Snowmass2021 - Letter of Interest: a kiloton-scale water-based liquid scintillator detection concept for the Advanced Instrumentation Testbed in Northern England

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A new generation of neutrino detectors is being developed to provide excellent sensitivity to a broad range of neutrino physics, ranging from long-baseline neutrino oscillations using accelerator beams to the detection of the the diffuse neutrino flux from ancient supernovae, and other low energy neutrino phenomena. The WATCHMAN collaboration is a USA-UK collaboration that is designing a kiloton-scale $\overline{\nu}_e$ detector for the purpose of nuclear non-proliferation. The detector is under consideration for deployment in Neutrino Experiment One (NEO), the first of a series of experiments envisioned for the Advanced Instrumentation Testbed at the Boulby mine in the UK (see companion LOI on AIT and NEO). The proposed detector would test new technology for neutrino detection in addition to providing a direct demonstration of the power of this technique by monitoring the Hartlepool nuclear reactor complex from a distance of about 25 km. Detection of $\overline{\nu}_e$ from weapons production reactors holds promise as a non-intrusive means to monitor nuclear reactors, thereby verifying arms control and cooperative monitoring agreements, in a way that is very difficult if not impossible to spoof. This LOI describes the development of Water-based Liquid Scintillator (WbLS) as one possible target medium for NEO, or a subsequent experiment at AIT, including ongoing effort to characterize WbLS performance and develop production and recirculation technology needed for a practical deployment.

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
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (IF6) Calorimetry
■(IF9) Cross-Cutting and Systems Integration

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The NEO Detector: Figure 1 (left) shows a drawing of the proposed NEO detector, which will be located 1.1 km underground at STFC's Boulby Underground Laboratory in the UK, about 25 km from the 3.15 MWt Hartlepool nuclear power generating station. Roughly 1-2 events per day are expected, over a less well-known but similar scale of background events from ambient radioactivity, cosmogenic spallation products, and external radiogenic neutrons. Details of the design and sensitivity are in an independent LOI, and more information is available in the literature. [1,2] This LOI will discuss the use of Water-based Liquid Scintillator (WbLS), a new technology for nuclear non-proliferation reactor $\overline{\nu}_e$ detection, under consideration for NEO.

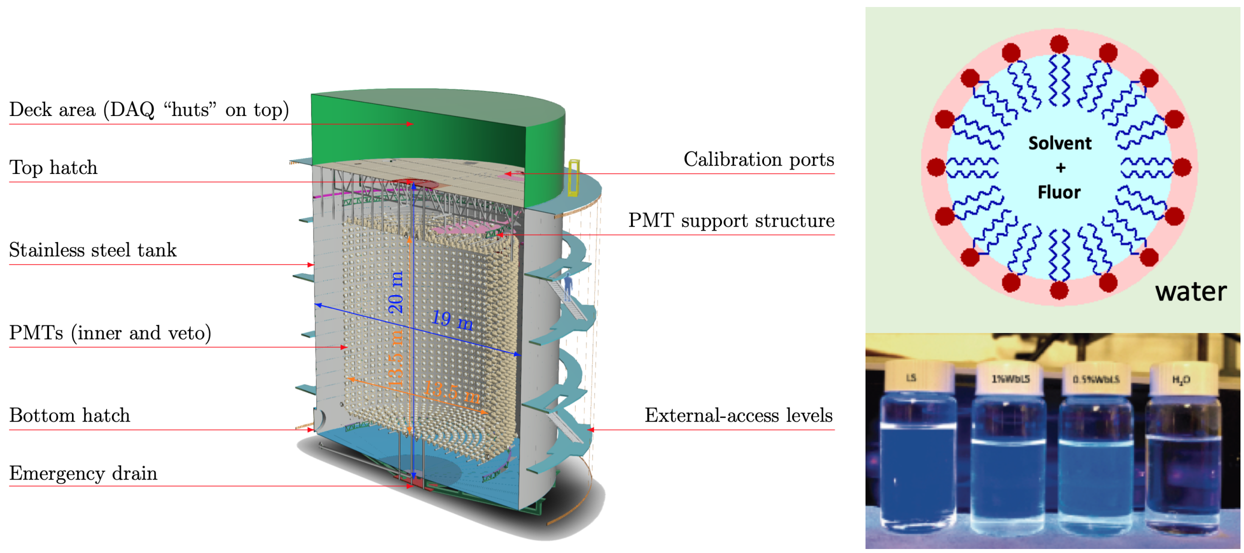

FIG. 1. (center) Conceptual drawing of the NEO detector atthe Boulby Underground Lab (right) LS encapsulated in a micelle, and jars holding (right to left) water, 0.5% WbLS, 1% WbLS, and conventional LS.

WbLS is formed by encapsulating Liquid Scintillator (LS) into nm-scale objects called *micelles* using surfactant chemistry similar to that used in household liquid soaps. This allows normally non miscible liquids to be mixed together, stable over years and a wide range of temperature and pH. Figure 1 (right) shows a conceptual drawing of a micelle composed of a central LS core surrounded by surfactant molecules, each with a hydrophilic head, and a hydrophobic tail. Also shown are examples of WbLS in jars compared to pure water and pure LS.

For NEO WbLS may allow a reduction in the $\overline{\nu}_e$ detection threshold. Instead of the typical 7-8 p.e./MeV to be expected in a typical water Cherenkov detector with 20% HQE PMT coverage, WbLS concentrations of even a few percent can double or triple the number of detected p.e.s. The isotropic scintillation light enables vertex fitting based solely on the spatial distribution of charge, in addition to the usual timing fits. Since both fitting methods have significant but very different non-Gaussian tails , requiring agreement between them may reliably reject backgrounds near the edge of the detector. Both these methods are currently being explored by NEO. The inclusion of gadolinium also impacts the design and performance of the medium. If gadolinium is not included in the WbLS cocktail, neutron detection efficiency may drop, due to the loss of the $\sim 4\ MeV$ visible energy from the capture cascade gammas, or rise, due to the increased light yield compared to water. However, inclusion of gadolinium increases the difficulty of recirculation and purification. The question of the need and benefit of gadolinium in WbLS is also being actively explored by the collaboration.

WbLS in NEO or a follow-on experiment would also be important to the High Energy Physics community. The proposed THEIA detector [6,7,8] is a optical hybrid detector that will observe particle direction and species using Cherenkov light while also having the improved energy resolution and low threshold of a scintillator detector. In support of this R&D effort, the ANNIE experiment at FNAL [9,10] is proposing to deploy a 0.4 ton WbLS target in the neutrino Gd-loaded water target tank in 2021 for testing high-energy reconstruction with WbLS and fast timing. A full 25 ton WbLS fill is being actively discussed as a possible Phase 3 for ANNIE following 2022. Use of WbLS in NEO would be an important intermediate step between a small prototype line ANNIE and a large detector like THEIA .

There is significant on-going R&D into deploying WbLS in neutrino detectors. The CHESS experiment [11,12] has performed detailed measurements of the timing and light yield of WbLS, and long-arm (5-10 m) scale attenuation measurement devices are being constructed at UC Davis and LLNL to characterize scattering and absorption on a distance scale relevant for large detectors.

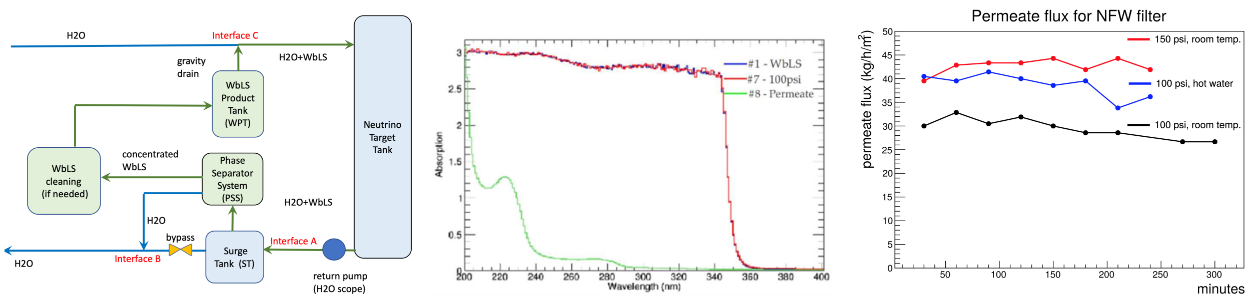

FIG. 2. (left) The general idea for WbLS is to encapsulate conventional LS in a surfactant micelle. (center) The absorbance in a 10-cm UV-Vis cell for (right) The flow rates achieved with a CF-42 test device and commericial NF tuned to WbLS. There is a dependence on temperature and pressure in the performance should be optimized for THEIA .

It is expected that for large-scale detectors recirculation will be needed to remove optical absorbers that leach from detector materials. The extent to which this is necessary depends critically on the materials used in the construction. All water Cherenkov detectors have had recirculation systems that remove these contaminants at a rate that (in steady state) balances the input rate from leaching or other mechanisms. Deionization, reverse osmosis, UV sterilization, and ultrafiltration have been used successfully in large detectors. For WbLS it is expected that recirculation will also be required. A quantitative assessment will require a 10-100 ton scale prototype. A technical challenge is that WblS includes a significant organic component that will not pass through a standard water system. (This is analogous to the problem of Gd recirculation in water.) Fig. 2 depicts a concept for WbLS recirculation that is being explored for THEIA . A Phase Separator System (PSS) is used to separate out the organic micelles from the water, after which the permeate (water and dissolved ions) are sent to a conventional water treatment plant. The organic concentrate is cleaned (if necessary) using separate technology. PSS has been demonstrated to work at the bench top level, as shown by the center and right plots in Fig. 2. These show the performance of a commercial Nanofiltration (NF) system for removal of $> 99.9\%$ the micelles (center) at flowrates that should suffice for NEO.

In summary, use of WbLS for neutrino detection in support of nuclear non-proliferation activities is being studied by the WATCHMAN collaboration to quantify the costs and benefits of its use in NEO, or in follow on AIT experiments. Use of WbLS in AIT would also be significant for the HEP community for future hybrid optical detectors such as THEIA .

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