Journal of Physics: Conference Series

**PAPER** • **OPEN ACCESS**

# Prospects for THEIA: an advanced liquid scintillator neutrino experiment

To cite this article: D Guffanti and on behalf of the THEIA Proto-Collaboration 2020 *J. Phys.: Conf. Ser.* **1468** 012124

# Prospects for THEIA: an advanced liquid scintillator neutrino experiment

**D Guffanti on behalf of the THEIA Proto-Collaboration**

Institute of Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

E-mail: `daniele.guffanti@uni-mainz.de`

**Abstract.** THEIA is a proposed large-scale neutrino experiment based on advanced liquid scintillator and readout by high-quantum efficiency and fast photosensors. In order to combine the advantages of water Cherenkov detectors (i.e. large mass, direction reconstruction and low cost) with the ones of liquid scintillator (high light yield, low threshold) THEIA will deploy a Water-based Liquid Scintillator, which is currently at the center of an active R&D program. This detector concept has the potential to pursue a broad physics program that is summarized in this contribution. As a long baseline experiment installed at Homestake, THEIA will be complementary to the forthcoming DUNE experiment for the determination of the neutrino mass hierarchy and of the CP phase. At the same time, the low energy threshold and efficient neutron tagging makes THEIA an excellent detector for solar and supernova neutrinos measurements as well as for the search of neutrinoless $\beta\beta$-decay and of other rare phenomena.

## 1. Introduction

Recent advances in Liquid Scintillators and in photodetector technology open the way for a new generation of neutrino experiments which aim to combine two extremely successful detector concepts, namely Water Cherenkov (WCD) and Liquid Scintillator (LSD) Detectors. The THEIA experiment proposes a multi-kton detector with the capability to exploit both the Cherenkov and Scintillation detection channel thanks to the development of Water-based Liquid Scintillators and of ultra-fast, high QE photodetectors that are reviewed in Sec. 2. This innovative technique represents a breakthrough that will allow THEIA to pursue an extremely broad physics program that is summarized in Sec. 3.

## 2. Towards an Advanced Liquid Scintillator Detector

The key feature of THEIA is the possibility to separate the Cherenkov and scintillation light signal. While the specific pattern of Cherenkov photons allows for the reconstruction of the track direction for charged ultra-relativistic particles, the high light yield of LS makes it possible to achieve a very low energy threshold and a good energy resolution. A combination of these detection channels will result in a low-threshold, directional detector with a huge potential for neutrino physics. The separation of Cherenkov and scintillation signal can be achieve based on timing, hit pattern and wavelength or a combination of them as it has been demonstrated in many laboratory-scale experiment [1, 2, 3, 4].

Regardless of the separation method, for a large scale neutrino experiment it is essential to have a long attenuation length for photons in the optical range. While a very large attenuation length has been already achieved in WCD, in LS experiments it is limited by the absorption of organic molecules. The recent development of Water-based Liquid Scintillator (WbLS) [5] offers a way to overcome this limitation. In WbLS, LS molecules are dissolved in water thanks to the action of a surfactant agent which encloses LS inside micelle structures. This innovative detection medium has a time response similar to the one of standard LS, an increased transparency and makes it possible to exploit metal loading techniques already developed for WCD. Another interesting feature of WbLS is that the light yield of the cocktail depends upon the fraction of LS dissolved and can therefore be tuned according to the specific physics goal of the experiment.

For the accurate reconstruction of events and to achieve a time-based separation of the prompt Cherenkov signal and the delayed scintillation photons, a fast photodetction system is needed. The recent developments in the field offer different options to achieve a time resolution below 2 ns, such as fast PMTs optical modules, SiPM arrays and the recently developed Large Area Picosecond PhotoDetectors (LAPPDs).

LAPPDs [6] are novel photodetectors based on a Multi-Channel Plate technology with a planar geometry and dimensions of $20 \times 20\,\mathrm{cm}^2$. The key feature of this device is the impressive time resolution of 50 ps for single photoelectron, that combined with a spatial resolution $\lesssim 5\,\mathrm{mm}$ can significantly improve the event reconstruction in the detector [7].

Both WbLS and LAPPDs are very recent technological developments in the field, and THEIA will benefit by the experience gained by other experiments (such as ANNIE [8]) that plans to adopt these solutions in the near future.

## 3. The THEIA physics program

The THEIA experiment will integrate cutting edge technology such as WbLS and LAPPDs in the well tested design of multi-kton neutrino detectors such as Super-Kamiokande and SNO+. The aforementioned technological innovation combined with advanced event reconstruction techniques [9, 10] pave the way for an extremely broad physics program.

As discussed in Sec. 2, the concentration of LS in the detection medium can be tuned according to the main physics goal, therefore it is possible to implement a staged approach for the experiment. In the following sections, three experimental stages are described: in the first the performance of THEIA as a long baseline neutrino experiment are shown; the second section discusses the sensitivity to low-energy (anti)neutrinos; the third presents the prospects for the search of neutrinoless $\beta\beta$-decay in THEIA.

These studies have been presented in a white paper [11] which develops concepts already outlined in [12]. The detector is assumed to be installed at the Sanford Underground Research Facility (SURF, 4300 m.w.e.) and two different configurations are considered: a baseline option with a 25 kton (17 kton FV) detector that will fit a SURF cavern, and an ideal configuration foreseeing a 100 kton (70 kton FV) experiment.

### *3.1. The High-energy program*

As a long baseline experiment at SURF, THEIA will exploit the LBNF neutrino beam (1300 km baseline) as the DUNE experiment. Far from being in competition with DUNE, THEIA will provide a complementary measurement of neutrino oscillation parameters obtained with a detector affected by different systematics, thus strengthening the oscillation results on the LBNF beam.

The THEIA sensitivity to mass hierarchy and to $\delta_{\mathrm{CP}}$ has been studied using the GLoBES framework [13, 14] under the conservative assumption that THEIA will reproduce the detector performance of current WCD. The results of the analysis, obtained considering 9 samples of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ events divided for different topology, are presented in Fig. 1 and shows that in the baseline configuration THEIA has a sensitivity compatible with a single DUNE module. It is worth to stress that WbLS and ultra-fast photodetectors are expected to bring substantial improvement to the sensitivity. Given the relatively high energy of the products of GeV neutrinos interactions, a $\approx$ 1% LS loading is indeed expected to enhance the event reconstruction by measuring hadronic recoils below Cherenkov threshold as well as final state neutrons.

In addition to the accurate measurement of neutrino oscillation parameters, the large mass of THEIA and its excellent particle identification capabilities will make it an excellent tool for the search of nucleon decay [11].

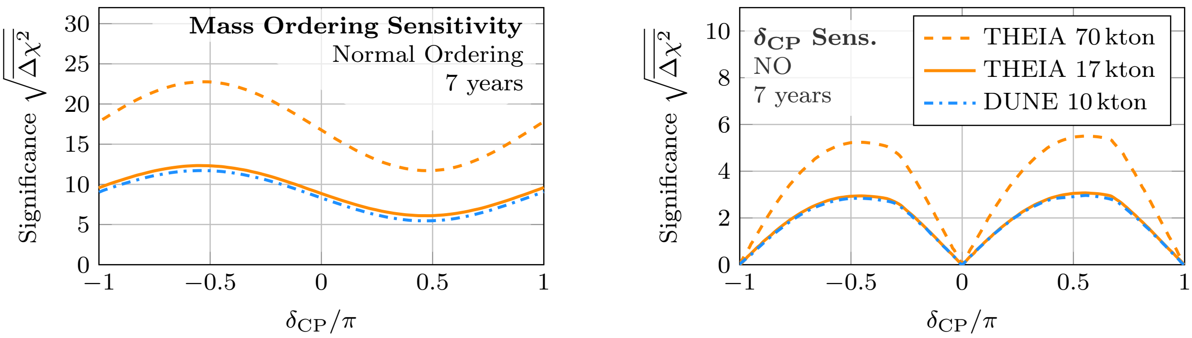


**Figure 1.** Sensitivity of THEIA to mass ordering (*left panel*) and CP-violating phase (*right panel*) obtained assuming the normal mass ordering and 7 years exposure [11]. The sensitivity for a single DUNE module as expected from the DUNE CDR [15] is shown for comparison.

### *3.2. The Low-energy program*
An higher concentration of LS in water (5–10%) will further lower the detection threshold of THEIA, thus expanding its physics reach to include solar and supernova neutrinos, geo-neutrinos and reactor neutrinos. In the following paragraphs the potential for some selected topics is briefly discussed.

*Solar neutrinos* The large exposure of THEIA will allow to collect a huge number of electrons recoiling after being scattered by solar neutrinos. In this connection, the possibility of achieving directional reconstruction for $\approx$ 1 MeV neutrinos would be a breakthrough for solar neutrino physics leading to a significant background suppression. It has been shown in [16] that the directional information will make it possible to measure the flux of the still undetected neutrinos produced by the CNO cycle, that will provide precious information about the Sun metallicity. On the other hand, using water as solvent it will be possible to load the WbLS with isotopes like $^{7}$Li to study the solar $\nu$ Charged Current interaction [11]. In this interaction the $\nu_e$ transfers almost all of its energy to the produced electron, thus permitting an accurate reconstruction of the original neutrino energy. Such information will open the way for the search of new physics in the transition region between vacuum–dominated and matter–enhanced oscillation (2–7 MeV) that is covered by $^{8}$B neutrinos [17].

*Supernova neutrinos* Deploying a 100 kton detector mass, THEIA is expected to detect $\approx$ 23000 neutrino events for a Supernova (SN) explosion at a distance 10 kpc [11], providing a substantial contribution considering the experiments planned for the near future. Most of the events ($\approx$ 19800) are Inverse Beta Decay and can be tagged thanks to the excellent neutron detection efficiency of WbLS that can be further improved by Gd loading. The remaining events come from interaction channels that are extremely useful to separate the contributions of $\bar{\nu}_e$ (IBD, $^{16}$O$(\bar{\nu}, e^{+})^{16}$N), $\nu_e$ (ES, $^{16}$O$(\nu_e, e^{-})^{16}$F) and $\nu_x$ (ES, $^{16}$O$(\nu_x, \nu_x)^{16}$O$^{*}$), providing crucial information for a global flavour analysis of the SN neutrino spectrum [11].

THEIA also has a great potential to perform the first measurement of the Diffuse Supernova Neutrino Background (DSNB). As for SN neutrinos, the IBD represents the main interaction channels but in LS experiments the sensitivity is limited by NC interactions of atmospheric $\nu$ on $^{16}$O that can mimic its signature. THEIA might be able to discriminate this background using the Cherenkov/Scintillation signal ratio to distinguish the prompt energy deposition of the IBD ($e^+$ and annihilation) from the one due to nuclear fragments (below Cherenkov threshold) recoiling after the interaction of high energy atmospheric neutrinos [11].

*3.3. Neutrinoless $\beta\beta$-decay search*

THEIA offers very interesting prospects also for the search of neutrinoless $\beta\beta$-decay ($0\nu\beta\beta$). The detector configuration for this measurement foresees a $0\nu\beta\beta$ candidate isotope dissolved into 8 m radius nylon balloon filled with ultra-pure LS and immersed in the target volume that shields it from environmental radioactive background. Tellurium-130 is considered a very promising option for the search of $0\nu\beta\beta$ in THEIA given its large natural abundance and the solubility in LS already demonstrated by the SNO+ Coll. The sensitivity to a $0n\beta\beta$ signal depends crucially on the exposure, energy resolution and background level of the experiment. The energy resolution of the detector has been assumed to be $\approx 3\%/\sqrt{E}$, that is achievable using a cocktail of LAB + 2 g/l of PPO and a very high photocoverage of $\sim 90\%$. The main background sources are expected to be the irreducible $2\nu\beta\beta$ decays of $^{130}$Te and $^{8}$B solar neutrinos, while radioactive contamination in the LS and in the nylon vessel as well as cosmogenic background are assumed to be under control thanks to advanced purification procedures, volume fiducialization and tagging techniques based on events topology and space-time correlation.

Provided these experimental conditions are met and given its very large mass, with a 10 years exposure THEIA will be competitive with the next generation of $0\nu\beta\beta$ experiment, being capable to cover the entire parameters space allowed by Inverse Mass Ordering ($m_{\beta\beta} < 6.3$ meV, $T_{1/2} > 1.1 \times 10^{28}$ yr 90% C.L.) [11].

## 4. Outlooks

Exploiting the most recent developments in LS and photodetector technology to achieve Cherenkov/Scintillation separation, THEIA will shape the next generation of neutrino experiments. Thanks to the flexibility of the detector concept, THEIA will be able to cover a vast physics program with an excellent discovery potential spanning from high energy physics to neutrino astrophysics and rare events searches.

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