Future prospects for the CUPID Experiment

T. O’Donnell
Center for Neutrino Physics
Virginia Tech

DBD 2018 - Oct 23 2018
Outline

• CUPID Goal: Probing the inverted hierarchy
• CUORE: Status for TeO$_2$ bolometers
• Progress of enriched $^{100}$Mo bolometers
• Prospects for enriched $^{130}$Te bolometers
• CUPID Collaboration forming
Goals for CUPID

- CUPID: CUore Upgrade with Particle ID
- Fully probe the inverted hierarchy of neutrino masses
- Baseline target isotope is 100Mo embedded in LiMoO4 scintillating bolometers
- Viable alternative is 130Te embedded in TeO2 instrumented with advanced cryogenic light detectors

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<th>Isotope</th>
<th>BI (c/kev/kg/yr)</th>
<th>T1/2 sensitivity (90% C.L)</th>
<th>mbb (meV)</th>
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<td>100 Mo</td>
<td>&lt;10^{-4}</td>
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<td>5x10^{27}</td>
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At DNP see:
EN.00009:
Li2MoO4 for 0 decay search in CUPID - The Physics case and current status
B. Schmidt
CUORE - reminder

- Array of 988 $^{nat}\text{TeO}_2$ bolometers (750kg)
- Operated as thermal detectors ($T \sim 10\text{mK}$)
- Target isotope $^{130}\text{Te}$ (206kg)
- Q-value: 2527.5 keV

13 floors per tower 19 towers in total
CUORE Cryogenics

- Capable of cooling detector payload down to 7mK
- Demonstrates it is practical to operate tonne-scale detector at mK temperatures!

Not shown: Superinsulation (SI)
CUORE results

$0\nu\beta\beta$ search PRL 120 132501 (2018)

$\beta \beta$ measurement (in preparation)

$2\nu\beta\beta$ measurement (in preparation)

$0\nu\beta\beta$ search PRL 120 132501 (2018)

See L.A. Winslow’s talk

$\beta \beta$ measurement (in preparation)

$2\nu\beta\beta$ measurement (in preparation)

$T^{1/2} > 1.5 \times 10^{25}$ yr (90% C.L.)

BI = $(1.4 \pm 0.2) \times 10^{-2}$ cnts/keV · kg · yr

Effective resolution (FWHM) @Qbb: 7.7 keV

$T^{2\nu}_{1/2} = (7.9 \pm 0.1 \text{(stat)} \pm 0.2 \text{(syst.)}) \times 10^{20}$ yr

At DNP see EN.00007: Neutrinoless Double Beta Decay And Other Rare Event Searches With CUORE D. Speller, Oct 25

At DNP see MN.00007: CUORE Measurement of Two-Neutrino Double-Beta Decay (C. Davis, Oct 27 3.30pm)
Interpretation of 0vbb search

• The combined 90% C.L. limit is

\[ T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{25} \text{ y} \]

\[ m_{\beta\beta} < 110 - 520 \text{ meV} \]

Projected CUORE Sensitivity

• CUORE sensitivity (5yrs livetime)

\[ T_{1/2}^{0\nu\beta\beta} = 9.0 \times 10^{25} \text{ y} \]

\[ m_{\beta\beta} < 50 - 200 \text{ meV} \]

NME:
JHEP02 (2013) 025
Prospects to explore the inverted hierarchy

- Requires half-life sensitivity on the order of $10^{27}$ years!
- To do this with 250~500 kg of isotope in a reasonable time (10 y) requires background free experiment ($b < 10^{-4} \text{c/kev/kg/y}$)
CUORE Background budget   ROI @ 2528 keV

CUORE-0 Bkg Model

HPGe & NAA

Fluxes at LNGS


Current CUORE Bkg ~0.01 c/keV/kg/y
CUORE Background budget   ROI @ 2528 keV

CUORE-0 Bkg Model

HPGe & NAA

Fluxes at LNGS

TeO₂: natural radioactivity
CuNOSV: natural radioactivity
CuNOSV: cosmogenic activation
TeO₂: cosmogenic activation
CuOFE: natural radioactivity
RomanPb: natural radioactivity
ModernPb: natural radioactivity
SI: natural radioactivity
Rods and 300KFlan: natural radioactivity

Environmental μ
Environmental n
Environmental γ

1E-06 1E-05 1E-04 1E-03

counts/keV/kg/y

90%CL limit
• Value


Goal for CUPID ~ 10⁻⁴ c/keV/kg/yr
Background from surface alphas are the dominant source.
CUORE Background budget  ROI @ 2528 keV

CUORE-0 Bkg Model

HPGe & NAA

Fluxes at LNGS


CUORE data will help quantify backgrounds that are poorly constrained by radio assay measurements
CUORE Background budget  ROI @ 2528 keV


Active cosmic ray veto required (or a deeper site)

Improved materials selection required for CUPID with 130Te

For higher Q-value isotope (e.g. 100Mo @ 3034keV) β/γ background is decreased by ~20 fold
CUPID: CUORE Upgrade with Particle ID

- Dominant background is degraded alphas from surface contamination
- Leverage other energy loss mechanisms to tag particle type

![Graph showing discrimination between alpha, beta/gamma, and nuclear recoils](image)

- More rejection power needed: 99.9% alpha background suppression. Light detector R&D for better resolution.
- Background free search.

![Diagram of a bolometer](image)

- Maturing R&D and demonstrator efforts
  - Enriched Li\(^{100}\)MoO\(_4\) scintillating bolometers
  - Enriched Zn\(^{82}\)Se scintillating bolometers
  - Enriched \(^{130}\)TeO\(_2\) bolometer with Cherenkov readout
**CUPID: Li$_{2}^{100}$MoO$_{4}$**

- $^{100}$Mo is an excellent choice for scintillating bolometer 0vbb search
- Q-value: 3034 keV
- Natural abundance: 9.7%, enrichment to ~97% is demonstrated
- Seminal R&D from Lumineu project
- Possible to grow large, high purity, high optical quality LMO crystals and operate as scintillating bolometers
- Vendors capable of growing high-quality LMO identified in Russia, US, China and France

0.2 kg LMO scintillating bolometer

Main crystal, Ge wafer cryogenic light detector readout by NTDs

CUPID: Li$_2^{100}$MoO$_4$

- LMO alpha/beta discrimination using heat and light signals

Figs. Courtesy of Andrea Giuliani, CSNSM, Saclay
CUPID: Li$_{2}^{100}$MoO$_{4}$

- Energy resolution demonstrated to be 5~6 keV FWHM
- Current limits on internal radio purity are compatible with requirements

<table>
<thead>
<tr>
<th>Detector’s ID</th>
<th>Crystal’s mass (g)</th>
<th>FWHM (keV) at 2615 keV</th>
<th>LY$_{\gamma(\beta)}$ (keV/MeV)</th>
<th>$\alpha/\gamma(\beta)$ Separation above 2.5 MeV</th>
<th>Activity (µBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>enrLMO-1</td>
<td>186</td>
<td>5.8(6)</td>
<td>0.41</td>
<td>$9\sigma$</td>
<td>$\leq4$</td>
</tr>
<tr>
<td>enrLMO-2</td>
<td>204</td>
<td>5.7(6)</td>
<td>0.38</td>
<td>$9\sigma$</td>
<td>$\leq6$</td>
</tr>
<tr>
<td>enrLMO-3</td>
<td>213</td>
<td>5.5(5)</td>
<td>0.73</td>
<td>$14\sigma$</td>
<td>$\leq3$</td>
</tr>
<tr>
<td>enrLMO-4</td>
<td>207</td>
<td>5.7(6)</td>
<td>0.74</td>
<td>$14\sigma$</td>
<td>$\leq5$</td>
</tr>
</tbody>
</table>

$Q_{\beta\beta}^{100}$Mo at LSM (17 mK) and LNGS (12 mK), respectively. The performed analysis is similar to the one described in detail in [7].
CUPID: $\text{Li}_2^{100}\text{MoO}_4$

- BB-decay results from Lumineu

$T^{2\nu}_{1/2} = (6.92 \pm 0.06\text{(stat)} \pm 0.36\text{(syst.)}) \times 10^{18}\text{yr}$

$T^{0\nu2\beta}_{1/2} \geq 0.7 \times 10^{23}\text{ yr}$

CUPID-Mo Demonstrators

- **Phase 1**: Array of 20 enriched 0.2 kg Li$_2^{100}$MoO$_4$ crystals operated a Lumineu-style scintillating bolometers (LMO)
- Deployed in the Edelweiss cryogenic setup at Modane lab
- Goal is an extended run to confirm LMO operation and reach higher-sensitivity on internal radio purity
- Currently running at Modane Underground lab
- **Phase 2**: Additional 20 modules to be deployed in the CUPID-0 R&D cryostat at LNGS

Figs courtesy of CUPID-Mo collaboration
CUPID-Mo Demonstrators

- Expected sensitivity of the CUPID-Mo program
- Assumptions
  - $BI = 1 \text{ count/(keV/ton} \times \text{yr)}$ in 10 keV window around Q-value

<table>
<thead>
<tr>
<th>CUPID-0/Mo configuration</th>
<th>Exposure (kg×yr of $^{100}$Mo)</th>
<th>$\lim T_{1/2}^{0\nu\beta\beta}$ (yr)</th>
<th>$\lim \langle m_{\beta\beta} \rangle$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 20×0.5 crystal×yr</td>
<td>1.2</td>
<td>$1.3 \times 10^{24}$</td>
<td>0.33–0.56</td>
</tr>
<tr>
<td>(2) 20×1.5 crystal×yr</td>
<td>3.5</td>
<td>$4.0 \times 10^{24}$</td>
<td>0.19–0.32</td>
</tr>
<tr>
<td>(3) 40×3.0 crystal×yr</td>
<td>14</td>
<td>$1.5 \times 10^{25}$</td>
<td>0.10–0.17</td>
</tr>
</tbody>
</table>

At DNP see:
EN.00009:
Li2MoO4 for 0 decay search in CUPID - The Physics case and current status
B. Schmidt

FN.00009
Background projections for CUPID
G. Benato
CUPID: Zn$^{82}$Se

- $^{82}$Se embedded in ZnSe scintillating bolometers
- Q-value: 2998 keV
- CUPID-0 Se demonstrator now operating at LNGS

See L. M. Pattivina’s talk

- 95% enriched Zn$^{82}$Se bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
  - 10.5 kg of ZnSe
  - 5.17 kg of $^{82}$Se $\rightarrow$ $^{N}_{\beta\beta} = 3.8 \times 10^{25}$ $\beta\beta$ nuclei
- LD: Ge wafer operated as bolometer

- Copper structure (ElectroToughPitch)
- PTFE holders
- Light Reflector (VIKUITI 3M)
CUPID: Zn$^{82}$Se

- Light detector: Ge-wafer bolometer readout with NTDs

![Diagram of the CUPID-0 detector system]

Calibration scatter plot of a ZnSe crystal

See L. M. Pattivina’s talk

CUPID-0 is the first array of scintillating bolometers for the investigation of $^{82}$Se $\nu^{\beta\beta}$

This design has the main goal of

- Minimize mass of passive materials

$\nu^{\beta\beta}$ Q-value 2998 keV

- 95% enriched $^{82}$Se bolometers

- 26 bolometers (24 enr + 2 nat) arranged in 5 towers

- 10.5 kg of ZnSe

- $^{82}$Se $\nu^{\beta\beta}$ nuclei: $3.8 \times 10^{25}$

- LD: Ge wafer operated as bolometer

- Simplest modular detector

- Copper structure (ElectroToughPitch)

- PTFE holders

- Light Reflector (VIKUITI 3M)
Background data selection

UEML Simultaneous fit over the datasets

Slide from L. M. Pattivina’s talk

Exposure: $5.46 \text{ kg} \cdot \text{y of ZnSe}$

Energy resolution in ROI: $23.0 \pm 0.6 \text{ keV}$

Total signal efficiency: $75 \pm 2\%$

$m_{\beta\beta} < (290-596)^1 \text{ meV}$

$T_{1/2}^{(82\text{Se} \rightarrow 82\text{Kr})} > 4.0 \cdot 10^{24} \text{ yr @ 90C.L.}$

NEMO3 measurement $3.6 \cdot 10^{23} \text{ yr @ 90C.L.}$

CUPID: TeO2 prospects

- As proposed in EPJC65 (2010) 359 exploit Cherenkov emission to tag beta/gamma events vs alpha events

- Challenge: very low light emission (~100 eV) vs a few keV of light in scintillating bolometers

Expected (theory) Cherenkov Yield

- Ge cryogenic light detector
  
  EPJC 75 12 (2015)

At DNP see DM.00009:
Measurements of Light Emissions in TeO2 Crystals
(R. Huang Oct 25 11.00 am)

• EPJC 65 (2010) 359
CUPID: TeO2 prospects

• R&D to discriminate electron/alpha events based on Cherenkov light emission in TeO2 is yielding positive results

• Low threshold bolometric light detectors are steadily improving, exploiting Neganov-Luke amplification


• Light detector thermometry can be done with standard NTD

• Other light detector readout schemes TES and KIDs are being investigated

Fig. Courtesy of Andrea Giuliani, CSNSM, Saclay
CUPID: TeO2 prospects

- R&D to discriminate electron/alpha events based on Cherenkov light emission in TeO2 is yielding positive results

- Low threshold bolometric light detectors are steadily improving exploiting Neganov-Luke amplification

- 99.9% alpha rejection with >95% signal acceptance in CUORE-sized crystal
R&D on 130Te enrichment

- Test run at LNGS with 2x 435g enriched 130TeO2 crystals

<table>
<thead>
<tr>
<th>Isotope</th>
<th>ICP-MS [%]</th>
<th>Certification [%]</th>
<th>Natural [%]</th>
</tr>
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<tbody>
<tr>
<td>130Te</td>
<td>92.26</td>
<td>92.13</td>
<td>34.08</td>
</tr>
<tr>
<td>128Te</td>
<td>7.71</td>
<td>7.28</td>
<td>31.74</td>
</tr>
<tr>
<td>126Te</td>
<td>0.015</td>
<td>0.02</td>
<td>18.84</td>
</tr>
<tr>
<td>125Te</td>
<td>0.006</td>
<td>0.01</td>
<td>7.07</td>
</tr>
<tr>
<td>124Te</td>
<td>0.0005</td>
<td>≤ 0.005</td>
<td>4.74</td>
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bolometric performance

Det 1

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<th>Energy res. (FWHM @2615 keV)</th>
<th>Det 2</th>
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<tr>
<td>6.5 keV</td>
<td>4.3 keV</td>
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alpha rejection for 95% signal acceptance

98.21% 99.99%
R&D on 130Te enrichment

• Ongoing R&D item to purify crystal materials 130Te (zone refining)

• Larger exposure demonstrator under development


<table>
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<tr>
<th>Chain Nuclide</th>
<th>Det 1 uBq/kg</th>
<th>Det 2 uBq/kg</th>
<th>CUORE uBq/kg</th>
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<tr>
<td>232Th</td>
<td>&lt;4.3</td>
<td>&lt;4.8</td>
<td>&lt;0.8</td>
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<tr>
<td>238U</td>
<td>8 +/- 3</td>
<td>15 +/- 4</td>
<td>&lt;0.6</td>
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Bolometer readout based on NTD thermistors have been demonstrated to meet the technical requirements for alpha discrimination for CUPID.

There is active R&D to explore alternative temperature readout schemes.

CUPID-US group exploring Transition edge sensor (TES) readout.

CALDER project in Europe exploring kinetic inductance detectors (KIDS).

Advanced light detector technologies benefit both the 100Mo and 130Te strategies.
### TES readout for CUPID

- Demonstration with tungsten TES (developed in CRESST)
- 3.7σ separation of α events from β/γ with 98% signal acceptance
- W-TES are difficult to produce reproducibly

### Superconducting bilayers

- Ongoing R&D activity to use TES sensors fabricated from Ir/Au, Ir/Pt bilayers
- Bilayers with low Tc demonstrated

At DNP see

DM.00008:
Development of cryogenic optical-photon detectors with Ir/Pt-based transition edge sensors for CUPID
V. Singh (Oct 25 8.45 am)

EN.00008:
Application of Cryogenic TES based Light Detectors for CUPID
B. Welliver (Oct 25 8.45pm)
• CUPID: CUore Upgrade with Particle ID
• Fully probe the inverted hierarchy of neutrino masses
• Baseline target isotope is 100Mo embedded in LiMoO4 scintillating bolometers
• Viable alternative is 130Te embedded in TeO2 instrumented with advanced cryogenic light detectors

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Conclusions

- CUORE (750 kg TeO2 array) shows it is possible to operate a large array of macro bolometers at ultra-low cryogenic temperatures.

- CUORE will continue to push sensitivity to 0vbb decay of 130Te and measure intrinsic background levels in the cryogenic system.

- There is active R&D program in the US and Europe to realize a next generation experiment with the background, resolution and target mass required to probe the inverted hierarchy.

- Small (~20 detector) scintillating bolometer arrays have made tremendous progress (CUPID-0 Se, Lumineu).

- Lithium molybdate scintillating bolometers enriched in 100Mo is the baseline choice for CUPID:
  - excellent alpha suppression
  - excellent energy resolution
  - high Q-value (above most environmental beta/gamma background)
  - good radio purity with improved limits expected from CUPID-Mo demonstrator

- Emergence of low noise cryogenic light detectors make enriched 130TeO2 bolometers a viable option for CUPID although lower Q-value requires additional care in materials selection for some cryogenic components.
A CUPID interest group meeting is planned aimed at forming the CUPID collaboration and developing the conceptual design report

- When: November 19 and 20 2018
- Where: Gran Sasso Laboratory
- Contacts: cupid_kickoff@mit.edu
- More information: http://cupid.mit.edu/

Open to any one interested in collaborating
Acknowledgements

CUORE Funding Support

CUORE

Massachusetts Institute of Technology

INFN

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University of California

South Carolina

UCLA

Berkeley Lab

Virginia Tech

Invent the Future

Yale

CNEN

University of CASSINO e DEL Lazio

DEGLI STUDI

DI MILANO

BICOCCA

Universita' di Firenze

INFN

Lawrence Livermore National Laboratory
Acknowledgements

CUPID-Mo
CUORE Upgrade with Particle Identification in Molybdenum
Overview of experimental setup

- Y beam
- Main Support Plate
- Cryostat
- $\text{H}_3\text{BO}_3$ panels
- Polyethylene
- Screw jacks
- Movable platform
- Minus-K isolators
- Support columns
- External lead shield (~70 t)
- Concrete walls
- Seismic isolators
The CUORE cryostat

- Cryogen-free cryostat
- Fast Cooling System ($^4$He gas) down to ~50K
- 5 pulse tubes down to ~4K
- Dilution refrigerator to operating temperature ~10 mK
- Nominal cooling power: 3 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO$_2$)