CUPID, CUPID-1T, and the DEMETER demonstrator

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UC Berkeley

Snowmass CSS  
Neutrino Early Career Talks  
“The Future is Now”  
24 July 2022
CUPID, CUPID-1T, and the DEMETER demonstrator

➢ How to build a 0νββ detector
➢ The CUPID experiment
➢ Towards the normal hierarchy
  ○ CUPID-1T
  ○ DEMETER
Double Beta Decay

Rare radioactive decay, found in even-even nuclei where single-beta decay is energetically forbidden (e.g. $^{100}\text{Mo}$)

- Two-neutrino ($2\nu\beta\beta$) ⇒ Observed with $T_{1/2} > 10^{18}$ years

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\nu_e $$

- Neutrinoless ($0\nu\beta\beta$) ⇒ Expected $T_{1/2} > 10^{25}$ years

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- $$

Observation of $0\nu\beta\beta$ is a critical tool to study neutrinos:

- Majorana or Dirac nature
- Lepton Number violation ($\Delta L = 2$)
- $\nu$ mass scale and ordering

$$ \nu = \bar{\nu} ? $$
How to build a $0\nu\beta\beta$ detector

Double-beta Decay Signal

\[ \frac{dN}{dK_e/Q} \]

\[ K_e/Q \]

$0\nu\beta\beta$

$n \rightarrow p$

$W^- \rightarrow e$ 

$W^- \rightarrow e$

How to build a $0\nu\beta\beta$ detector

$F_{T1/2} \propto \epsilon \cdot \eta \frac{\sqrt{M \cdot T}}{A \cdot b \cdot \Delta E}$

* assumes nonzero background in ROI

Large exposure ($M \cdot T$)
(large mass, long live-time)

Large $\eta$
(isotopic abundance or enrichment)

Large $\epsilon$
(signal efficiency)

Small $b$
(low background)

Small $\Delta E$
(good energy resolution)

Four fundamental requirements for modern experiments:

- Large amount of candidate isotope
- Underground location
- Ultra low background materials
- Signal / background discrimination
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru} + 2e^-$

$^{100}\text{Mo}$ is an excellent candidate for this search:

- a high Q-value (3034 keV) above the bulk of $\gamma$ environmental background,
- favorable nuclear & kinematic factors which yield an expected decay rate 10x faster than other leading isotopes, and
- ease of embedding into scintillating crystals.
CUPID: CUORE Upgrade with Particle IDentification

- 1596 Li$_2$MoO$_4$ cryogenic calorimeters will be instrumented with NTD thermistors for heat signal read out.

- Each crystal will be $45 \times 45 \times 45 \text{ mm}^3$, corresponding to a mass of $\sim 280 \text{ g}$ each and enriched to $>95\%$ $^{100}\text{Mo}$.

- Each LMO crystal will also face two Ge light detectors, instrumented with NTDs (a total of 1710 light collectors).

- The addition of a photon signal allows for rejection of $\alpha$ backgrounds — CUPID-0 [1] and CUPID-Mo [2] have demonstrated this technique with a success rate of $>99\%$.

CUPID

Discovery sensitivity (3σ, 10 yr)

1 x 10^{27} year
m_{ββ} < 10^{-17} meV

<table>
<thead>
<tr>
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</tr>
<tr>
<td>100Mo mass (kg)</td>
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</tr>
<tr>
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Large exposure (M*T) (large mass, long live-time)

Large η (isotopic abundance or enrichment)

Large ε (signal efficiency)

Small b (low background)

Small ΔE (good energy resolution)

m_{ββ} exclusion sensitivity (90% C.L.)

m_{ββ} discovery sensitivity (3σ) 10–17 meV

1 x 10^{27} year
m_{ββ} < 10^{-17} meV

Livetime (years)

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Half-life exclusion sensitivity (90% C.L.)

1.4 x 10^{27} y

Half-life discovery sensitivity (3σ)

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m_{ββ} exclusion sensitivity (90% C.L.)

10–17 meV

m_{ββ} discovery sensitivity (3σ)

12–20 meV
The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazional di Fisica Nucleare (INFN); by the European Research Council (ERC) under the European Union Horizon 2020 program; by the Italian Ministry of University and Research (MIUR). This material is also based upon work supported by the US Department of Energy (DOE) Office of Science and Office of Nuclear Physics. This work was also supported by the Russian Science Foundation and the National Research Foundation of Ukraine. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.
CUPID-Baseline is conservative.
CUPID-Reach is feasible.

### Parameter Comparison

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CUPID Reach

Identical detector to CUPID-Baseline, but operating in near-zero background.

Additional R&D:

- Reduce bulk and surface backgrounds from crystals
  - Additional purification of LMO crystals
  - Elimination of backgrounds by PSD
- Replace some cryogenic vessels and shields with cleaner materials
- Reduce $2\nu\beta\beta$ pileup background

Pileup:

- Slow pulses $\Rightarrow$ O(10) ms risetime
- Fast $^{100}$Mo $2\nu\beta\beta$ decay $\Rightarrow$ $7.1 \times 10^{18}$ year
- High mass, enriched detector

$\Rightarrow$ High probability of simultaneous $2\nu\beta\beta$ events in the same crystal

Mitigation ongoing:

- CNN algorithms
- Timing-focused analysis

Image courtesy M. Beretta
The Future of CUPID: CUPID-Reach

CUPID-Baseline is conservative.
CUPID-Reach is feasible.

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One Possible Future of CUPID: CUPID-1T

CUPID-Baseline is conservative.
CUPID-Reach is feasible.
CUPID-1T is a possible future for CUPID.

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CUPID-1T is an Inverted Hierarchy precision measurement device across multiple isotopes or a Normal Hierarchy explorer.

1871 kg of Li$_2^{100}$MoO$_4$ for 1000 kg of $^{100}$Mo

$\Rightarrow$ 4x scale up of CUPID-baseline

Possible multi-isotope deployment

Zn$^{82}$Se, Li$_2^{100}$MoO$_4$, $^{116}$CdWO$_4$, $^{130}$TeO$_2$

Possible modes of deployment:

- Larger cryostat allows for self-shielding
- Distributed multi-cryostat setup

Background goal of 5×10$^{-6}$ counts/(keV-kg-yr)

- Reduce background $\mu$, $\beta/\gamma$, $\alpha$ discrimination
- Consider pileup and subdominant backgrounds
Quantum sensors ... for > 10,000 channels!
- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

Low-impedance TES: Production is easy to scale, & compatible with multiplexing.
- Energy resolution = 100 eV
- Timing resolution = 10 μsec

MKIDs: Natively pairs with frequency MUX through tuning of individual devices. Ongoing work of CALDER.
- Noise RMS = 90 eV (vibration dominated)
- Risetime = 120 μsec
R&D towards CUPID-1T

Quantum sensors … for > 10,000 channels!
- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
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DEMETER
Demonstrator Experiment with Multiplexed Event Topology and Energy Reconstruction

DEMETER is a collaboration between UC Berkeley CUPID and LBNL CMB groups.

⇒ test stand for development of multiplexing applications, which will be required for CUPID-1T >10k channels.
DEMETER: MUX at Ultra-Cryogenic Temperatures

TES readouts at the level of ten thousand channels have been demonstrated using multiplexing technologies.

We have selected frequency-domain multiplexing (FDM) for our preliminary tests.

**MHz FDM**
- Independent TES AC bias, individual optimization, amplified with DC SQUIDs.
- CMB experiments have multiplexing factors as high as 68. [SPT-3G]
- CUPID can plan on a factor of $O(10)$

**GHz FDM ("μMUX")**
- Sets of TES, coupled to RF SQUIDs, & DC biased.
- Significant thermal loading on cryogenic stage
- Multiplexing factors projected at $O(10^3)$ but not fielded at that scale.

Alternative options:

**Time-division multiplexing (TDM)**
- Requires thousands of wires from cryogenic stage to room temperature electronics
- Decreasing wire density has reportedly degraded noise performance
- Cryo CMOS (JINST 15 (2020) P06026)

DEMETER: MUX at Ultra-Cryogenic Temperatures

Implementing in ultra-cryogenic experiments like CUPID-1T will need R&D.

MUX has not been demonstrated at operating temperatures of mK at this scale including the following: (outside to inside)

- Cables must be shielded from magnetic flux, which has not been demonstrated in CUPID-like environments
- Cable impedance must allow for signal-readout without additional modulation
- Crosstalk between TES devices is a predicted issue, and must be resolved at this scale

Also, radioactivity is naturally occurring in the normal materials for readouts ⇒ backgrounds in CUPID-like experiments.
DEMETER: Event Topology at the Crystal Level

Quantum sensors

- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

- CUPID’s heat/light collection provides excellent particle discrimination, but there’s not yet sensitivity to topology (energy / position reconstruction) at the single-crystal level.

- DEMETER focuses on both phonon and photon reconstruction at the single-crystal scale to provide physics information & background identification to large scale detectors like CUPID-1T. **We could distinguish between one- and two-electron events for a truly background-free measurement.**

- Potentially transformative technology: Modular TeO$_2$ calorimeters with topological reconstruction and PID (Cherenkov and phonon imaging) could **mitigate the need for enriched detectors.**
DEMETER: Simulations Status

Detailed simulations ongoing:

- Scintillation & Cherenkov photon simulations
  - With and without reflective surfaces, with and without anti-reflective coatings.
  - Preparing to calibrate w/ CUPID-like setup (Co-60 source) above ground.
  - Currently limited by understanding microscopic properties of LMO at 10mK.

- Complemented by phonon simulations based on G4CMP (CMS) (photon simulations of LDs are mature, simulations of crystal are in development)
  - Surface events show obvious position dependence!
  - Volume events show some, but we need convincing.
DEMETER Working Group
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One future of cryogenic calorimeters for $0\nu\beta\beta$

**Toward CUPID-1T**
*(Snowmass Contributed Paper)*

You are here!

**E.V. Hansen**
Snowmass CSS 24 July 2022

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