron capture is
  - \(\sim 49,000\) barns for natural Gd
  - \(0.3\) barns for H
  - \(0.2\%\) Gd concentration results in \(\sim 90\%\) of neutrons capturing on Gd

AIT-WATCHMAN analysis goals

1. Perform the experiment with full knowledge of both reactors’ ON/OFF status (unblinded)

2. Perform the experiment with knowledge of a single reactor as a background, with a remaining unknown reactor.

3. Perform the experiment with no knowledge of either reactor (fully blinded)

<table>
<thead>
<tr>
<th>Component</th>
<th>Events/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 1 (signal)</td>
<td>4.8</td>
</tr>
<tr>
<td>Core 2 (background)</td>
<td>4.8</td>
</tr>
<tr>
<td>World Reactors</td>
<td>1.5</td>
</tr>
<tr>
<td>Cosmogenic radionuclides</td>
<td>0.1</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.6</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.6</td>
</tr>
</tbody>
</table>
From reactor to detector ...

\[ \approx 6 \times 10^{21} \rightarrow 10^{22} \rightarrow \text{“a few”} \]

Antineutrinos per nuclear fission \quad Fissions per second in a 3 GWt reactor \quad Antineutrinos per second from a 3 GWt reactor (all directions) \quad Antineutrino interactions per day (per 1 kton volume, at \sim 25 \text{ km standoff})

Distance to detector, small interaction cross section

25 km
Dwell time to reactor on/off determination

Confidence Limit of days needed until WATCHMAN confirms on/off cycle at Boulby

Periods of time when one reactor core is off
AIT-WATCHMAN detector design

- ~1 kTon fiducial volume
- ~1.5m active veto region
- ~20m tank height and diameter
- 0.1% Gd-loaded water
- Inward-facing PMTs mounted on stainless steel frame inside tank
- 20%-25% PMT coverage
- 10” HQE low radioactivity PMTs under characterisation (approx. 3600-4400 required)
UK activity: PMT testing

- Develop procedures for PMT testing at Boulby, both on the surface and underground.

- A long list of PMT characteristics to be determined including:
  - Gain calibration, reproducibility
  - Peak to valley ratio
  - Dark rate
  - Afterpulsing, etc.
Scaling up to kTon masses requires a good understanding of background sources and rates.

(Left) Muogenic beta delayed precursors

(Right) Fast neutron rate capable of producing two correlated events in a detector.
Multiplicity and Recoil Spectrometer

- Muon veto added around detector Muon veto to reject muogenic neutron production within MARS
- A single fast neutron entering the detector can produce a multiplicity of particles that may mimic an anti-neutrino signal in water
Understanding backgrounds - WATCHBOY

- **WATCHBOY** - a “mini-WATCHMAN” detector with 2 ton target and 10 ton veto

- Designed to measure muogenic radionuclides, e.g.: $^9\text{Li}$, $^8\text{He}$, etc.

- Event time after identified muon in WATCHBOY.

- Tagging procedure allows removal of nearly all backgrounds due to pile up of other muons.

- Uncorrelated events are fitted between 1 ms and 2 s - good agreement between the data and the uncorrelated expectation.
Beyond WATCHMAN: AIT

- Once the primary goal of AIT-WATCHMAN is complete the experiment may be used as a testbed for novel instrumentation and techniques including, e.g.:
  - LAPPDs (large area MCP photodetectors with picosecond timing resolution and high gain)
  - WbLS (water-based liquid scintillator with significant increase in light yield compared with water Cerenkov)
  - Directionality studies (use of elastic scattering events to provide some directional information on the incoming anti-neutrino)
  - This would enhance capability for non-proliferation but also open up the possibility of scientific studies such as geo-neutrinos, CNO solar neutrinos, neutrino less double beta decay, etc.
AIT-WATCHMAN timescales

Standoff for observing small reactor operations
Within days to months

>10^1 km
>10^2 km
~10^3 km

~10^8 ton
Megaton-scale detector with directionality

~10^6 ton
Megaton-scale Gd-doped or water based scintillator

~10^3 ton
Advanced Instrumentation Testbed and WATCHMAN

~10^2 ton
WATCHBOY, MARS, EGADS (complete)

2012-2017 activities

~6 year Lifecycle Plan (this project)

Long-term vision
Conclusions

✦ AIT-WATCHMAN will build a ~1 kTon Gd-loaded water Čerenkov detector as a nuclear non-proliferation demonstrator

✦ Hartlepool/Boulby in the UK has been selected for the site for AIT-WATCHMAN

✦ Tank design is almost complete, cavern excavation to start in 2020, large scale PMT tests underway

✦ Once the non-proliferation demonstration is complete AIT-WATCHMAN is well-suited for use in sterile neutrino searches, supernova studies, as well as a testbed for advanced light sensors and water-based scintillator studies.