Snowmass2021 - Letter of Interest

Toward Sensitivity to the Neutrino Normal Hierarchy with Quantum Calorimetry

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: RF4) Baryon and Lepton Number Violating Processes
■ (Other: CF1) Dark Matter: Particle-like
■ (Other: IF1) Quantum Sensors
■ (Other: IF2) Photon Detectors
■ (Other: UF03) Underground Detectors
■ (Other: IF7) Electronics/ASICS

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Abstract: (maximum 200 words)

Abstract

Current experiments to search for broken lepton-number symmetry through the observation of neutrinoless double-beta decay ($0\nu\beta\beta$) provide the most stringent limits on the Majorana nature of neutrinos and the effective Majorana mass ($m_{\beta\beta}$). The next-generation experiments will focus on the sensitivity to the $0\nu\beta\beta$ half-life of $\mathcal{O}(10^{27}$–10^{28} years) and $m_{\beta\beta} \lesssim 15$ meV, which would provide the complete coverage of the so-called Inverted Hierarchy region of the neutrino mass parameter space. By taking advantage of recent technological breakthroughs in quantum sensors and quantum information science (QIS), new, future calorimetric experiments at the 1-ton scale can increase the sensitivity by at least another order of magnitude, exploring the large fraction of the parameter space that corresponds to the Normal neutrino mass ordering. In case of a discovery, such experiments would provide essential information on the mechanism of $0\nu\beta\beta$.

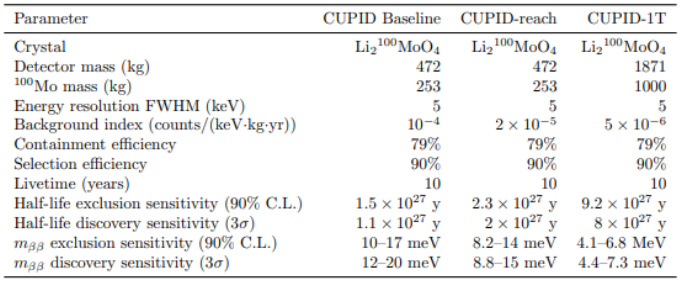
Introduction

Cryogenic calorimeters (bolometers) play a unique role in the search for rare events and new processes, in which sharp resolution and low backgrounds enable sensitivity to weak interactions that can only be seen with very low energy thresholds. As a result, the complementarity of these experiments to data obtained from colliders, accelerators, and satellite experiments has long been exploited in direct dark matter searches. The same characteristics make these experiments ideal detectors for neutrinoless double beta decay. In recent years, breakthroughs in high-purity crystal production have mitigated the early challenges of the scalability of cryogenic crystal calorimeters.

A future experiment with $1000\,\mathrm{kg}$ of the isotope of interest could potentially reach half-life sensitivities greater than $8 \times 10^{27}\,\mathrm{yr}$ at the 3σ level. This corresponds to an effective Majorana mass ($m_{\beta\beta}$) in the range 4–$7\,\mathrm{meV}$, and discovery potential within the allowed region of the Normal ordering of the neutrino masses (provided that the mass of the lightest neutrino is larger than $\sim 10\,\mathrm{meV}$). Current concepts toward development of such an experiment include CUPID-1T, a potentially multi-site, highly-segmented calorimeter with $\approx 1\,\mathrm{t}$ of isotopic mass.

Requirements for CUPID-1T

Reaching the sensitivity for coverage of the normal hierarchy requires a continued ***emphasis on background reduction and the development of a robust readout system for large macrocalorimeter arrays***. CUPID-1T will require a background index of approximately $5 \times 10^{-6}\,\mathrm{cts\,keV^{-1}\,kg^{-1}\,yr^{-1}}$— a challenging but achievable goal 20 times lower than the conservative goal for the upcoming CUPID experiment. In addition, CUPID-1T will require the rapid and reliable readout of over 10,000 channels, including both phonon sensors and the accompanying advanced light detectors. Additional requirements include the ability to acquire a sufficient amount of isotope for the experiment, and the cryogenic expertise to operate large, stable cryogenic systems for long periods of uninterrupted livetime. Ideally, the expertise gained from the current CUORE experiment and partners in dark matter, CMB experiments, and QIS can be applied to systems with volumes up to 4 times larger than that of the current CUORE experiment, and potentially replicated in multiple underground laboratories across the world.



Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

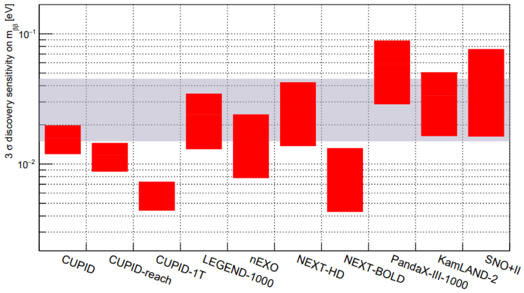


Figure 1: ***Left:*** Sample parameters for CUPID-1T, compared with the baseline and optimistic scenarios for the upcoming CUPID experiment. ***Right:*** Discovery sensitivity for a selected set of next-generation ton-scale experiments. The grey shaded region corresponds to the parameter region allowed in the Inverted Hierarchy of the neutrino mass. The red error bars show the $m_{\beta\beta}$ values such that an experiment can make at least a 3σ discovery, within the range of the nuclear matrix elements for a given isotope. *(Table 10 and Figure 47 from the CUPID pre-CDR[1].)*

Multiple Visions for the Expansion to CUPID-1T

The realization of CUPID-1T could be achieved by building a larger cryostat to house the increased volume of crystals. This has the advantage of the outer crystals acting as shielding for the inner-most crystals; the outer ”veto” layers of the crystal array could be made out of unenriched material or larger crystals to reduce costs. The design of such a cryostat would be a natural extension of the CUORE expertise.

Alternatively, CUPID-1T could leverage international enthusiasm for bolometers to stage the experiment in multiple cryostats around the world or multiple cryostats at the same location. This topology mirrors what is currently being implemented for quantum computers based on superconducting qubits. We note that there are >10 kg-scale demonstrator experiments like CUPID-Mo (Modane)[2], CROSS (CanFRANC)[3], and AMoRE (Korea)[4], and single crystal R&D is proceeding in Japan and China. Such a diffuse staging of the experiment would naturally lead itself to a multi-target observatory and the possibility of multiple $0\nu\beta\beta$ isotopes and additional physics topics (see Physics section below).

Longer-term R&D on advanced detector technologies

US groups are actively involved in leading or contributing to several key efforts to support the dual goals of multiplexed readout and background reduction. Areas of particular interest for CUPID-1T include the use of high-speed superconducting sensors for thermal[5] or athermal[6] phonon detection; the adaptation of multiplexed readout technologies (synergy with CMB) to macrobolometers; the development of an active γ veto (in synergy with low-mass dark matter experiments); and the incorporation of CMOS and ASIC developments for quantum sensors (in synergy with CMB, DM, and QIS)[7]. All of these efforts, as well as international R&D on the use of superconducting crystal coatings to enhance PSD capabilities (including work by CROSS at CanFRANC[3]) have the potential to profoundly impact the design and fabrication of bolometric detectors for fundamental science.

Physics Beyond Neutrinoless Double-Beta Decay

The development of a ton-scale, multi-site, calorimetric detector would provide an opportunity to perform a wide array of searches for physics beyond the Standard Model. In fact, the discovery of $0\nu\beta\beta$ would be an immediate indicator of broken lepton number symmetry. In addition to shedding light on the mechanism of $0\nu\beta\beta$, a ton-scale cryogenic calorimeter would be sensitive to searches for low-mass dark matter candidates, the neutrino magnetic moment (using external sources), solar axions, symmetry (Lorentz, CPT) violations, Majorons, lightly-ionizing and fractionally charged particles, and could serve as an observatory for the study of coherent neutrino scattering and cosmic-ray muons.

Outlook and Acknowledgements

This letter of intent features the ongoing work of multiple collaborations within the CUORE/CUPID line of $0\nu\beta\beta$ detectors. Current R&D efforts to push development of the background-reduction techniques and readout capabilities necessary to realize these detectors are underway. With current projections, CUPID-1T could begin construction as early as the late 2020’s, and commissioning in the early 2030’s. The development of systems for the stable multiplexing and readout of large arrays of macrobolometers, and continued innovation in low-background techniques and facilities, are key components for truly ton-scale searches for $0\nu\beta\beta$, and important areas of overlap between Snowmass frontiers.

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