Snowmass2021 - Letter of Interest

Astrophysical neutrinos at THEIA

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
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: A large hybrid optical neutrino detector, capable of leveraging both Cherenkov and scintillation light in a single detector, has great potential for measurements of neutrinos from astrophysical sources: the Sun, supernovae, and the diffuse supernova neutrino background (DSNB). In particular, directional sensitivity at low threshold allows for improved background rejection and excellent signal efficiency, along with additional handles on particle and event identification from the Cherenkov / scintillation ratio. A large (water-based) liquid scintillator (WbLS) detector such as THEIA would be capable of better than 10 (1)% precision on the CNO solar neutrino flux with a WbLS (pure LS) target, as well as sensitivity to the shape of the low-energy ^{8}B spectrum, providing sensitivity to non-standard effects in the vacuum-matter transition region. THEIA would provide $\sim 10^4$ neutrino events in case of a galactic Supernova (SN). Delayed tagging in WbLS permits to distinguish different reaction channels and, hence, neutrino flavors, at the same time providing excellent pointing capability for the SN position of better than 1°. Finally, co-detection of Cherenkov and scintillation signals provides a very efficient means of background suppression in the search for the Diffuse Supernova Neutrino Background. The notorious background induced by the NC interactions of atmospheric neutrinos can be reduced to percent level while maintaining a signal efficiency of more than 80 %, opening the way for a 5σ discovery within 1.5 years of data taking.

I. THE THEIA DETECTOR

THEIA would be a large-scale (25–100 kton) detector, achieving a broad range of physics by exploiting new technologies to act simultaneously as a (low-energy) scintillation detector and a (high-energy) Cherenkov detector [1]. Scintillation light provides the energy resolution necessary to constrain or reject the majority of radioactive backgrounds and provides the ability to see slow-moving recoils; Cherenkov light enables event direction reconstruction, which provides particle ID at high energies and background discrimination at low energies. Thus, the scientific program hinges in many cases on the ability of THEIA to discriminate efficiently and precisely between "scintons" (scintillation photons) and "chertons" (Cherenkov photons).

Discrimination between chertons and scintons can be achieved in several ways. The use of a cocktail like water-based liquid scintillator (WbLS) provides a favorable ratio of Cherenkov / scintillation light [2, 3]. Combining angular and timing information allows discrimination between Cherenkov and scintillation light for high-energy events even in a standard liquid scintillator like LAB-PPO [4–6]. Slowing the scintillator emission time by using slow secondary fluors can also provide excellent separation between Cherenkov and scintillation components [7–9]. Recent R&D with dichroic filters to sort photons by wavelength has shown separation of long-wavelength chertons from the typically shorter-wavelength scintons even in LAB-PPO, with only small reductions in the total scintillation light [10, 11]. In principle, all of these techniques could be deployed together if needed to achieve the full THEIA physics program. New reconstruction techniques, to leverage the multi-component light detection, are being developed and with the fast timing of newly-available PMTs and the ultra-fast timing of Large Area Picosecond Photon Detectors (LAPPDs) [12–14], allow effective tracking for high-energy events and excellent background rejection at low energies.

II. SOLAR NEUTRINO SENSITIVITY

A full study of the sensitivity of THEIA to CNO solar neutrino detection is presented in [1, 15, 16]. THEIA capabilities leverage a number of benefits: large target mass; low background due to fiducialisation; low threshold and good energy resolution; directional sensitivity for signal identification and background rejection; and additional background rejection via particle ID based on the Cherenkov / scintillation ratio. Various detector configurations and background assumptions have been studied, including a target mass from 25–100 kton total, variations in coverage, and photon detector time precision, and intrinsic background assumptions. THEIA is found to have percent-level sensitivity to CNO neutrino detection in the case of a pure LS detector with fast photon detectors, for enhanced direction sensitivity, and better than 10% sensitivity for a WbLS detector. This would improve on the first detection by the Borexino collaboration (who achieved approx 30% precision) and provide a good constraint on the metallicity of the solar core, with the necessary precision to distinguish between different solar models. THEIA's energy threshold and resolution would also permit a precision measurement of the shape of the ^{8}B spectrum in the transition region between vacuum- and matter-dominated oscillations, thus providing a precision probe of possible non-standard effects in this regime. ^{8}B neutrinos provide the most sensitive probe of these effects due to their production region deep inside the core of the Sun.

III. SUPERNOVA NEUTRINOS

A 100-kiloton scale WbLS detector will record a burst of ~20,000 neutrino events from a galactic Supernova at 10 kpc and even a handful of events from a SN explosion in Andromeda.

Like in organic scintillator or water Cherenkov detectors, this signal will be dominated by the Inverse Beta Decays (IBDs) of $\bar{\nu}_e$'s. However, due to the low energy threshold and a functioning neutron tag, CC and NC interactions on oxygen or carbon can be discriminated, providing additional information on the other neutrino flavors. Elastic scattering of electrons offers the possibility to determine the origin of the signal. Actually, WbLS is expected to provide here more accurate pointing than a pure water Cherenkov detector as the background from IBD positrons can be removed by the neutron tag. A resolution better than 1° is achievable [1].

THEIA's SN capabilities would be especially interesting if located close to the LAr-TPCs of the DUNE far detectors: WbLS provides superior timing and a clear SN trigger signature even in case of a far-off galactic Supernova. Moreover, a combined analysis of the $\bar{\nu}_e$ signals in WbLS and the ν_e-dominated signals in argon provides the possibility to study spectral and oscillation features in the ν and $\bar{\nu}$ sectors without systematic effects that might arise due to the neutrinos having different paths through the Earth matter.

IV. DIFFUSE SUPERNOVA NEUTRINO BACKGROUND (DSNB)

The DSNB is an ubiquitous but very faint signal, with expected event rates of $\mathcal{O}(1)$ per 10 kt per year. Hence, current DSNB searches require very large detectors providing ultra-low background levels. In this, WbLS and slow scintillators are very attractive target media since they provide excellent background rejection.

DSNB detection via the IBD is possible only in an energy window from about 10 to 30 MeV, limited by the indiscriminable backgrounds of reactor and atmospheric neutrino CC interactions [17, 18]. Within this window, the most relevant backgrounds are the NC interactions of atmospheric neutrinos [18–20] that often create mixed final states of nuclear fragments, de-excitation gammas and, crucially, neutrons that can mimic the IBD coincidence. In this context, co-detection of Cherenkov and scintillation light in a WbLS offers several very efficient techniques for background discrimination: counting of Cherenkov rings to reject final states with multiple particles; determining the ratio of Cherenkov / scintillation photons produced to reject nuclear fragments; and the tagging of delayed decays that give evidence of product nuclei from NC interactions. Combining these methods, signal efficiencies greater then 80 % can be achieved while reducing NC background levels by almost two orders of magnitude, outperforming all other proposed detection techniques [21].

Full-scale THEIA (100 kt) will detect ~20 DSNB events a year with a very favorable signal-to-background ratio of 2.2 [21]. For standard flux assumptions, an exposure of 150 kt·yrs will be sufficient for a 5σ discovery of the DSNB signal [21]. Accumulating statistics over a decade, spectroscopy of the DSNB to extract information on cosmic star formation rates, failed Supernovae and the average SN neutrino spectrum will come within reach.

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