Snowmass2021 - Letter of Interest

THEIA: Water-based Liquid Scintillator

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
■ (IF2) (IF2) Instrumentation Frontier/Photon Elements

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Collaboration: THEIA

Abstract: A new generation of neutrino detectors is being developed to provide excellent sensitivity to a very 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, solar neutrinos, and neutrinoless double beta decay. The THEIA detector has been proposed for the new Long Baseline Neutrino Facility at SURF. This paper describes the physics sensitivity to be gained by the use of a Water-based Liquid Scintillator (WbLS) as a target medium. It also discusses ongoing efforts to characterize WbLS performance and develop production and recirculation technology needed for a practical deployment.

The THEIA Experiment: New developments in Water-based Liquid Scintillator (WbLS) [1], high-efficiency, fast photon detectors [2], and chromatic photon sorting [3] have opened up the possibility for building a large-scale detector that can discriminate between Cherenkov and scintillation signals, opening up a new dimension in the detection of neutrinos and other particles. THEIA [4,5,6] is a proposed optical hybrid detector that will exploit these two distinct signals to observe particle direction and species using Cherenkov light while also having the excellent energy resolution and low threshold of a scintillator detector. Such a detector situated at the new LBNF, could achieve unprecedented levels of background rejection, thus enabling a rich physics program that would span topics in nuclear, high-energy, and astrophysics. The scientific program would include observations of low- and high-energy solar neutrinos, determination of neutrino mass ordering and measurement of the neutrino CP violating phase, observations of diffuse supernova neutrinos and neutrinos from a supernova burst, sensitive searches for nucleon decay and, ultimately, a search for neutrinoLess double beta decay with sensitivity reaching the normal ordering regime of neutrino mass phase space. Details on the scientific reach are presented in the recent THEIA White Paper [5]. A depiction of THEIA25, a detector proposed for the 4th experimental hall at the LBNF as part of the DUNE program is shown in Figure 1. A 100 kton version (THEIA100) has also been proposed as a independent detector concurrent with, or following the DUNE program.

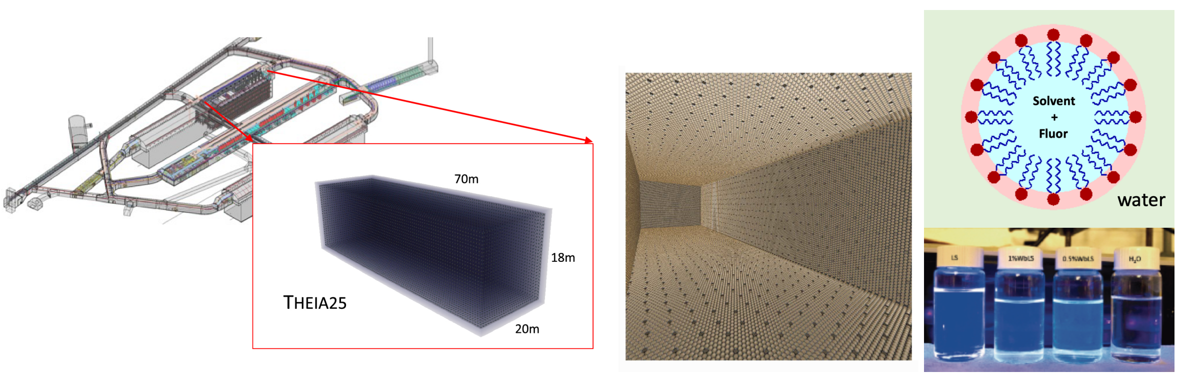

FIG. 1. (left) The THEIA25 detector, designed to fit within an LBNF experimental hall as a 4th detector for DUNE. (center) Internal view showing an array of conventional PMTs and fast photosensors (e.g. LAPPDs). (right) LS encapsulated in a micelle, and jars holding (right to left) water, 0.5% WbLS, 1% WbLS, and conventional LS.

Deployment of WbLS in a large scale detector is a challenging but not overwhelming technical problem. First, it will be necessary to produce WbLS on a kiloton scale. Fortunately, unlike conventional liquid scintillators WbLS is neither flammable or combustible, and thus the safety issues associated with transport and use underground are much more tractable. Indeed, it has been demonstrated in bench top experiments that the WbLS organic component can be mixed into pure water *in situ*, greatly simplifying the transport issues in addition to fire and chemical safety considerations. Fig. 1 (right) shows the basic idea behind encapsulating liquid scintillator in surfactant micelles to enable stable mixing with water. The components of WbLS formulations typically use a common surfactant in widespread commercial use in the soap industry, plus a relatively benign solvent such as Linear Alkyl Benzine (LAB) and trace amounts of the usual fluors and preservatives. Thus, typically WbLS has low toxicity relative to more standard liquid scintillators. Figure 1 (right) shows the basic idea behind encapsulating liquid scintillator in surfactant micelles to enable stable mixing with water.

There is significant interest and on-going R&D into deploying WbLS in neutrino detectors. The

CHESS experiment [7,8] 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. Prototypes to demonstrate practical WbLS production and deployment are also underway or being planned. 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, and a full 25 ton WbLS fill is being actively discussed as a possible Phase 3 for ANNIE following 2022. At an even larger scale, the WATCHMAN collaboration is also considering the use of WbLS for the 6 kiloton Neutrino Experiment One (NEO), which is in the conceptual design stage for deployment at the Boulby Underground Laboratory [11]. Both of these concepts are presented in separate LOIs.

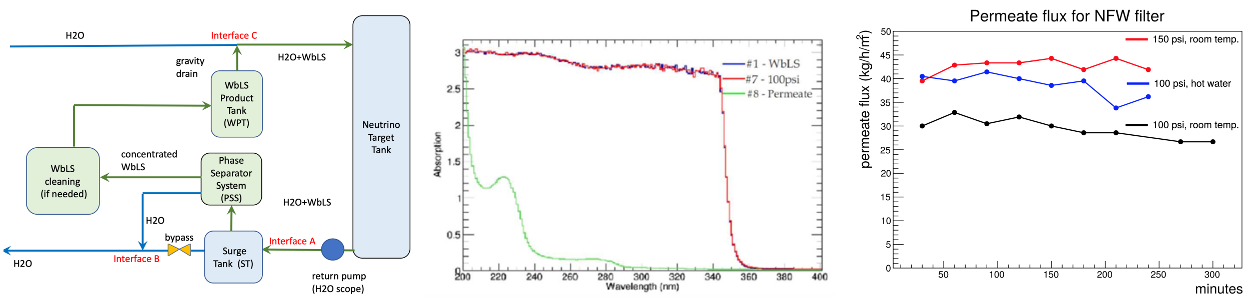

FIG. 2. (left) The general idea for WbLS is to encapsulate conventional LS in a surfactant micelle. (center) The absorbance in a 10-cm UV-Vis cell for (right) The flow rates achieved with a CF-42 test device and commericial NF tuned to WbLS. There is a dependence on temperature and pressure in the performance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

It is expected that a practical large-scale detector will have to be recirculated to remove optical absorbers that leach into the WbLS from detector materials, although the extent to which this is necessary depends critically on the materials used in the construction. Examples of such contaminants include dissolved ions such as ^{+2}Fe, UV absorbing chemicals leaching from plastics, and possible iron colloids and/or bacteria forming in the water. Thus, 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. These systems use a combination of deionization, reverse osmosis, UV sterilization, and ultrafiltration have been used successfully in large detectors. For WbLS it is expected that some recirculation will also be required, although a quantitative assessment will require a 10-100 ton scale prototype. A technical challenge is that WblS (obviously) includes a significant organic component that will not pass through a standard water system. 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 matrix, after which the permeate (water and dissolved ions) are sent to a conventional water treatment plant and 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, which show the performance of a commercial Nanofiltration (NF) system for removal of $> 99.9\%$ the micelles (center) at flowrates that are expected to be sufficient for THEIA.

In summary, WbLS detectors would greatly expand the physics sensitivity of future neutrino detectors. Thus, there is a significant amount of R&D is underway to solve the technical challenges associated with the practical deployment of such systems, including development of support technology and mid-scale prototypes.

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