A Snowmass2021 Letter of Interest for Encapsulation of Photosensors in kton–Mton Scale Neutrino Detectors

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The encapsulation of photosensors in kton–Mton neutrino detectors confers numerous advantages. In addition to physically protecting pressure-sensitive devices like photomultiplier tubes, encapsulation prevents radon from escaping the PMT, preventing a nettlesome background source from reaching the fiducial volume of low-energy neutrino detectors. Encapsulation simplifies the use of local high voltage generation, self-triggering, digitization and pulse extraction, and the concurrent elimination of long and bulky high-voltage cables improves signal quality and reduces installation complexity. The encapsulating vessel interior provides a chemically inert gaseous environment, enabling the deployment of calibration devices without the need for complicated housings. If the vessel is sufficiently large, it can also house light concentrators without the need for special coatings to withstand chemically aggressive pure water or liquid scintillator. Encapsulation may allow for a reliable penetrator-free design that reduces deployment time, improves detector scalability, and simplifies maintenance. In this LOI we describe the encapsulation design planned for use by AIT–NEO

at the Boulby Underground Laboratory in the UK. We also describe enhancements to the design that can be tested *in situ*.

Topical Groups:

- ■ (NF01) Neutrino oscillations
- ■ (NF04) Neutrinos from natural sources
- ■ (NF05) Neutrino properties
- ■ (NF07) Applications
- ■ (NF09) Artificial neutrino sources
- ■ (NF10) Neutrino detectors
- ■ (IF02) Photon Detectors
- ■ (IF04) Trigger and DAQ
- ■ (IF09) Cross Cutting and Systems Integration

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THE AIT–NEO DETECTOR

The Advanced Instrumentation Testbed (AIT) for developing and testing large standoff neutrino-based nuclear non-proliferation techniques will be built in the Boulby Underground Laboratory [1] situated at a depth of about 1.1 km (2800 mwe). The first detector planned for the site, Neutrino Experiment One (NEO), will be composed of several thousand photomultiplier tubes (PMTs) in a cylindrical geometry, surrounding a fiducial mass comprising approximately one kiloton of purified water, doped with gadolinium and/or water-based liquid scintillator [2]. It will be sensitive to the light produced by inverse beta decay events due to reactor $\bar{\nu}_e$ interactions that deposit several MeV of energy in the detector. A schematic diagram of the detector is shown in Fig. 1 The WATCHMAN Collaboration is currently designing AIT–NEO, and the sponsoring agencies have encouraged the exploration of possible future upgrades through a vigorous R&D program.

The detector design envisions each 10 inch PMT housed inside a 16 inch (40 cm) acrylic vessel (AV), following the successes with similar designs for harsher environments by IceCube and others [3–9]. High voltage for the PMT will be generated and controlled within the AV. Triggering on PMT pulses, digitizing them, extracting their arrival times and charge amplitudes, and transmitting the extracted information to a central trigger will all be accomplished by readout electronics in the AV. The electronics will be custom-designed using commercial off-the-shelf parts, with custom firmware and software written to control the flow of data in real time, building on previous design work done for IceCube. A cable providing power and data communications (e.g., Power over Ethernet (PoE)) will penetrate the AV and connect it to a small number of racks above the detector. The AV itself will consist of two acrylic hemispheres that will be mated together in the final assembly step, prior to installation underground. We denote the AV and everything inside it the Contained Underwater Photosensor and Pulse-extraction Apparatus (CUPPA) module.

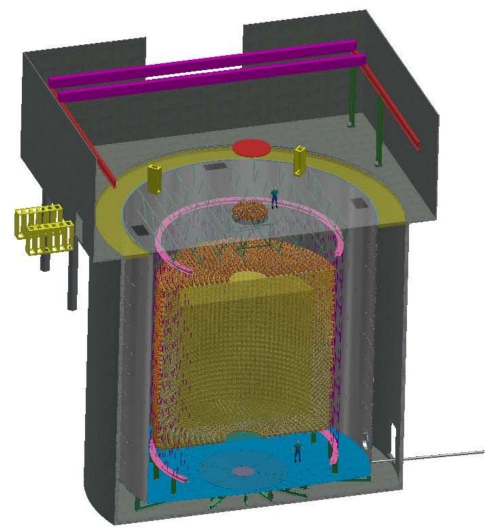

FIG. 1. A preliminary concept for a kton-scale, 20 m high by 20 m diameter detector to be deployed at AIT.

THE CONTAINED UNDERWATER PHOTOSENSOR AND PULSE-EXTRACTION APPARATUS (CUPPA) MODULE

The CUPPA module AV will be made of UV-transparent acrylic with a nominal thickness of 0.5 cm. Acrylic is very radiopure, transparent, chemically inert, impermeable to radon, and mechanically strong enough to withstand the static pressure of a 20 m water column. Acrylic hemispheres are produced commercially for a variety of purposes. Inside the AV, the PMT will make optical contact with the hemisphere's inner surface using a thin layer of optical gel. The addition of a light collection enhancer, such as a Winston cone, would increase the space between the inner surface of the AV and the PMT. This space could be filled with a suitably-shaped acrylic insert. Again, optical gel would be used to fill in any resulting gaps in transition regions from, e.g., acrylic to glass.

Each PMT will be powered by a 1-2 kV, low ripple, miniature high voltage supply. Signals from the PMT will be processed by readout electronics that continously shape and digitize each signal pulse.

The digitization will be performed by two 250 MSPS commercial ADCs clocked 180° out of phase for an effective 500 MSPS digitization rate (at reduced cost), or alternatively by a single 250 MSPS ADC if studies show that it can provide adequate timing resolution. Laboratory measurements indicate that the roughly 1 ns transit time spread of the PMT will dominate the per-channel timing resolution.

Custom firmware running on a commercial FPGA, such as the Xilinx Spartan 7, will control the flow of digitized data, form a trigger, perform on-board calibrations and self-tests, and extract timing and amplitude information from single photoelectron (SPE) signals. For multi-photoelectron signals, this information could be used to seed more sophisticated algorithms running on an embedded micro-controller unit (MCU), programmable in a high-level language. The MCU can also extract timing and amplitude information from more complex waveforms created by throughgoing muons (with a rate of $\sim$0.1 Hz in NEO). Assembled modules can be verified as fully operational prior to installation, and immediately identified once deployed, simplifying detector assembly operations.

The CUPPA design will be modular and extensible. It is anticipated that some modules will house remotely-controlled *in situ* calibration light sources, other calibration devices, and different light sensors for in-place R&D studies.

Power and data communications can be provided by a Cat 6 cable connected to commercial PoE switches just above the detector. At the CUPPA module, pending a cost/benefit evaluation, the cable will either come directly out of the module as a "pigtail" with just the far end connectorized, or it will attach to an underwater connector just outside the AV.

Relative module-to-module timing can be provided by a system similar to that used by IceCube [10] or by using oscillators in each CUPPA module that are periodically synchronized with remotely-controlled *in situ* light sources. Global timing will be provided by a GPS unit on the surface of the Boulby mine and connected underground by an optical fiber cable.

POSSIBLE FUTURE ENHANCEMENTS

One of the principal goals of the WATCHMAN Collaboration, and of AIT–NEO, is to demonstrate technology that can be scaled up to improve the reach and non-proliferation utility of a reactor anti-neutrino detector. Replacing the penetrator that provides power and data communications with wireless technologies would simplify deployment and maintenance for a larger, higher channel count detector. Neutrally-buoyant modules could be inserted into position on a pre-cabled mechanical structure, as the detector is filled with liquid. Detector maintenance by module replacement could feasibly be performed by a remotely-operated vehicle in the liquid, obviating the need for costly, long-duration detector maintenance shutdowns that require emptying and refilling the detector.

We plan to perform *in situ* tests on a small number of channels of wireless power to provide the $\sim$5 W needed by the CUPPA module PMT and electronics. The Qi system, following the standard created by the Wireless Power Consortium [11], is one option under consideration. For data transmission at roughly 1 Mbit/s, custom RF systems using inexpensive, focused Vivaldi [12] antennae may be suitable.

CONCLUSIONS

Photosensor encapsulation has myriad advantages for kton–Mton scale neutrino detectors. In addition to protecting the photosensor itself, the encapsulation material is impermeable to radon emitted by the sensor, provides a friendly environment for co-located electronics and light collection enhancements, and may ultimately allow for a completely penetrator-free design.

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