Status of the CUORE program in neutrinoless double beta decay

Tom Banks, on behalf of the CUORE Collaboration (UC Berkeley, LBNL, LNGS)

EPS HEP 2013 conference
Stockholm, Sweden
July 20, 2013
1. confirm neutrinos are Majorana particles (i.e., $\nu = \bar{\nu}$);

2. set constraints on the effective Majorana mass $\langle m_{\beta\beta} \rangle$, providing information about the absolute $\nu$ mass scale;

3. provide information about the mass hierarchy.

If $0\nu\beta\beta$ decay is observed, it would
Detecting $0\nu\beta\beta$ decay

**General approach:** Detect the two final-state electrons

**Signature:** Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for $\beta\beta$ decay in the isotope under study
Primary objective is to search for $0\nu\beta\beta$ decay in $^{130}\text{Te}$
CUORE program

Cuoricino
2003–2008
11 kg $^{130}$Te

CUORE-O
2013–2015
11 kg $^{130}$Te

CUORE
2015–2020
206 kg $^{130}$Te

COMPLETE
Cryogenic bolometers

Ultracold TeO$_2$ crystals function as highly sensitive calorimeters.
At $T=10$ mK, particle interactions inside TeO$_2$ crystal produce a measurable rise in its temperature.

Amplitude of temperature pulse is proportional to deposited energy.
The energy spectrum of detected pulses is compiled...

...and the signature of $0\nu\beta\beta$ in $^{130}\text{Te}$ would be a small peak at $\sim 2527$ keV.
LNGS underground lab

- Gran Sasso, Italy
- 1.4-km rock overburden
The past: Cuoricino

Energy spectrum

$^{130}\text{Te}$ Q-value = 2527.5 keV
Background: \( \frac{0.169 \pm 0.006 \text{ counts/keV/kg/y}}{130\text{Te}} \)

Lower limit, half-life: \( T_{1/2}^{0\nu\beta\beta}(130\text{Te}) \geq 2.8 \times 10^{24} \text{ y} \) (90% C.L.)

Upper limit, Majorana \( \nu \) mass: \( \langle m_{\beta\beta} \rangle < 300 - 710 \text{ meV} \)

The present: CUORE
CUORE

- Pulse tubes (5)
- Dilution refrigerator
- Outer lead shield
- PET + boric acid shield
- Copper thermal shields (6)
  (300, 40, 4, 0.6, 0.06, 0.004 K)
- Roman lead shield
- 988 TeO$_2$ crystal detectors
  (19 towers of 52 crystals)
Detector improvements

- Cleaner crystals
- Cleaner copper, and less of it
- Cleaner assembly environment
- Less vibration in copper frames
- Better self-shielding & anticoincidence coverage

<table>
<thead>
<tr>
<th></th>
<th>Cuoricino</th>
<th>CUORE-O</th>
<th>CUORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{130}$Te mass (kg)</td>
<td>11</td>
<td>11</td>
<td>206</td>
</tr>
<tr>
<td>Background (c/keV/kg/y) @ 2527.5 keV</td>
<td>0.17</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>$E$ resolution (keV) FWHM @ 2615 keV</td>
<td>$\sim 6$</td>
<td>5–6</td>
<td>5</td>
</tr>
<tr>
<td>$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.</td>
<td>300–710</td>
<td>204–533</td>
<td>51–133</td>
</tr>
</tbody>
</table>
Hut

1st — clean room

2nd — electronics

0th — cryostat equipment
Crystals are prepared & assembled into towers inside N₂-filled glove boxes in clean room
First tower from CUORE assembly line

Purpose:

1. Test CUORE assembly line
2. Surpass Cuoricino while CUORE is being assembled

Assembled in Apr 2012

Operating in former Cuoricino cryostat since Mar 2013
CUORE-0 assembly

Gluing

Assembly

Installation
51 crystals were instrumented with thermistors; all survived cooldown

49/52 crystals have active thermistor and heater
CUORE-0 calibration

From $^{232}$Th source strings lowered along outside of cryostat
CUORE-0 energy resolution

Preliminary FWHM (@ 2615 keV) = 6.3 keV

But not yet optimized with pulse-shape cuts!
CUORE activities in progress

Commissioning & characterization of custom dilution refrigerator
CUORE activities in progress

Tower assembly: 6 built to date, 2 of them finished
CUORE activities in progress

4K cold test of partial cryostat & calibration setups
CUORE status

**COMPLETED**
- Hut + clean room commissioned
- All crystals delivered to LNGS
- All thermistors delivered to LNGS
- Outer 3 cryostat vessels delivered to LNGS

**IN PROGRESS**
- Machining + cleaning of copper tower parts
- Assembly of detector towers
- Manufacture of inner 3 cryostat vessels
- Commissioning of dilution refrigerator
- Commissioning of cryogenic system
- Commissioning of detector calibration system
Experimental sensitivities

Cuoricino: \( T^{0\nu\beta\beta}_{1/2}(^{130}\text{Te}) \geq 4.2 \times 10^{24} \text{ y} \) (1\( \sigma \))

CUORE-0: \( T^{0\nu\beta\beta}_{1/2}(^{130}\text{Te}) \geq 9.4 \times 10^{24} \text{ y} \) (1\( \sigma \); 2 years)

CUORE: \( T^{0\nu\beta\beta}_{1/2}(^{130}\text{Te}) \geq 1.6 \times 10^{26} \text{ y} \) (1\( \sigma \); 5 years)

See “Sensitivity of CUORE to Neutrinoless Double-Beta Decay” (arXiv:1109.0494v3 [nucl-ex])
Experimental reach

See “Sensitivity of CUORE to Neutrinoless Double-Beta Decay” [arXiv:nucl-ex/1109.0494v3]
Experimental reach

See “Sensitivity of CUORE to Neutrinoless Double-Beta Decay” [arXiv:nucl-ex/1109.0494v3]
TeO$_2$ bolometers offer a well-established, competitive technique to search for $0
\nu\beta\beta$ decay

Cuoricino did not observe evidence of $0\nu\beta\beta$ decay of $^{130}$Te

CUORE-0 is now taking data in the former Cuoricino cryostat at LNGS; initial results are promising.

Preparations for CUORE are in progress, with data taking scheduled to start in 2015
Fine
$^{130}\text{Te}$ as $0\nu\beta\beta$ decay candidate

- High natural abundance $\Rightarrow$ no enrichment necessary
- Good Q-value above natural $\gamma$ energies + large phase space
**Cryogenic bolometers**

- 10 mK heat sink (Cu)
- Weak thermal coupling (PTFE)
- Absorber (TeO$_2$ crystal)
- Sensor (thermistor, 100 MOhm)

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

\[ \tau = \frac{C}{G} \]

\[ C \sim 10 \text{ MeV/mK} \]
Cuoricino results

2008 Result

data: 2003 — 2006
11.8 kg-yr $^{130}\text{Te}$ exposure

$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 3.0 \times 10^{24}$ y (90% C.L.)


2010 Result

data: 2003 — 2008
19.8 kg-yr $^{130}\text{Te}$ exposure

$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 2.8 \times 10^{24}$ y (90% C.L.)

Cuoricino + TTT results

data: 2003 — 2010
19.9 kg-yr $^{130}\text{Te}$ exposure

Background: $\sim 0.16$ counts/keV/kg/y

Lower limit, half-life: $T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 3.0 \times 10^{24}$ y (90% C.L.)
Half-life sensitivity depends on detector parameters

Sensitivity is the max signal that could be hidden by a background fluctuation (at specified confidence level)
Cryostat improvements

Cuoricino  ➔  CUORE

► New custom dilution refrigerator
► Cryogen-free ➔ more live time
► Better suspension ➔ less vibration
► 50% more Pb shielding
► Cleaner
Cryostat

- Dilution Unit
- Y-Beam
- Detector suspension
- Pulse Tube

- Outer Vacuum Chamber (OVC) (300K)
- Radiation Shield (40K)
- Inner Vacuum Chamber (IVC) (4K)
- Still Shield (0.6-0.9K)
- Mixing Chamber Shield (0.01K)

- OVC plate
- 40K plate
- IVC plate
- Still plate
- MC plate
- Lateral Pb shield
- Mixing Chamber
- Top Pb shield
- Detector
- 988 TeO₂ crystals
- IVC shield
**DCS** = **D**etector **C**alibration **S**ystem

- 12 gamma source strings lowered in between crystal towers through guide tubes – no vertical access
- strings are Kevlar with crimped $^{56}$Co and/or $^{232}$Th source capsules at intervals
- thermalization requirements
- integration with other systems
Roman lead shield

- Ancient Roman lead bricks for low-activity shielding
- Recovered in late ‘80s from shipwreck off Sardinian coast
- Obtained through agreement between INFN and Italian historical society
- 270 bricks, 33 kg each = 7 tons (after inscriptions removed)