Snowmass2021 - Letter of Interest

Antineutrino detection 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:

THEIA is a proposed large-scale (10s to 100-kton) novel neutrino detector designed with the ability to discriminate between Cherenkov and scintillation signals. The baseline design consists of a cylindrical tank viewed by inward-looking PMTs and filled with water-based liquid scintillator (WbLS), a novel target which would combine reconstruction of particle direction from the Cherenkov signal, with the energy resolution and low threshold of a scintillator detector. THEIA would have a broad physics program ranging from low-energy solar to high-energy accelerator neutrinos.

A WbLS detector will be especially efficient to detect anti neutrinos from far-distant nuclear reactors and the Earth via inverse-beta decay interactions on protons. These antineutrinos have an MeV-scale energy spectrum, thus, although a fraction of resulting positrons do fall above Cherenkov threshold, they are challenging to detect and identify in a conventional Cherenkov detector. The additional scintillation yield from the WbLS organic compound is expected to increase the detection efficiency by lowering the threshold. For events with an appreciable Cherenkov signature, separation between Cherenkov and scintillation signals offers particle identification capabilities for additional discrimination between signal and background.

I. THE THEIA DETECTOR

With a broad range of low- and high-energy neutrino physics, THEIA [1] will be a multi-purpose detector with unsurpassed sensitivity to a range of topics. THEIA is expected to exploit new technologies in order to increase and maximally leverage the separation of Cherenkov and Scintillation light. The detector will be filled with a cocktail of water-based liquid scintillator (WbLS) [2], or a related cocktail, potentially with additives designed to slow the scintillation emission time. Fast photosensors, such as new large-area PMTs or the much-faster LAPPDs [3], could be used to separate photons based on their time-of-flight. These photosensors could be complemented with enhanced reflectors and collectors able to separate Cherenkov and scintillation photons based on their wavelength, such as dichroicons [4]. These technologies can be deployed in combination in order to achieve the broadest sensitivity across a range of energies.

The benefits of such a detector for antineutrino detection include: 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.

II. GEO- AND REACTOR ANTINEUTRINOS

Geoneutrinos are neutrinos produced by naturally-occurring radioactive decay in the Earth's crust and mantle. A measurement of these fluxes offers a novel and, presently, unique method by which to probe the Earth's interior, by measuring the U/Th ratio of the mantle, and the proton-to-nucleon ratio of the outer-core, which are the strongest discriminant numbers among the geological models [5]. Measuring Earth's internal heat budget is a challenging task for geophysicists, and a global assessment of the U/Th ratio could give insights into the early evolution of the Earth and its differentiation, meaning its transformation from a homogeneous object into a body of layered structure.

THEIA would offer the first high-statistics measurement of geoneutrinos in North America, with the potential to extract the U/Th ratio from a spectral fit. Fig. 1 shows the anti neutrino flux at the Sanford Underground Research Facility (SURF), scaled for a 50 kT water target.

Nuclear reactors emit 10^{10} electronic anti neutrinos per GW of thermal power per second, isotropically. Many experiments have detected and measured this flux by setting detectors at relatively short distances, at the $\mathcal{O}(1)$ km scale, whilst the furthest would be KamLAND at the order of $\mathcal{O}(100)$ km. Detecting reactor anti neutrinos at even larger distances, such as at THEIA, would allow for an increased accuracy for the global measurements of neutrino oscillation parameters, but could also open the way for long distance monitoring of nuclear reactors activity and remote reactor discovery.

III. ANTINEUTRINO DETECTION IN THEIA

We will use the well-known Inverse-Beta Decay (IBD) interaction on protons,

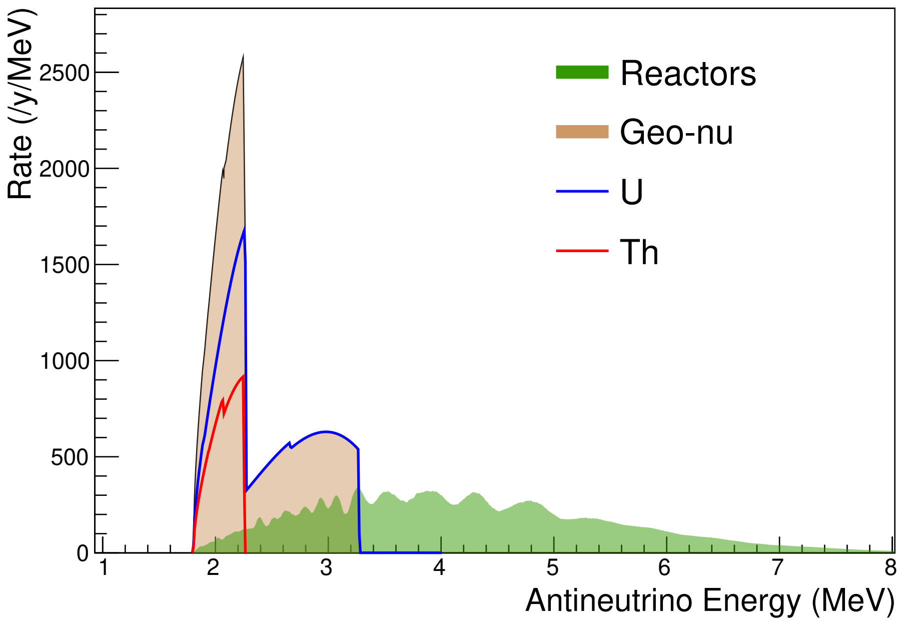

FIG. 1. The detected energy spectrum at SURF of the predicted rate of anti neutrinos from nuclear power reactors and Earth, assuming a 50 kT water target.

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

which offers a distinctive time-correlated signature, with the prompt annihilation of the positron followed by delayed neutron capture. This feature alone allows for strong discrimination against background. At short baselines, a ton-scale experiment with a combination of active vetoes and passive shielding, and with sufficient light yield, can successfully observe antineutrino interactions. For longer baselines, a much larger detector is required. THEIA offers a large target volume, with the benefit of fiducialization to significantly reduce backgrounds from external regions such as the light detectors, and cavern rock. Use of novel technology to permit Cherenkov/scintillation separation will offer several additional handles for particle ID. Positron annihilation on electrons produces two gammas, which will Compton scatter inside the detector, boosted by the direction of the incoming positron. Background sources include single gammas, β-γ events, alphas, and proton recoils. Each of these will have distinct signatures, with possible rejection power from the Cherenkov/scintillation ratio.

The convergence of a new target material design for both high light yield and long attenuation length, with advances in fast photo-detection, would lead to the first tens to hundred kilotons scale experiment to detect these very low-energy antineutrinos.

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