CUORE: Cryogenic Underground Observatory for Rare Events

Lindley Winslow
Massachusetts Institute of Technology
CUORE Collaboration
This is why we are all here:

Lepton Number Violation!
Light Majorana Neutrino Exchange (LMNE)
<table>
<thead>
<tr>
<th>Isotope</th>
<th>Endpoint</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.271 MeV</td>
<td>0.187%</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.367 MeV</td>
<td>5.6%</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.350 MeV</td>
<td>2.8%</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.034 MeV</td>
<td>9.6%</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.995 MeV</td>
<td>9.2%</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.802 MeV</td>
<td>7.5%</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.533 MeV</td>
<td>34.5%</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2.479 MeV</td>
<td>8.9%</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.039 MeV</td>
<td>7.8%</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>0.868 MeV</td>
<td>31.7%</td>
</tr>
</tbody>
</table>

See ATOMIC DATA AND NUCLEAR DATA TABLES 61, 43-90 (1995) for all 69+19!
How do we measure this signal?
Experimental Considerations:

• Energy Resolution
• Scalability
• Active Background Rejection
• Flexible Isotope Choice
How Bolometers work:

Heat Measurement: Absorber + Thermometer
How Bolometers work:

Simple Model

\[ T \quad C \quad R \quad T_0 \]

\[ \Delta T = \frac{E}{C} \]

\[ \tau = RC \]

From: J. Ouellet, Thesis 2015
How Bolometers work:

Energy Deposition causes rise in temperature inversely proportional to the heat capacity.

\[ \Delta T = \frac{E}{C} \]

\[ \tau = RC \]

From: J. Ouellet, Thesis 2015
How Bolometers work:

Simple Model

The decay time of the signal is proportional to the thermal resistance.

From: J. Ouellet, Thesis 2015
How Bolometers work:

Heat capacity follows Debye Law

\[ C(T) \propto k_B \left( \frac{T}{\Theta_D} \right)^3 \]

At 10 mK, this corresponds to a 0.1 mK rise in temperature.
How Bolometers work:

Energy Resolution

\[ \sqrt{\langle \Delta E^2 \rangle} \propto k_B T \left( \frac{T}{\Theta_D} \right)^{3/2} \]

Theoretically, this could be as low as 10 eV.

Dark matter, coherent neutrino scattering, and light detectors for DBD are driving R&D here.

From: J. Ouellet, Thesis 2015
How Bolometers work:

For CUORE-style bolometers, the current goal is 5 keV at 2.5 MeV.
More Bolometer Talks:

Luca Pattavina - New Results on Double Beta Decay with CUPID-O

Yong-Hamb Kim - The AMoRE project

T. O’Donnell (WJB.00001) : Status of the CUORE and prospects for CUPID

A. Drobitshev (DM.00007): Ultralow-Radon Environment for the Installation of the CUORE $0\nu\beta\beta$ Decay Detector

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

R. Huang (DM.00009): Measurements of Light Emissions in TeO2 Crystals

D. Speller (EN.00007): Neutrinoless double-beta decay and other rare event searches with CUORE

B. Welliver (EN.00008): Application of Cryogenic TES based Light Detectors for CUPID

B. Schmidt (EN.00009): Li2MoO4 for $0\nu\beta\beta$ decay search in CUPID - The Physics case and current status

G. Benato (FN.00009): Background projections for CUPID

A. Leder (MN.00004): Measurement of Quenched Axial Vector Coupling Constant in In-115 Beta Decay and its Impact on Future $0\nu\beta\beta$ Searches
The highly forbidden $^{115}\text{In}$ decay prevents this crystal from being viable for CUPID, but the precision spectrum measurement can inform the nuclear matrix calculations (quenching of $g_A$).
Experimental Considerations:

• Energy Resolution
• Scalability
• Active Background Rejection
• Flexible Isotope Choice
CUORE:
Cryogenic Underground Observatory for Rare Events

The Detector

- 19 Towers, 988 TeO$_2$ crystals operated as bolometers.
- It is the “Coldest cubic meter in the known universe”, arXiv:1410.1560
The History of Bolometric Detectors

- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
- 2025

$t_{1/2}^{0\nu} (90\% \text{ C. L.}) \text{[yr]}$

Running period

10^19
10^20
10^21
10^22
10^23
10^24
10^25
10^26


MiDBD
Cuoricino
CUORE-0
CUORE

4 crystal array
334 g
73 g
34 g
21 g
6 g
CUORE Projected Background Model

Goal:
\[ 1 \times 10^{-2} \text{ counts/keV/kg/year} \]

CUORE Projected Sensitivity

CUORE:
Cryogenic Underground Observatory for Rare Events
The First Data Release:

Dataset 1: May - June
Detector Optimization Campaign

Dataset 2: August - September

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td></td>
</tr>
</tbody>
</table>

Blue = Physics
Red = Calibration
Pink = Setup/Configuration
Green = Test

All physics runs bracketed by a calibration run.
The First Data Release:

Dataset 1: May - June
Detector Optimization Campaign

Dataset 2: August - September

Acquired statistics used for this search: (Dataset 1 + Dataset 2):

- nat\text{TeO}_2 exposure: 86.3 kg yr (37.6 kg yr + 48.7 kg yr)
- $^{130}\text{Te}$ exposure: 24.0 kg yr
Calibration

- Summed energy spectrum of all the CUORE detectors-datasets
- Calibration data used for:
  - energy scale calibration
  - thermal gain stabilisation
  - detector response (line shape) study

239 keV - $^{212}\text{Pb}$
338, 911, 969 keV - $^{228}\text{Ac}$
583, 2615 keV - $^{208}\text{Tl}$
Detector Response: Line Shape

Fit components:

(a) triple gaussian for the photopeak
(b) step-wise smeared multi-compton background
(c) combination of gaussian X-rays escape lines
(d) linear background
(e) single gaussian line for the coincident absorption of 2615-keV and 583-keV followed by a single escape process

The fit is done tower-by-tower. The plot shows the sum of the result.
A total of 1811 (92% of live channels) channels-dataset couples were used in this analysis; discarded channels had poor line or pulse shapes, or the energy couldn’t be reconstructed accurately.

### Energy Resolution

**Calibration resolution at 2615 keV**

- @ 2615 keV
- exposure-weighted harmonic mean
- 8.0 keV FWHM
The gamma lines in the background spectrum have been fitted with the complete detector response function (line shape) to estimate the energy scale bias. $(0 \pm 0.5) \text{ keV}$
It is also used to scale the energy resolution down to the region of interest.

Dataset 1 \((8.3 \pm 0.4)\) keV
Dataset 2 \((7.4 \pm 0.7)\) keV
Analysis Procedure

- Acquisition of continuous waveforms
- Triggering
- Data preprocessing: estimation of raw parameters
- Pulse filtering with Optimum Filter
- Thermal Gain Stabilization (TGS): calibration and heater-based
- Energy calibration and best energy estimator selection
- Particle event selection - Pulse Shape Analysis
- Coincidence analysis w/ detector response synchronization and software threshold @ 150 keV (to prevent any spectral shape distortion due to threshold effects in the ROI)
- Energy spectrum

Very similar to what was developed and used for CUORE-0 (Phys. Rev. C 93, 045503 (2016))
## Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Dataset 1</th>
<th>Dataset 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger</strong></td>
<td>$(99.766 \pm 0.003) %$</td>
<td>$(99.735 \pm 0.004) %$</td>
</tr>
<tr>
<td><strong>Energy reconstruction</strong></td>
<td>$(99.168 \pm 0.006) %$</td>
<td>$(99.218 \pm 0.006) %$</td>
</tr>
<tr>
<td><strong>Base cuts (pile-up, global data quality)</strong></td>
<td>$(95.63 \pm 0.01) %$</td>
<td>$(96.69 \pm 0.01) %$</td>
</tr>
<tr>
<td><strong>Anti-coincidence</strong></td>
<td>$(99.4 \pm 0.5) %$</td>
<td>$(100.0 \pm 0.4) %$</td>
</tr>
<tr>
<td><strong>Pulse shape analysis</strong></td>
<td>$(91.1 \pm 3.6) %$</td>
<td>$(98.2 \pm 3.0) %$</td>
</tr>
<tr>
<td><strong>All cuts except containment</strong></td>
<td>$(85.7 \pm 3.4) %$</td>
<td>$(94.0 \pm 2.9) %$</td>
</tr>
<tr>
<td><strong>0νββ containment</strong></td>
<td>$(88.35 \pm 0.09) %$</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$(75.7 \pm 3.0) %$</td>
<td>$(83.0 \pm 2.6) %$</td>
</tr>
</tbody>
</table>

Event selection occurs after periods of low-quality data ($\sim 1\%$ of the total live time) are removed.
Blinding

- To blind our data we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa.

- The blinding algorithm produces an artificial peak around the NDBD Q-value hiding the real NDBD rate of $^{130}\text{Te}$.

This method of blinding the data preserves the integrity of the possible signal while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum.
155 Events in the ROI
**Fit in the ROI**

Simultaneous UEML (Unbinned Extended Maximum Likelihood) fit

Energy region 2465-2575 keV

- **The fit has 3 components:**

  1. Posited peak at the **Q-value of $^{130}$Te:**
     - energy scale defined relative to the $^{208}$Tl line in calibration data to account for residual mis-calibration between channels
     - signal normalization common to all detectors-datasets (1 free parameter)

  2. Floating peak to account for the $^{60}$Co **sum gamma line** (2505 keV):
     - energy scale defined relative to the $^{208}$Tl line in calibration data to account for residual mis-calibration between channels
     - rate common to all detectors-dataset, with a correction accounting for the time elapsed between the two datasets (1 free parameter)

  3. **Flat background**, attributed to multi scatter Compton events from $^{208}$Tl and surface alpha events:
     - common to all detectors in a single dataset, two independent parameters for the two datasets to account for differences in the background rejection efficiency (2 free parameters)

- **The peaks in each channel-dataset are fitted with its own line shape** (fixed from calibration data)
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Absolute uncertainty [$10^{-24}$ yr]</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>-</td>
<td>1.5%</td>
</tr>
<tr>
<td>Q-value location</td>
<td>-</td>
<td>0.2%</td>
</tr>
<tr>
<td>No subpeaks</td>
<td>0.002</td>
<td>2.4%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>2.4%</td>
</tr>
<tr>
<td>Linear fit</td>
<td>0.005</td>
<td>0.8%</td>
</tr>
</tbody>
</table>
ROI background index: \((1.49_{-0.17}^{+0.18}) \times 10^{-2} \text{ c/(keV} \cdot \text{kg} \cdot \text{yr)}\)

\((1.35_{-0.18}^{+0.20}) \times 10^{-2} \text{ c/(keV} \cdot \text{kg} \cdot \text{yr)}\)

Best fit for \(^{60}\text{Co mean}: (2506.4 \pm 1.2) \text{ keV}\)
The Result

Best fit decay rate: $(-1.0_{-0.3}^{+0.4} \text{ (stat.)} \pm 0.1 \text{ (syst.)}) \times 10^{-25} \text{ / yr}$
The Result

No evidence of signal
Profile likelihood integrated on the physical region 
($\Gamma^{0\nu} > 0$)

Decay rate limit (90% CL, including systematics): $0.51 \times 10^{-25} / \text{yr}$
Half-life limit (90% CL, including systematics): $1.3 \times 10^{25} \text{yr}$
Median expected sensitivity: $7.0 \times 10^{24} \text{yr}$
We combined the CUORE result with the existing $^{130}$Te:
$19.75 \text{ kg}\cdot\text{yr of Cuoricino and } 9.8 \text{ kg}\cdot\text{yr of CUORE-0}$

The combined 90% C.L. limit is $T_{0\nu} > 1.5 \times 10^{25} \text{ yr}$
In terms of the Majorana Mass:

NME:
JHEP02 (2013) 025
Phys. Rev. C 87, 064302 (2014)

Experiment:
130Te: $1.5 \times 10^{25}$ yr from this analysis PRL 120, 132501 (2018)
76Ge: $8.0 \times 10^{25}$ yr from PRL 120, 132503 (2018)
136Xe: $1.1 \times 10^{26}$ yr from Phys. Rev. Lett. 117, 082503 (2016)
100Mo: $1.1 \times 10^{24}$ yr from Phys. Rev. D 89, 111101 (2014)
82Se: $2.4 \times 10^{24}$ yr from Phys. Rev. Lett 120, 232502 (2018)
CUORE sensitivity: $9.0 \times 10^{25}$ yr

The limit corresponds to $m_{\beta\beta} < 140–400$ meV
Understanding the Background

- Backgrounds generally consistent with expectations
- $^{210}$Po excess appears to be from shallow contamination in copper around the detectors
  - Current estimated contribution to ROI at the level of $10^{-4}$ cnts/(keV kg yr)

$\gamma$ background is significantly reduced

Still working to understand this excess...

- Most $\alpha$ backgrounds consistent with CUORE-0

Counts / (keV kg yr)

Reconstructed Energy (keV)
Building the Model

- 86.3 kg·yr of TeO₂ from summer 2017
- Split data into inner and outer layers
- Split data into Multiplicity 1 (M1), Multiplicity 2 (M2), and Multiplicity 2 Sum (Σ2) spectra
  - Higher multiplicity spectra sensitive to backgrounds
Details of the Model

- Simulate the contaminations coming from different cryostat components using a detailed Geant4 MC simulation
- About 60 independent parameters representing various contaminations that could contribute to the CUORE background model
- Perform a large Bayesian fit to the data using a MCMC Gibbs sampler
- Flat priors on all parameters except muons which come from a cosmogenic analysis

<table>
<thead>
<tr>
<th>Volume</th>
<th>Type</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO₂</td>
<td>Bulk</td>
<td>$^{232}$Th, $^{238}$U, $^{210}$Bi, $^{108}$mAg</td>
</tr>
<tr>
<td></td>
<td>Surface (0.01 µm)</td>
<td>$^{210}$Pb, $^{228}$Ra-$^{208}$Pb, $^{238}$U-$^{230}$Th, $^{226}$Ra-$^{210}$Pb, $^{40}$K, $^{60}$Co, $^{125}$Sb, $^{199}$Pt</td>
</tr>
<tr>
<td>TeO₂</td>
<td>Surface (1 µm)</td>
<td>$^{210}$Pb, $^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>TeO₂</td>
<td>Surface (10 µm)</td>
<td>$^{210}$Pb, $^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>CuNOSV</td>
<td>Bulk</td>
<td>$^{232}$Th, $^{238}$U, $^{40}$K, $^{60}$Co, $^{54}$Mn</td>
</tr>
<tr>
<td>CuNOSV</td>
<td>Surface (0.01 µm)</td>
<td>$^{210}$Pb, $^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>CuNOSV</td>
<td>Surface (1 µm)</td>
<td>$^{210}$Pb, $^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>CuNOSV</td>
<td>Surface (10 µm)</td>
<td>$^{210}$Pb, $^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>Roman lead</td>
<td>Bulk</td>
<td>$^{232}$Th, $^{238}$U</td>
</tr>
<tr>
<td>Top lead</td>
<td>Bulk</td>
<td>$^{232}$Th, $^{238}$U, $^{210}$Bi</td>
</tr>
<tr>
<td>Ext. lead</td>
<td>Bulk</td>
<td>$^{210}$Bi</td>
</tr>
<tr>
<td>CuOFE</td>
<td>Bulk</td>
<td>$^{232}$Th, $^{238}$U, $^{60}$Co</td>
</tr>
<tr>
<td>External</td>
<td>-</td>
<td>Cosmic muons</td>
</tr>
</tbody>
</table>
Able to reconstruct the major features of the observed spectrum in CUORE

Fitting the Background
Fitting the Background

Multiplicity 1 - Inner Layer

Multiplicities 1 and 2

Many contaminations constrained by the higher multiplicity spectra

Multiplicity 1 spectra very sensitive to signal events
Measuring the $2\nu\beta\beta$ Half-life

In CUORE-0, $2\nu\beta\beta$ decay spectrum accounts for $\sim 20\%$ of the signal in the range 1 - 2 MeV.

In CUORE, $2\nu\beta\beta$ decay spectrum accounts for nearly all of the signal in the range 1 - 2 MeV.

In CUORE Preliminary

Exposure: 33.4 kg·yr


Exposure: 86.3 kg·yr

Multiplicity 1 -- Inner Layer
Measuring the $2\nu\beta\beta$ Half-Life

$\Gamma_{1/2}^{2\nu} = [8.7 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (syst.)}] \times 10^{-22} \text{ yr}^{-1}$

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

(For Reference)

CUORE-0 : $T_{1/2}^{2\nu} = [8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \times 10^{20} \text{ yr}$

NEMO-3 : $T_{1/2}^{2\nu} = [7.0 \pm 0.9 \text{ (stat.)} \pm 1.1 \text{ (syst.)}] \times 10^{20} \text{ yr}$

(CUORE Preliminary)

Exposure: 86.3 kg yr

Marginal p.d.f.

Counts/keV

Reconstructed Energy (keV)
Detector Optimization

- October - December 2017: Scan of detector performance vs temperatures
  - Selecting a new operating temperature of 11mK
- January - March 2018: Warmed the cryostat to 100K to upgrade a set of gate valves
- Returned to base temperature in early March
- March 2018, performed Pulse Tube Phase Scan

All Channels AP Weighted Total Noise Median

PT PHASE CAN CHANGE NOISE BY AN ORDER OF MAGNITUDE!
Current Status

- April calibration data characterized by energy resolution of 7.6 keV FWHM with 93% of channels passing cuts (using same processing procedures)
- Still working to achieve the energy resolution goal of 5 keV FWHM
- Back to stable physics data taking in May 2018
- Many potential physics searches:
  - Symmetry violation searches: $0\nu$, Majoron emission, CPTV
  - Low energy searches: Dark Matter, axions
  - Nuclear physics measurements: other $\beta\beta$ decays and decays to excited states, $\beta^+$/E.C. decays
Future Outlook

- With 7 weeks of data, set the most stringent limit on the $0\nu\beta\beta$ half-life of $^{130}\text{Te}$ to date
- Made the most precise measurement of the $2\nu\beta\beta$ half-life of $^{130}\text{Te}$ to date
- We have restarted physics data taking
- CUORE will continue to be one of the most sensitive searches for $0\nu\beta\beta$ over the coming years
  - Ultimate 90% sensitivity to $0\nu\beta\beta$ half-life of $T_{1/2} = 9 \times 10^{25}$ yr