Snowmass2021 - Letter of Interest

A Neutrinoless Double-Beta Decay Search 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: The possibility of a Majorana neutrino, and of lepton number non-conservation, are among the most fundamental open questions in particle physics. A broad international program employing a wide variety of detector types is underway to address these these important questions via searches for neutrinoless double-beta decay (NLDBD). The THEIA program builds on the success of NLDBD searches using large liquid scintillator detectors loaded with double-beta decay isotopes, and leverages novel detector technologies to enable world-class sensitivity at the level of $m_{\beta\beta} \sim 5$ meV. This is enabled by a very large target mass coupled with excellent background rejection achieved via fast timing, advanced photon detectors, optimized scintillator properties, and next-generation reconstruction and analysis techniques.

The search for neutrinoless double-beta decay (NLDBD) is among the most compelling experimental prospects in particle physics today. If observed, this decay process $(A,Z) \rightarrow (A,Z+2)+2e^-$ would simultaneously demonstrate that the neutrino is a Majorana fermion where $\nu_R = \nu_L^c$ and that lepton number is not conserved ($\Delta L = 2$), and provide information about the absolute mass scale of the neutrinos. This would have profound implications for the Standard Model, where new physics is implied by the Majorana mass term, and for leptogenesis, for which lepton number non-conservation is a necessary condition.

This important physics has motivated a vibrant international experimental program, with groups pursuing a wide array of detector technologies, radiological background mitigation strategies, and analysis techniques. One promising technology is the loading of NLDBD candidate isotopes in liquid scintillator detectors. A notable advantage of the liquid scintillator approach is the broad program of potential physics measurements with such a detector, including for example solar, supernova, and terrestrial (geo-) neutrinos. This synergy leads to a highly cost-effective experimental program. Liquid scintillator offers several additional advantages as a technology:

- Liquid scintillator detectors are a well-known and relatively low-cost technology with demonstrated low-background capabilities and particle identification techniques
- Through dissolution or chemical methods, it is possible to load large (multi-ton) quantities of the NLDBD isotope
- Massive, monolithic detectors allow substantial reduction of backgrounds due to detector materials via fiducialization
- Extraction and exchange of the NLDBD isotope, including enrichment and/or depletion, allows for *in situ* confirmation of a detected signal

The scalability is a particularly motivating feature. With very large achievable target masses, relatively inexpensive liquid scintillator detectors can offer excellent potential for NLDBD discovery. In the case of a null result, such a program can quickly rule out large swaths of parameter space, narrowing the focus for high-resolution and zero-background technologies.

The Theia detector concept (see Reference [1] and references therein) builds on the advantages of liquid scintillator NLDBD searches by integrating emerging detector technologies:

- A liquid scintillator-based target allows tuning of the scintillation yield, timing, and other characteristics, in order to optimize the energy resolution and particle identification
- Fast photon detectors and spectral sorting enable separation of the Cherenkov and scintillation optical signals, enabling improved background mitigation through track direction reconstruction

The Theia concept places a 25–100 kton WbLS detector deep underground at SURF. Exposed to the LBNF beam, such a detector would be capable of a broad physics program, including a long-baseline oscillation program complementary to DUNE and Hyper-Kamiokande, sensitive solar and supernova neutrino measurements, nucleon decay searches, and — with isotope doping — NLDBD. The NLDBD search at Theia would be achieved by deploying an inner containment balloon with a pure scintillator or scintillator-rich WbLS doped with the NLDBD isotope, e.g. natural tellurium (34% ^{130}Te) or enriched xenon ($\sim$ 90% ^{136}Xe), at the percent level by mass. A high effective coverage of efficient, fast photodetectors, achieved through a combination of large photo-sensitive area and light concentration, will enable an energy resolution of $\sim$ 3% in the few-MeV energy range of interest. A 100 kton Theia detector with such a configuration would achieve world-leading sensitivity at the $\sim$ 5 meV level for the effective Majorana neutrino mass $m_{\beta\beta}$, beginning to probe the challenging parameter space in the case that the neutrino mass ordering is 'normal' ($m_1 < m_3$).

Realizing such a novel experiment will require R&D both in detector technology and analysis. The scintillator loading chemistry builds from previous successful efforts, but will require dedicated optimization including the photon yield, timing, and spectral properties of the scintillation light. Both the production and filtration will also need to be expanded to a much larger scale for the full 100 kton detector, relative to previous experiments. Photon detector R&D is also crucial; techniques to improve event identification, such as through fast timing or wavelength sorting of photons, will allow recovery of a faint, directional Cherenkov cone amid the much larger isotropic scintillation signal. The ability to reconstruct event direction provides a powerful handle to reduce backgrounds due to solar neutrinos, and could provide further improvements via topological particle identification. A containment balloon system and readout instrumentation also require optimization and design. Analysis techniques leveraging these hardware developments, and in particular fast timing and spatial resolution, are an exciting frontier. Novel techniques for event reconstruction and particle identification using machine learning and other new technologies offer benefits both to the Theia physics program and the broader community of optical detectors.

A highly sensitive NLDBD search at Theia, as a component of a broad portfolio of physics measurements, would provide an excellent opportunity to cover a wide range of the allowed NLDBD parameter space, with highly competitive potential for discovery. This next-generation multi-purpose detector would afford many physics opportunities complementary to the existing program on the timeline considered during the Snowmass 2021 process.

References:

[1] M. Askins *et al.* (THEIA Collaboration), "Theia: An advanced optical neutrino detector," Eur. J. Phys. C 80, 416 (2020).

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