CUORE Results and the CUPID Project

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Outline

• Introduction to cryogenic bolometers

• The CUORE experiment
  ▶ Detector Design
  ▶ Cryogenic infrastructure
  ▶ CUORE Results

• The CUPID Project
A. Campani, *The Bayesian software for the 0νββ CUORE analysis* (Poster #101 Session 1)

G. Fantini, *Latest results from the CUORE experiment on ββ decay of 130Te to the first 0+ excited state of 130Xe* (Poster #295 Session 2)

V. Singh, *Precise measurement of 2νββ decay half-life of 100Mo using enriched Li2100MoO4 scintillating crystals* (Poster #525 Session 2)

I. Colantoni, *A dual-readout cryogenic detector for double-beta decay: the CUPID-0 experiment* (Poster #111 Session 3)

V. Dompè, *Understanding the contributions to the CUORE background* (Poster #146 Session 3)

T. Dixon, *CUPID-Mo, first sensitivity estimates for 2νββ(0νββ) decay of 100Mo to excited states* (Poster #382 Session 4)

B. Welliver, *Implementation of an Optimal Trigger in CUPID-Mo to allow for low energy searches* (Poster #448 Session 4)

V. Singh, *Development of transition-edge sensor based large area photon detectors for CUPID* (Poster #97 Session 2)

P. Loaiza, *Background model of the CUPID-Mo 0νββ experiment* (Poster #418 Session 2)

R. Huang, *Characterization of 180 nm CMOS technology at 100 mK for rare event searches* (Poster #98 Session 3)

B. Schmidt, *New limit from the search for 0νββ of 100Mo with the CUPID-Mo experiment* (Poster #419 Session 3)

M. Zarysky, *Calibration of Li2100MoO4 bolometers with 56Co sources for searches of 0νββ decay of 100Mo* (Poster #374 Session 4)

D. Poda, *The CUPID-Mo double beta decay bolometric experiment and performance* (Poster #404 Session 4)
Macro Bolometer Technique

- The absorbed energy causes an increase in absorber temperature
- Use temperature change to measure energy absorbed
- For dielectric crystal absorbers, heat capacity $\sim T^3$
- Typically operated at $\sim 10\text{mK}$
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved

CUORE uses this technique
Scintillating Macro Bolometer

- If the absorber also scintillates measuring both the thermal and light signal enables particle discrimination.

  ![Diagram](image)

- Light detection at mK temperatures is achieved with secondary bolometer (such as Ge wafer).

  ![CUPID will use this technique]
CUORE: Cryogenic Underground Observatory for Rare Events

- Hosted at Gran Sasso Underground Lab
- Close-packed array of 988 $^{nat}$TeO$_2$ bolometers (Total active mass: 742 kg)
- Operated at $T \sim 11$ mK
- Primary physics goal: 0νββ decay of $^{130}$Te
  - Isotopic abundance 34% $\Rightarrow$ 206 kg
  - Q-value: 2527.5 keV
- CUORE design goals:
  - Energy resolution: 5 keV FWHM near $Q_{\beta\beta}$
  - Background: 0.01 c/keV/kg/y near $Q_{\beta\beta}$
  - 0νββ sensitivity for 5 years of livetime:
    \[
    T_{1/2}^{0\nu} = 9 \times 10^{25} \text{ yr}
    \]
milli-Kelvin facility for tonne-scale detectors

- Powerful $^3$He-$^4$He dilution refrigerator cooling power: 5 µW at 10 mK
- Precooled by 4 pulse tubes
- Cryogenic vessels and shielding:
  - 13 tonnes < 4 K
  - 5 tonnes < 50 mK
  - 1500 kg @ 10 mK (detectors + materials)
- Experimental volume ~1 m$^3$ a.k.a “Coldest cubic meter in the known universe”
-Cooldown time ~ 1 month
-External Shielding:
  - 18 cm polyethylene + 2 cm borated material
  - 30 cm lead
• Data taking started in Spring 2017
• After initial data taking phase, significant effort devoted to understanding the system and optimizing data taking conditions
• Since March 2019 data taking is continuing smoothly with > 90% uptime
• CUORE “data set”: ~1 month of background data taking with a few days of calibration at the start and end

Stable conditions allowed continued data taking with minimal onsite activity during recent lockdowns

We evaluate the bias induced by each nuisance parameter in the isotopic abundance. We implement all systematics as adjustments to the energy scale, energy resolution, analysis, and containment model. A median 90% CI exclusion sensitivity of 1 with the standard signal-plus-background model and background-only model. We fit each pseudo-experiment in the physical range (rates non-negative), uniform prior on $\Gamma_{0v}$, Likelihood model: flat continuum (BI), and posited decay component fixed to 0.

The best fit-curve with the 90% CI limit (dashed blue).

FIG. 4. ROI spectrum with the best-fit curve (solid red) and 90% CI is shown in blue.

- No evidence for $0\nu\beta\beta$ decay

$T^{0\nu}_{1/2} > 3.2 \times 10^{25}$ yr (90% C.I.)

- Interpretation in context of light Majorana neutrino exchange

$m_{\beta\beta} < 75 - 350$ meV

CUORE: $0\nu\beta\beta$ Search

Total exposure $\text{TeO}_2$: 372.5 kg \cdot yr

Bayesian Analysis (BAT)

Likelihood model: flat continuum (BI), posited peak for $0\nu\beta\beta$ (rate), peak for $^{60}\text{Co}$ (rate + position)

Unbinned fit on physical range (rates non-negative), uniform prior on $\Gamma_{0v}$

Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

Detector Performance Parameters

Background Index

$(1.38 \pm 0.07) \times 10^{-2}$ cnts/(keV \cdot kg \cdot yr)

Characteristic FWHM $\Delta E$ at $Q_{\beta\beta}$

$7.0 \pm 0.3$ keV

CUORE: 0νββ Search

- Total exposure TeO₂: 372.5 kg · yr
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (BI), posited peak for 0νββ (rate), peak for ⁶⁰Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on Γ₀ν
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

- No evidence for 0νββ decay
  $$T^{0ν}_{1/2} > 3.2 \times 10^{25} \text{ yr (90\% C.I.)}$$

- Interpretation in context of light Majorana neutrino exchange
  $$m_{ββ} < 75 - 350 \text{ meV}$$

See A. Campani, Poster #101 Session 1


Detector Performance Parameters

Data taking continues smoothly — next unblinding 1 tonne · yr

Stay tuned!
CUORE: $2\nu\beta\beta$ decay measurement

- Reconstruct CUORE continuum background
- GEANT4 simulation + measured detector response function to produce expected spectra
- 62 sources considered, Bayesian fit with flat priors (except for muons)
- Exploit coincidences & detector self-shielding to constrain location of sources

$^{130}\text{Te} 2\nu\beta\beta - M1$

Systematic Uncertainties

- Data selection:
  - geometric splitting, time splitting, fit range
- Choice of $2\nu\beta\beta$ spectrum (single state vs. higher state dominance*)
- Unconstrained fallout products ($^{90}\text{Sr}$)

\[
T^{2\nu}_{1/2} = [7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.17}_{-0.15}(\text{syst.})] \times 10^{20} \text{ yr}
\]
CUORE: Search for $\beta\beta$ decay to excited states

- $^{130}\text{Te}$ may also $\beta\beta$ decay to excited states of $^{130}\text{Xe}$ (this decay has never been observed)
- Cascade of de-excitation $\gamma$s in coincidence with $\beta$s produces multi-site signatures

\[ 0^+ \rightarrow 0^+ \]
\[ ^{130}_{52}\text{Te} \rightarrow ^{130}_{54}\text{Xe} \]

\[ ^{130}_{52}\text{Te} \rightarrow ^{130}_{54}\text{Xe} \]

\[ 0^+ \rightarrow 1^+ \rightarrow 1^+ \]
\[ 1^+ \rightarrow 1^+ \rightarrow 1^+ \]
\[ 2^+ \rightarrow 1^+ \rightarrow 1^+ \]
\[ 1^+ \rightarrow 1^+ \rightarrow 1^+ \]
\[ E_1 = 536\text{ keV} \]
\[ E_2 = 1257\text{ keV} \]

$T_{1/2}^{0\nu} > 5.4 \times 10^{-24}\text{ yr (90\% C.I.)}$
$T_{1/2}^{2\nu} > 1.1 \times 10^{-24}\text{ yr (90\% C.I.)}$
CUPID: CUORE Upgrade with Particle ID

- Array of 1500 \( \text{Li}_2^{100}\text{MoO}_4 \) **scintillating** bolometers
- Enriched to >95% in \(^{100}\text{Mo}\) (250kg of \(^{100}\text{Mo}\))
- \(^{100}\text{Mo}\) Q-value: 3034 keV β/γ background significantly reduced
- Exploit Particle ID using scintillation bolometer technique
  - Technique robustly demonstrated by CUPID-0 and CUPID-Mo
- Reuse CUORE cryogenic infrastructure at LNGS
- Add external muon veto

**CUPID baseline goals are within the reach of existing detector technology and infrastructure**

No further R&D is needed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CUPID Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>( \text{Li}_2^{100}\text{MoO}_4 )</td>
</tr>
<tr>
<td>Detector mass (kg)</td>
<td>472</td>
</tr>
<tr>
<td>(^{100}\text{Mo}) mass (kg)</td>
<td>253</td>
</tr>
<tr>
<td>Energy resolution FWHM (keV)</td>
<td>5</td>
</tr>
<tr>
<td>Background index (counts/(keV-kg-yr))</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>Containment efficiency</td>
<td>79%</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Livetime (years)</td>
<td>10</td>
</tr>
<tr>
<td>Half-life exclusion sensitivity (90% C.L.)</td>
<td>(1.5 \times 10^{27}) y</td>
</tr>
<tr>
<td>Half-life discovery sensitivity (3σ)</td>
<td>(1.1 \times 10^{27}) y</td>
</tr>
<tr>
<td>(m_{ββ}) exclusion sensitivity (90% C.L.)</td>
<td>10–17 meV</td>
</tr>
<tr>
<td>(m_{ββ}) discovery sensitivity (3σ)</td>
<td>12–20 meV</td>
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https://arxiv.org/abs/1907.09376

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In the rest of this section, we describe the results achieved in CUPID-Mo and its preparation measures.

As in CUORE, a NTD Ge thermistor will be glued to the crystal on a flat surface, in order to provide an absolute temperature measurement.

For triggering purposes, we deploy an AME898S COTS analog preamplifier, with a rise time of 250 ns and a gain of 200. The thermistor is operated at a temperature of 20 mK, which is achieved with a copper radiation shield. The temperature is monitored with a Lake Shore Cryotronics 331 temperature controller, which provides a resolution of 0.001 K. The temperature stability is better than 0.01 K.

Table 3: Summary of CUPID-0 parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CUPID Baseline</th>
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</tbody>
</table>
From CUORE to CUPID

- Data driven background model shows existing technology and infrastructure compatible with CUPID baseline goals —> no further R&D is needed

<table>
<thead>
<tr>
<th>CUORE background model</th>
<th>CUPID-0 background model</th>
<th>CUPID-Mo Li$_2$MoO$_4$ performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterize $\beta/\gamma$ background from cryogenic system and detector holders in the 3034 keV ROI</td>
<td>Alpha-rejection capable array Confirms the $\beta/\gamma$ background from detector holders in the 3034 keV ROI</td>
<td>Array of large of highly enriched Li$_2^{100}$MoO$_4$</td>
</tr>
</tbody>
</table>
| Model is fit to CUORE data | Model is fit to CUPID-0 data | Data confirms:  
  - $\alpha$ tagging performance  
  - Radiopurity of crystals  
  - Energy resolution |
From CUORE to CUPID: CUORE

- $\beta/\gamma$ background in TeO$_2$ in the $^{100}$Mo region of interest (3034 keV)

- $\gamma$ interaction probability in Li$_2$MoO$_4$ is $\sim 3$x smaller than in TeO$_2$ in this ROI

- Muon veto will be added for CUPID
From CUORE to CUPID: CUPID-0

- 26 ZnSe scintillating bolometers (24 95% enriched in $^{82}$Se + 2 natural)
- Ge wafers cryogenic light detectors
- $^{82}$Se 0νββ decay Q-Value: 2998 keV
- Hosted in the same CUORE-0 dilution refrigerator (Hall A)

CUPID-0 Background Model

<table>
<thead>
<tr>
<th>Source</th>
<th>ROI Background Index [10^{-4} counts/(keV·kg·y)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\nu\beta\beta$ $^{82}$Se</td>
<td>$6.0 \pm 0.3$</td>
</tr>
<tr>
<td>ZnSe Crystals</td>
<td>$11.7 \pm 0.6^{+1.6}_{-2.2}$</td>
</tr>
<tr>
<td>Detector Material</td>
<td>$2.1 \pm 0.3^{+0.8}_{-1.0}$</td>
</tr>
<tr>
<td>Cryostat &amp; Shields</td>
<td>$5.9 \pm 1.3^{+1.2}_{-0.9}$</td>
</tr>
<tr>
<td>Muons</td>
<td>$15.3 \pm 1.3 \pm 2.5$</td>
</tr>
<tr>
<td>Total</td>
<td>$41 \pm 2^{+4}_{-5}$</td>
</tr>
</tbody>
</table>

- $\text{Li}_2\text{MoO}_4$ radiopurity is 10x better than ZnSe
- CUPID detector holder will adopt reduced mass design
- CUORE/CUPID cryostat is cleaner than CUPID-0 cryostat
- Muon tagging with external veto

See I. Colantoni
Poster #111 Session 3


From CUORE to CUPID: CUPID-Mo

- Array of 20 Li$_2^{100}$MoO$_4$ detectors ~210 g each
- Enriched to 97% in $^{100}$Mo (2.26 kg $^{100}$Mo)
- Hosted in Modane underground lab 4800 m.w.e. overburden in EDELWEISS cryogenic system (20 mK)
- Ge wafer light detectors

- Physics data taking March 2019 - June 2020
- All Li$_2^{100}$MoO$_4$ bolometers and 19 light detectors operational
- Energy resolution @ $Q_\beta$ (3034 keV): ~8 keV FWHM (operating temp = 20 mK)
- Good uniformity and stable performance (suitable for larger arrays in CUPID)

Alpha Rejection

- Light yield for $\beta/\gamma$ events is 5x greater than for $\alpha$ particles
  - > 99.9% $\alpha$ separation
  - > 99.9% $\beta/\gamma$ acceptance

Meets the requirement for CUPID

Excellent Radiopurity

$^{210}$Po: 100µBq/kg

$^{238}$U/$^{232}$Th: (0.3 - 1)µBq/kg

Meets the requirement for CUPID

See D. Poda
Poster #404 Session 4
CUPID-Mo: Results

- CUPID-Mo has a vibrant physics program
- New world-leading limit on $0\nu\beta\beta$ decay of $^{100}$Mo

**CUPID-Mo Preliminary**

$T_{1/2}^{0\nu} > 1.4 \times 10^{24}$ yr (90% c.i)  

(stat. + syst.)

$m_{\beta\beta} < 310 - 540$ meV

See B. Schmidt  
Poster #419 Session 3

- Background index is very low despite conditions not optimized for $0\nu\beta\beta$

**CUPID-Mo Preliminary**

$\text{BI} : (4 \pm 2) \times 10^{-3} \text{ cnts/keV} \cdot \text{ kg} \cdot \text{ yr}$

See P. Loaiza  
Poster #418 Session 2

- High precision measurement of $2\nu\beta\beta$ decay of $^{100}$Mo using CUPID-Mo technology

$T_{1/2}^{2\nu} = [7.12^{+0.18}_{-0.14}(\text{stat.}) \pm 0.10(\text{syst.})] \times 10^{18}$ yr

arXiv: 1912.07272

See V. Singh  
Poster #525 Session 2

See also
T. Dixon  
Poster #382 Session 4
B. Welliver  
Poster #448 Session 4
M. Zarysky  
Poster #374 Session 4
Summary

- The era of tonne-scale cryogenic bolometers has started
- The CUORE physics program is ongoing and will continue in parallel with preparations for CUPID
- CUPID baseline sensitivity: $T_{1/2}^{0\nu} : 10^{27} \text{yr}$, $m_{\beta\beta} : 10 - 20 \text{ meV}$
- CUPID can achieve this with existing detector technology and infrastructure
  - ☑ CUPID-0 and CUPID-Mo robustly demonstrate the alpha rejection technique
  - ☑ Residual $\beta/\gamma$ background in $^{100}\text{Mo}$ ROI meets the requirements
  - ☑ Radio-purity and bolometric performance of large, highly enriched $\text{Li}_2^{100}\text{MoO}_4$ crystals demonstrated in CUPID-Mo
- The future is bright for next-generation cryogenic bolometers
Acknowledgements

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CUORE Event Selection

- Base Cuts: basic data cleaning, remove noisy periods, reconstruction etc
- Anti-coincidence Cut
- Pulse shape analysis (PSA)

Selection Efficiencies

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Efficiency (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction</td>
<td>(95.80 ± 0.003) %</td>
</tr>
<tr>
<td>Anti-coincidence</td>
<td>(98.7 ± 0.1) %</td>
</tr>
<tr>
<td>Pulse shape analysis</td>
<td>(92.6 ± 0.1) %</td>
</tr>
<tr>
<td>All w/o containment</td>
<td>(87.5 ± 0.2) %</td>
</tr>
<tr>
<td>0νββ containment</td>
<td>(88.35 ± 0.09) %</td>
</tr>
<tr>
<td>Total</td>
<td>(77.3 ± 0.2) %</td>
</tr>
</tbody>
</table>
Detector calibration systems

Internal system

External system

Th-232 strings deployed internally

Th-232/60-Co strings deployed externally
CUORE Interpretation NME Models

NMEs Used


\[ m_{\beta\beta} < 75 - 350 \text{ meV} \]
• Effective energy resolution at $Q_{\beta\beta}$: 7.0 +/- 0.3 keV (exposure weighted harmonic mean)
• Energy scale bias: <0.7 keV

CUORE Detector Performance

- Detector response function determined for 2615 keV line in calibration data
- Fit to prominent lines in the background data to determine energy bias and resolution vs. energy