A Snowmass2021 Letter of Interest for the deployment of kiloton-scale neutrino detectors at the Advanced Instrumentation Testbed in Boulby England

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Here we describe a new initiative known as the Advanced Instrumentation Testbed (AIT). 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. Antineutrino detectors could complement conventional safeguards methods to determine the power and fissile content of reactors, independent of knowledge of reactor operations, or even exclude the existence of reactors in wide geographical regions. The US and UK sponsors of AIT are conducting an independent evaluation of a number of possible detector designs for possible deployment at AIT. The first experiment at AIT is termed Neutrino Experiment One (NEO). Candidate detectors based on gadolinium-doped water and water-based liquid scintillator media are being considered in the effort - separate LOIs describe these detectors. The detectors make use of the inverse beta decay interaction, which produces a robust signal against most backgrounds. Anticipating possible nonproliferation and monitoring applications, one goal of the experiment is to determine the dwell-time needed to confirm with high confidence the presence of one or both reactors at the Hartlepool Nuclear Power Station, located

26 kilometers from the AIT, assuming no prior information about the reactors. Another goal is to determine the dwell-time needed to verify that the measured antineutrino output is consistent with known prior information about the reactor operational schedule, including outages. By measuring signal efficiencies and backgrounds in a controlled but realistic environment, AIT will help explore the prospect of detecting and monitoring smaller reactors at greater standoffs using a scalable water-based technology. Over its lifetime, AIT is envisioned to accommodate a series of experiments that permit testing of advanced neutrino/antineutrino detection technologies. In addition to its main nonproliferation missions, AIT can therefore play an important role as a testbed for concepts relevant to 21rst century fundamental neutrino physics. In this Letter of Interest, we describe the site, and point to opportunities for engagement and collaboration with the broad physics community on technology development for AIT. Companion LOIs describe detection concepts and a ranging application.

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
■ (IF2) Instrumentation Frontier/Photon Detectors
■ (IF9) Cross Cutting and Systems Integration

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I. A NEW TOOL FOR EXPLORING NONPROLIFERATION APPLICATIONS OF ANTINEUTRINOS

Monitoring plutonium production is one of the key challenges encountered in nuclear nonproliferation and safeguards. Even relatively small (research-grade) nuclear reactors can produce plutonium at a high enough rate to support a clandestine nuclear weapons program. For example, a typical research reactor operating at a power level of 40 $\mathrm{MW_{th}}$ can produce plutonium at an annual rate on the order of one significant quantity[1] . A typical power reactor operating at 3 $\mathrm{GW_{th}}$ power is capable of producing many tens of significant quantities annually.

For treaties which require that all reactors be declared, a capability to verify that there are no other operating reactors would be valuable. A significant challenge is to develop methods for remotely revealing or excluding the existence of undeclared nuclear reactors — especially smaller reactors that might otherwise avoid discovery. Such a capability, properly developed, could be of broad potential interest for the nonproliferation community.

Limitations in existing methods for remote discovery have motivated interest in antineutrino-based detection and monitoring methods [2], which exploit the characteristic antineutrino emission that accompanies fission, and its inherent immunity to shielding and spoofing. The approach may have relevance both near reactors (tens of meter standoff) and further out, from kilometer to one hundred kilometer standoffs and beyond. The technological problem is challenging: at one hundred kilometers, detector sizes would already approach the 100-kiloton scale even in favorable background conditions.

If increased standoff can be achieved, antineutrino methods offer advantages that are otherwise difficult to obtain. These include persistence; the ability to detect or exclude reactor activity in a wide geographical region without external cueing information; insensitivity to weather, shielding and other environmental factors; and the potential to place constraints on, or directly measure, the operational status and total thermal power of the reactor and thereby estimate the maximum possible rate of plutonium production in the discovered reactor. The disadvantages of antineutrino-based detection methods largely result from the very small interaction cross-sections of antineutrinos, which requires the detectors to be large, especially so in large-standoff detection scenarios. Successful identification of these relatively rare antineutrino interactions requires the application of methods to suppress the omnipresent backgrounds within the detector. Some of these backgrounds can be sufficiently reduced only by deploying the detectors underground, though the minimum depth is unknown. These considerations have a large impact on detector cost and deployability.

US and UK scientific and nonproliferation sponsors have teamed to develop the AIT site and NEO experiment that will at once explore and demonstrate the potential of antineutrino detectors for reactor monitoring, discovery and exclusion. The WATCHMAN collaboration supports this effort by providing detector designs and expertise for all phases of the effort. The AIT-NEO project is described below. Specific detector concepts are described in separate LOIs submitted by the WATCHMAN collaboration.

THE ADVANCED INSTRUMENTATION TESTBED

The Advanced Instrumentation Testbed (AIT) is a proposed new multi-purpose, multi-user facility co-sponsored by the Office of Defense Nuclear Nonproliferation Research and Development, part of the National Nuclear Security Administration within the US Department of Energy, by the Office of High Energy Physics in the US Department of Energy, and by the UK's Science and Technology Facilities Council and Ministry of Defence. AIT is planned to be located in the North-East of England in the Boulby Underground Laboratory [3] with a 1.1 km overburden of cosmic ray shielding. The laboratory is situated approximately 26 km from the Hartlepool Reactor Complex housing two operational 1.5 $\mathrm{GW_{th}}$ reactors — a copious source of antineutrinos. The overall goal of the AIT is to permit testing of state-of-the-art technology options for discovering and monitoring nuclear reactors over the widest possible range of standoff distances (10 km to several hundred km) using the reactor antineutrino signature. To accomplish this aim, the AIT is being designed as a flexible future-proofed facility. When complete, it will enable deployment of experiments employing innovations in antineutrino technology for both nonproliferation activities and for fundamental science.

AIT will house an integrated remote reactor antineutrino detection experiment, and possibly follow-on detectors for exploration of nonproliferation and/or physics goals. The first experiment, termed Neutrino Experiment One (NEO), will have two major nonproliferation goals: (1) demonstration of discovery and/or exclusion of nuclear reactor operations at long stand-off distances (*i.e.*, 10s to 100s of km); and (2) demonstration of verification of nuclear reactor operations, including the confirmation of reactor operation, power-plant status, and measurement of the reactor fissile inventory or determination of the inventory limits. Additional possible measurements include range estimates for the reactor standoff distance using spectral oscillations, and sensitivity to more distant reactors. The experiment will also have world-class real-time sensitivity to supernova, and can explore methods for reducing backgrounds relevant to directional sensitivity through the neutrino-electron scattering channel.

There are further scientific, cross-cutting, and innovation goals that are envisioned for AIT and NEO: (1) nonproliferation community technical and policy engagement; (2) promoting joint US/UK collaborative efforts, to include basic university research, development, and innovation activities; (3) complementary research on instrumentation and fundamental physics in collaboration with US and UK government agencies; and (4) support for research and development of advanced detection technologies and instrumentation as part of the kiloton-scale antineutrino detector demonstration at the AIT.

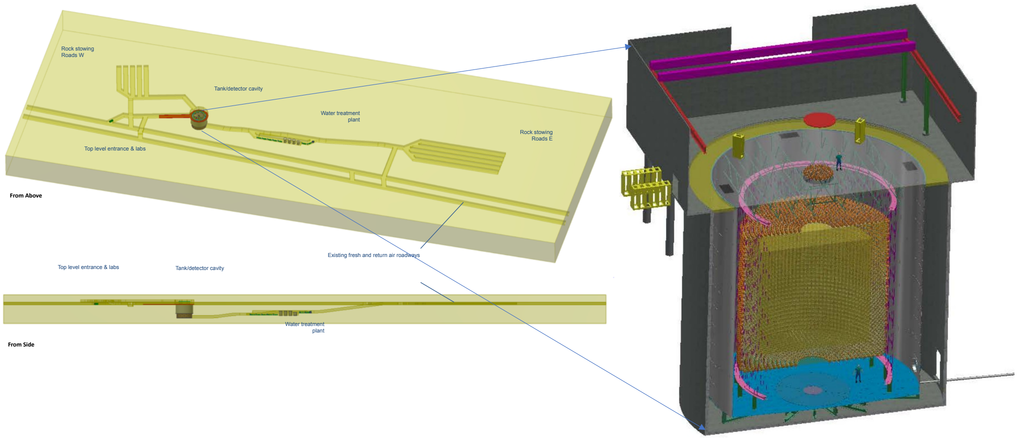

FIG. 1. *Left:* A concept for the AIT design, including the detector cavity, water-treatment plant, and access. *Right:* a cutaway view of a possible detector design for Neutrino Experiment One.

AIT has established several design criteria to enable the execution of NEO and subsequent experiments. An AIT design concept is shown in Fig. 1. The excavated detector area will accommodate a cylindrical tank with a 20 meter diameter and height. Clean-room standards of Class 1000 (ISO 6) are expected to be the best achievable in AIT. Finally, AIT is expected to have a 15 year lifespan, with a design philosophy embraces future-proofing for multiple experiments. Several other requirements are currently being determined, including radiopurity levels in key construction materials, utility needs, liquid treatment needs, and interface requirements and specifications for the tank.

TECHNOLOGY TESTING AT AIT

A key goal at AIT is to deploy a kiloton-scale nonproliferation demonstration detector (Fig. 1). A successful deployment will permit a realistic asssessment of backgrounds and signal efficiencies, and a platform to explore technologies that can improve scalability and performance for future detectors used in nonproliferation. Scalability, cost and deployability considerations, along with the prior experience and current plans for large scintillator-based neutrino detectors (KamLAND [4], Borexino [5], and JUNO [6]), have driven the technology choice for this project towards water-based detectors. There are two detection media being considered for NEO: gadolinium-doped water (Gd-H_2O) [7] and water-based liquid scintillator (WbLS) [8]. These designs are described in separate LOIs submitted by the collaboration.

The detector will require a sophisticated and sensitive light readout. Simulations show that a few thousand large (8–10") photomultiplier tubes (PMTs) will be required to achieve the baseline goals. The PMTs will be mounted in a custom support structure, provisioned with power, and interfaced to a data acquisition system. The timing and intensity of light flashes measured by the PMTs will be analyzed to reconstruct the event topology and reliably identify IBD events while rejecting non-reactor backgrounds. These events comprise the antineutrino signature of nuclear reactors.

In addition to the choice of medium, there are several supporting technologies under consideration for testing at AIT. Alternative light detection technology such as Large-Area Picosecond Photo-Detectors (LAPPDs) [9] could improve the resolution in event reconstruction and enable the separation of Cherenkov and scintillation signal in WbLS. Silicon photomultipliers (SiPMs), on the other hand, could considerably reduce instrumentation costs, should their electronic noise be sufficiently reduced. Additional concepts that may improve the light detection include wavelength-shifting plates, retroreflectors, light concentrators, integrated encapsulated optical modules, and the use of wavelength-shifting additives in water. Finally, significant improvements of cleanliness could offer a path to antineutrino detection via electron elastic scattering, which could result in directional sensitivity [10].

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[1] A significant quantity of plutonium, as defined [11] by the International Atomic Energy Agency, is the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. For plutonium, this amount is 8 kg.

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