Snowmass2021 - Letter of Interest

R&D Towards Beyond-the-Ton-Scale Double-Beta Decay Searches in 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
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: The observation of neutrinoless double-beta decay ($0\nu\beta\beta$) would show that lepton number is violated, reveal that neutrinos are Majorana particles, and provide information on neutrino mass. If $0\nu\beta\beta$ is discovered at the ton-scale, measurements with increased statistics, using a variety of isotopes, and incorporating directional reconstruction techniques could be used to give information as to the mechanism underlying the decay; if it is not, new techniques would be needed to reach sensitivities beyond 10^{28} years. Kiloton-scale liquid scintillator detectors are a promising technology to achieve these goals, but maximizing their sensitivity requires near-term research and development in a variety of areas: isotope enrichment and loading, Cherenkov/scintillation light separation techniques, low-cost and fast-timing photodetectors, modular and low-dead-time data acquisition technologies, and analysis methods that maximize the use of both spatial and temporal information, like machine learning-based techniques. Addressing these needs will require simulation-based studies and dedicated R&D facilities at small- and mid-scale.

I. SCIENTIFIC MOTIVATION

A global-scale experimental program is currently underway in search for neutrinoless double beta decay ($0\nu\beta\beta$). Observing this theorized process would prove that neutrinos are Majorana particles and demonstrate lepton-number violation, potentially solving the Standard Model mysteries of the non-zero neutrino masses and the origin of the matter/anti-matter asymmetry. As the upcoming ton-scale generation of experiments is built, it is key that research and development (R&D) efforts continue to explore how to extend experimental sensitivities to 10^{29} years and beyond, into what is termed the "normal hierarchy" $m_{\beta\beta}$ mass region. If $0\nu\beta\beta$ is not discovered at the ton-scale, this is rich parameter space to explore: reaching an $m_{\beta\beta}$ limit of $\sim 3\,\mathrm{meV}$ ($T_{1/2} >\sim 4\times10^{29}$ years) would correspond to a discovery probability of over 90%, even taking into account the limits on Σm_ν set by the Planck experiment [1]. If $0\nu\beta\beta$ is discovered at the ton-scale, measuring $0\nu\beta\beta$ in other isotopes, rarer processes like $0\nu\beta\beta$ decays to excited states, and the angular correlation between the outgoing β particles are natural next steps to understanding the nuclear and particle physics of $0\nu\beta\beta$ decay [2–5]. Measurements like these would be among the few available ways to further explore Majorana neutrinos as a path to leptogenesis following the discovery of $0\nu\beta\beta$.

Liquid scintillators (LS) are a promising candidate technology for beyond-the-ton-scale $0\nu\beta\beta$ searches. In addition to reaching among the highest sensitivities in the current generation of experiments, these detectors are highly scalable, can be loaded with a variety of isotopes, and could serve as flexible "neutrino observatories," enabling a rich physics program spanning topics in nuclear physics, high-energy physics, and astrophysics [6].

II. R&D FOR BEYOND-THE-TON-SCALE EXPERIMENTS

The feasibility and sensitivity of future multi-ton detectors would be improved by pursuing advances in a variety of R&D topics. A non-exhaustive list of the potential areas for improvement includes:

- *Isotope procurement and enrichment:* Future experiments will rely on 10s to 100s of tons of double-beta decay source isotope, straining the limits of the procurement and enrichment pathways that ton-scale experiments rely on. ^{130}Te loading in SNO+ LS will happen soon after the experiment finishes their LS fill. A successful demonstration of this loading technique in SNO+ would provide a low-risk loading option for future experiments, given its high natural abundance (33.8%). Of all the possible source isotopes, ^{48}Ca has the highest Q-value (4.272 MeV), placing its $0\nu\beta\beta$ region of interest above most naturally-occurring γ and β decay backgrounds. The high Q-value of the decay would also improve Cherenkov-based directional reconstruction. Calcium is readily available in large quantities, but the low natural abundance of ^{48}Ca and the difficulty of large-scale enrichment has been a barrier to its use [7]. The CANDLES collaboration has reported promising results using multi-channel counter-current electrophoresis, along with near-term plans to scale up the system. [8, 9] Given this success at benchtop-scale, studies must be conducted to evaluate whether the electrophoresis method could be used in an enrichment cascade design to reach the necessary ton-scale throughput.

- *High-Concentration Isotope Loading:* Scaling to multi-ton source masses would be facilitated by developing methods for higher-concentration isotope loading. The SNO+ Collaboration has demonstrated tellurium loading fractions of over 4% [10], with further improvement possible. The KamLAND-Zen Collaboration has proposed pressurized xenon loading to allow for loading fractions of over 3%, a method that could be tested in the R&D facilities described below. Quantum dot-based isotope loading [11] is another potentially-promising alternative; this option could be advanced by collaboration with materials science research groups, which are already working to improve the synthesis and stability of lead-free quantum dots.

- *Cherenkov Light-Based Directional Reconstruction:* A significant challenge facing the next generation of such detectors is the impact of backgrounds that scale with the volume of the detector, rather than with its surface area, and cannot be reduced via shielding and material selection. Using Chrerenkov light to reconstruct electron tracks in the LS would allow backgrounds featuring a single emitted electron, like ^{8}B solar neutrino elastic scattering events, or other complex topologies, like ^{10}C decays, to be distinguished from the two emitted electrons of $0\nu\beta\beta$. Both timing-based [12–14] and wavelength-based [15] methods of Chernekov/scintillation light separation have been demonstrated at small-scale. As discussed below, progress is underway on a demonstration of the timing-based technique in a more-realistic experimental configuration.

- *Low-Cost Fast-Timing Photodetectors* Improvements to photodetector cost, efficiency, and timing capabilities will translate directly to sensitivity gains in future LS experiments, affecting both energy resolution and background reduction capabilities. Improvements to photomultiplier tube (PMT) detectors are constantly underway, and are a viable option for future experiments, as demonstrated by active R&D efforts. Two promising alternative detector technologies are silicon photomultipliers (SiPMs), which are planned for use in the JUNO-TAO detector [16], and large-area picosecond photodetectors (LAPPDs), which are in use in the ANNIE experiment [17]. Along with dedicated $0\nu\beta\beta$ R&D efforts, these experiments will demonstrate the viability of these options and the sensitivity improvements that could be expected from their use.

- *DAQ and Analysis Development* Future LS experiments may have $\mathcal{O}(10^5)$ channels; therefore, modular data acquisition (DAQ) systems and advanced triggering approaches will drastically reduce their complexity. Low-background ASICs are already under development for use in ton-scale $0\nu\beta\beta$ searches [18, 19], and DAQ needs are also being addressed in the DOE Office of High Energy Physics (HEP) Basic Research Needs (BRN) Study on Detector R&D. New analysis methods, like the implementation of machine learning techniques, promise to further improve background rejection [20].

Many of these are broadly applicable to other efforts, including non-LS-based $0\nu\beta\beta$ searches, measurements of other neutrino properties, experiments in high-energy physics, and even medical physics needs. Studies of some of these techniques are growing beyond the bench-top scale, with dedicated facilities like NuDot beginning operation and R&D projects within large-scale experiments like ANNIE and KamLAND-Zen expected to yield exciting results. Other potential areas for improvement, like isotope enrichment, need additional dedicated study. In addition to measurements using specific techniques, flexible simulations of various instrumentation strategies would allow cost-optimization studies that will point the way towards promising beyond-the-ton-scale designs.

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