Snowmass2021 — Letter of Interest: a kiloton-scale gadolinium-doped water detection concept for Neutrino Experiment One at the Advanced Instrumentation Testbed in Northern England

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As described in a companion LOI submitted to Snowmass, AIT is a joint United States and United Kingdom project to test and demonstrate a range of antineutrino-based monitoring technologies for detecting nuclear reactors at a purpose-built facility in the North of England. The US and UK sponsors are conducting an independent evaluation of a number of possible detector designs for possible deployment at AIT. Candidate designs based on gadolinium-doped water and water-based liquid scintillator detection media are being considered for the first experimental effort at the AIT site, termed Neutrino Experiment One (NEO). Here we present a possible detector design for the gadolinium-doped water option. This design is identical in most respects to the design put forward by the WATCHMAN collaboration, as described in [1].

NF Topical Groups: (check all that apply ☐/■)
■ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
■ (NF7) Applications
☐ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors

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I. DESIGN OF A GADOLINIUM-DOPED WATER DETECTOR FOR AIT

As described in a companion LOI from the WATCHMAN collaboration, AIT is a joint United States and United Kingdom project to test and demonstrate a range of antineutrino-based technologies for detecting and monitoring nuclear reactors. A greenfield underground site at the Boulby mine was chosen because of its proximity to the twin-core Hartlepool reactor complex, at ~ 26 km standoff, and the strong existing scientific and safety infrastructure at the site, due to the presence of the currently operating Boulby Underground Science Facility.

The first experiment to be conducted at AIT is termed Neutrino Experiment One (NEO). NEO will have two major nonproliferation goals: (1) demonstration of discovery and/or exclusion of nuclear reactor operations at long standoff (*i.e.*, 10s to 100s of km); and (2) demonstration of verification of declared nuclear reactor operations, including operational status and fissile inventories. Additional possible measurements include estimation of the reactor standoff from the oscillated antineutrino spectrum, and sensitivity to more distant reactors. The experiment will also have world-class real-time sensitivity to supernova.

Gadolinum-doped water, (Gd-H_2O) is an attractive and well-studied option for the NEO target medium. The Gd-H_2O idea was put forward early in this millennium for both nonproliferation and physics purposes [2, 3]. The underlying physics concepts and engineering issues have been experimentally validated at scales ranging from ~ 1 to 100 tons [4–6], as well as directly in the Super-Kamiokande detector [7], giving a solid understanding of its properties, including an attenuation length comparable to that of pure water, as well as overall stability and maintenance requirements. The detector design presented here was first put forward by the WATCHMAN collaboration [1], and passed an external conceptual design review in 2019.

The Super-Kamiokande experiment is also adding gadolinium to the water medium in that detector [8]. Assuming gadolinium-doped water is used at AIT, the deployment would differ due to the focus on nonproliferation applications of the technology, especially the ability to monitor the operational status of individual reactors, as well as the planned flexibility of AIT to accommodate changes to the experimental configuration that can improve scalabilty, simplify deployment, and reduce costs in future nonproliferation deployments. The program will also support synergistic advances relevant for the international high energy physics community. Some examples are discussed here and in companion Letters of Interest from the collaboration (five in total.)

The inclusion of gadolinium as a dopant in the water is a key advantage for nonproliferation applications, and has strong potential for scaling to larger sizes. The signal induced by reactor antineutrinos is inverse beta decay (IBD), in which antineutrinos interact with a proton, generating a positron and neutron in the final state via W-particle exchange. By including 0.1% Gd (by mass) with the H_2O, the time to capture for thermalized neutrons is reduced from hundreds to tens of microseconds in water. The reduction of the neutron capture time is critical to suppression of antineutrino-like backgrounds. Additionally, the Gd-capture gamma-ray cascade results in high-energy deposition (about 4.3 MeV of detectable energy in water). Together, the increased light output and shorter time-interval to capture combine to improve the efficiency for neutron identification, and suppress backgrounds, compared to capture on hydrogen. The overall IBD efficiency is similarly enhanced compared to a pure water Cherenkov detector. The relatively low cost and ease of access to water, and the long attenuation length of the medium even with gadolinium-doping, make the option promising both at the kiloton-scale, and at the larger scales needed for more remote standoff monitoring and discovery of reactors.

An essential requirement for a Gd-H_2O detector is water filtration in the presence of gadolinium. This technology, termed 'molecular bandpass filtration', has been demonstrated by the EGADS [6] project. That project also demonstrated compatibility of the medium with materials similar to those to be used in the proposed design for NEO, long-term stability of operations, and an attenuation length roughly equivalent to that of pure (undoped) water.

Figure 1 shows a schematic of the current Gd-H2O baseline design.

In this design, the Gd-H_2O target is held in a 20 m free-standing stainless-steel tank. The Gd-H_2O is continuously circulated using the bandpass filtration system. The system separates Gd-H_2O taken from the main tank into streams of pure water and Gd-concentrated water. These are purified separately, then remixed on each recirculation/purification pass.

While the PMT choice is not finalized, a 10 inch photomultiplier tube was assumed to simulate sensitivity. The PMTs are affixed to a support structure inside the tank at a 670 cm radius. This support structure divides the full tank volume into inner and outer volumes. The outer volume is used as a veto region for cosmic muons, as well to block from the inner volume muogenic and ambient neutrons and gamma-rays generated in external rock. The baseline inner and veto volume photocoverages are 20% (3302 target PMTs) and 2% (359 veto PMTs), respectively. To minimize unwanted reflections in the inner volume, a light-absorbing blanket surrounds the PMTs on the inward side of the inner detector. To enhance light collection in the veto volume, light-reflecting material covers the outer side of the inner detector and the inner side of the tank.

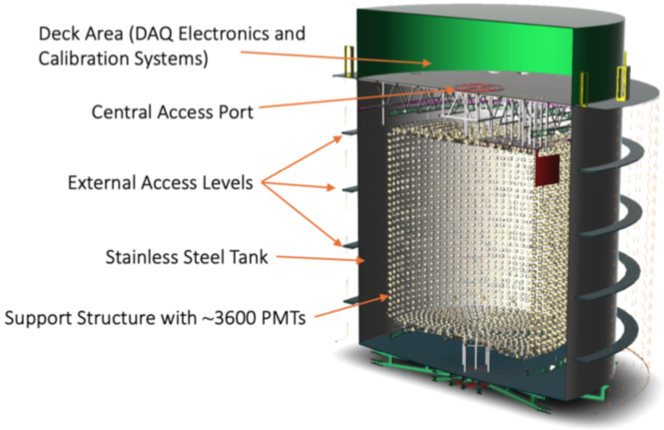

FIG. 1. Schematic for the baseline WATCHMAN Gd-H_2O detector design

II. PROJECTED SENSITIVITY AT THE AIT SITE

A number of monitoring scenarios can be explored at the AIT site. One scenario is the discovery of one of the two Hartlepool reactor cores, assumed unknown, in the presence of the other, assumed known. In this case, the known reactor (and more distant reactors) comprise the real antineutrino background for the discovery.

Table I shows the expected signal and background assuming a Gd-H2O detector at the AIT site, based on a detailed simulation of the detector and main backgrounds. The result is not fully optimized: further analysis is anticipated to reduce the dwell-time estimate. The simulations of the signal and most backgrounds were performed in a Geant4-based simulation framework known as RATPAC, except that fast neutron simulations were performed using a hybrid FLUKA-Geant4-based simulation framework. Events were reconstructed using the Bonsai algorithm [9].

TABLE I. Detection rates and dwell time for discovery of one Hartlepool core, with 5% false positive and 5% false negative probabilities.

One Hartlepool core [/day]	0.52
Total background [/day]	0.93
Accidental [/day]	0.16
Antineutrino background [/day]	0.70
Fast neutron [/day]	0.03
^{8}He [/day]	1.8e-5
^{9}Li [/day]	0.004
^{17}N [/day]	0.04
Dwell time (5%FP,5%FN) [days]	87^{+25}_{-23}(sys.)

Backgrounds can be divided into three categories: real reactor antineutrinos, depth-independent backgrounds arising from PMTs and detector construction materials, and surrounding rock, and depth-dependent backgrounds, including muons, cosmogenic backgrounds arising from surrounding rock, and long-lived muogenic radionuclides generated in the liquid medium. Dedicated experiments to measure cosmogenic backgrounds at various depths have been conducted by the WATCHMAN Scientific Collaboration [10, 11], helping to improve the accuracy of predictions of detector performance at depth.

III. SUMMARY

This LOI described a baseline Gd-H_2O detector design for NEO, and provides a first estimate of expected performance for one of the project's nonproliferation demonstration goals. The collaboration continues to examine other possible nonproliferation-relevant measurements, including the observation of remote reactors, possible estimation of the standoff of the Hartlepool cores using the spectral distortions caused by neutrino oscillations, as well as sensitivity to supernova antineutrinos and neutrinos.

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