Results of CUORE-0 and Prospects of the CUORE Experiment

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Aug. 26, 2014, Particles and Nuclei Interactional Conference, Hamburg, Germany
Hypothetical lepton number violating process

Observation of $0\nu\beta\beta$
- will establish that neutrinos are Majorana particles
- constrains on absolute $\nu$ mass
- may provide info on mass hierarchy

Experimental Signature

summed energy spectrum of final state $e^-$

Rule of Thumb

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

<table>
<thead>
<tr>
<th>a</th>
<th>isotopic abundance of source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>detection efficiency</td>
</tr>
<tr>
<td>$M$</td>
<td>total detector mass</td>
</tr>
<tr>
<td>$b$</td>
<td>background rate /mass/energy</td>
</tr>
<tr>
<td>$t$</td>
<td>exposure time</td>
</tr>
<tr>
<td>$\delta E$</td>
<td>energy resolution (spectral width)</td>
</tr>
</tbody>
</table>
$^{130}\text{Te}$ is a good 0νββ source (high isotopic abundance, relatively high Q-value)

$\text{TeO}_2$ bolometer provides excellent energy resolution (0.2% at Q-value)
CUORE

Cryogenic Underground Observatory for Rare Events

- Search for $0\nu\beta\beta$ in $^{130}\text{Te}$
- 741 kg of $^{\text{nat}}\text{Te}$, 206 kg of $^{130}\text{Te}$
- 988 $\text{TeO}_2$ crystals ($5 \times 5 \times 5$ cm$^3$) as an bolometric array, 19 Towers (13 floors × 4 crystals)
- 10 mK operation temperature
- Excellent energy resolution
- Located at LNGS (3650 m.w.e, $10^6 \mu$ reduction)
- Radiopure materials, surface background suppression, and clean tower assembly
- Complex cryogenic setup
- Also suitable for direct dark matter search
19 groups
(Italy, USA, China, France)

148 people
The CUORE $0\nu\beta\beta$ Search

CUORE: Phased $0\nu\beta\beta$ search Program

Cuoricino (2003-2008)

Achieved (2008)
$$\langle m_{\beta\beta} \rangle_{90\% \text{ C.L.}} = 300 - 710 \text{ meV}$$

Projected (2015)
$$\langle m_{\beta\beta} \rangle_{90\% \text{ C.L.}} = 204 - 533 \text{ meV}$$

CUORE-0 (2013-2015)

CUORE (2015-2020)

Projected (2020)
$$\langle m_{\beta\beta} \rangle_{90\% \text{ C.L.}} = 51 - 133 \text{ meV}$$
Cuoricino to CUORE

- More bolometers (Self-shielding, more powerful single crystal hit requirement).
- Crystals with higher radiopurity.
- Improved copper surface treatment, less copper.
- Optimized tower assembly procedure.
- Radiopure materials + Roman lead shield ($< 4\text{mBq/kg }^{210}\text{Pb}$) for cryostat.
- Pulse tube refrigerator, cryogen free dilution unit (DU).
- Separated DU suspension from crystal tower suspension.

<table>
<thead>
<tr>
<th></th>
<th>Cuoricino</th>
<th>CUORE-0 (Phase I)</th>
<th>CUORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{130}\text{I}$</td>
<td>$11$</td>
<td>$11$</td>
<td>$206$</td>
</tr>
<tr>
<td>Background [counts/(keV·kg·yr)] @ ROI</td>
<td>$0.17$</td>
<td>$0.07^*$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>E resolution (FWHM) [keV] @ 2615 keV</td>
<td>$\sim 6$</td>
<td>$5.7^*$</td>
<td>$5$</td>
</tr>
</tbody>
</table>

* Phase II data analysis shows lower values
The first CUORE-like tower hosted in old Cuoricino cryostat.
- 52 (13 x 4) crystals, 39 kg of TeO$_2$ (11 kg of $^{130}$Te), 4 kg of copper structure.
- Validated new cleaning and assembly procedures for CUORE.
- Taking 0νββ data since Mar. 2013.
- First results (Phase I data analysis) were released in Sep 2013.


- Phase II data w/ improved detector operation condition ongoing.
**Total** $^{232}\text{Th}$ activity of 100 Bq
- CUORE goal of ~ 5 keV FWHM near ROI was achieved w/ improved detector operating condition.
CUORE-0: Background

CUORE-0 Preliminary
Exposure: 18.1 kg \cdot yr

\[ Q_{\beta\beta} = 2528 \text{ keV} \]

<table>
<thead>
<tr>
<th>Event Rate [counts/keV/kg/yr]</th>
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<tbody>
<tr>
<td>208Tl</td>
</tr>
<tr>
<td>190Pt</td>
</tr>
<tr>
<td>210Po</td>
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</table>

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Event Rate [counts/keV/kg/yr]</th>
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<tbody>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
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<tr>
<td>6000</td>
<td></td>
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<tr>
<td>7000</td>
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CUORE-0 Preliminary Avg. flat bkg. [counts/(keV \cdot kg \cdot yr)]

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<tr>
<td></td>
<td>0\nu\beta\beta region (\alpha + \gamma/\beta)</td>
</tr>
<tr>
<td>Cuoricino (\varepsilon=83%)</td>
<td>0.153 ± 0.006</td>
</tr>
<tr>
<td>CUORE-0 (\varepsilon=78 %)</td>
<td>0.063 ± 0.006</td>
</tr>
<tr>
<td>Reduction factor</td>
<td>2</td>
</tr>
<tr>
<td>Due to</td>
<td>Better Radon control (</td>
</tr>
</tbody>
</table>

Consistent w/ Cuoricino background model
CUORE-0: Sensitivity

Assumptions: \(~ 5.2~\text{keV FWHM ROI resolution (}\delta E)\) and background rate \((b)\) of \(0.063 \pm 0.006~\text{counts/(keV·kg yr)}\) from the measurements.

Expected to surpass Cuoricino limit w/ about a year of live time.
CUORE-0 demonstrated that the background mitigation was successful.

CUORE MC for Bkg prediction using the results of CUORE-0 along with other screening campaign results as input shows the CUORE Bkg goal is within reach.

**CUORE Preliminary**

- **Near Surfaces**: 
  - TeO₂
  - Cu NOSV or PTFE
- **Near Bulk**: 
  - TeO₂
  - Cu NOSV
  - Cu NOSV
- **Cosm. Activ.**: 
  - TeO₂
- **Cosm Activ.**: 
  - Cu NOSV
- **Near Bulk**: 
  - small parts
- **Far Bulk**: 
  - COMETA Pb top
  - Inner Roman Pb
  - Steel parts
  - Cu OFE
- **Environmental**: 
  - muons
  - neutrons
  - gammas

**Bkg GOAL**: 0.01 c/keV/kg/y

Conservative extrapolation from the CUORE-0 region measurements assuming all background is from $^{238}\text{U}/^{232}\text{Th}/^{210}\text{Pb}$ individually.
CUORE: Sensitivity

- $1\sigma$ sensitivity $T_{1/2}^{0\nu\beta\beta} = 1.6 \times 10^{26} \text{ yr} \ (9.5 \times 10^{25} \text{ yr @ 90\% C.L.})$
- Effective Majorana mass $47 - 100 \text{ meV} \ (51 - 133 \text{ meV @ 90\% C.L.})$
  - Assumptions: 5 keV FWHM ROI resolution ($\delta E$), background rate ($b$) of 0.01 counts/(keV $\cdot$ kg $\cdot$ yr)
  - 5 years of live time.

arXiv:1109.0494
Status of CUORE: Detector

Assembly of all 19 towers is complete!
CUORE Cryogenic System

Detector: ~ 1 ton
Pb shields: ~ 10 tons
Cu shields/flanges: ~ 8 tons

Main Support Plate

Calibration System
Motion Box

Hoist System (Winch)

Y-Beam

3.1 m

1.7 m

Detector Suspension

Dilution Unit

Pulse Tube Refrigerator (5)

Cold Lead Plate (Top)

Cold Roman Lead (Side)

Detector

300 K

40 K

4 K

600 mK

50 mK

10 mK
Phased commissioning
- Adding complexity at each phase

**Phase I: 4K system check**
- Outer/Inner vacuum chamber test
- Cryogenic verification of detector calibration system
- Commissioning test of DU

**Phase II: full cryostat vessel check**
- Full assembly of cryostat
- Cool down of cryostat (ongoing)
- Integration of test tower, other subsystem

*Completion is expected in 2015*
Status of CUORE: Cryogenics
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Status of CUORE: Cryogenics

Mockup vessel

10 mK

300 K vessel

Super Insulation
Isotopic enrichment.

Particle discrimination by simultaneously measuring heat/light.
Isotopic enrichment.

Particle discrimination by simultaneously measuring heat/light.
Summary

- CUORE-0, the first CUORE-like tower is operated as a stand alone $0\nu\beta\beta$ search experiment at LNGS since March 2013.
- CUORE-0 demonstrates successful background mitigation and confirms the Cuoricino background model. It also demonstrates that 5 keV FWHM ROI energy resolution goal of CUORE is achievable.
- CUORE tower assembly is complete and cryogenic system commissioning is underway.
- Detector array deployment is expected in 2015.
- Low background and large mass of CUORE extend the physics reach of CUORE to other rare event searches such as direct dark matter and rare nuclear decays.
- Various R&D effort is ongoing for $0\nu\beta\beta$ search beyond CUORE.