Results from the search for neutrinoless double-beta decay of Te-130 with CUORE-0

Kyungeun E. Lim (on behalf of the CUORE collaboration)

Apr. 14, 2015, LNS Seminar, MIT
What we know about Neutrinos

Neutrino Mass Splitting

- Normal Hierarchy
- Inverted Hierarchy

100 - 500 meV

Degenerate

$m^2_1$, $m^2_2$, $m^2_3$

$solar \sim 7 \times 10^{-5} eV^2$

$atmospheric \sim 2 \times 10^{-3} eV^2$

$\nu_e$, $\nu_\mu$, $\nu_\tau$

What we don’t know about Neutrinos

Neutrino Mass Splitting

$\nu_e$  
$\nu_\mu$  
$\nu_\tau$

$m^2$

$0$

$m_1^2$  
$m_2^2$  
$m_3^2$

$\nu_e$  
$\nu_\mu$  
$\nu_\tau$

$m^2$

$100 - 500 \text{ meV}$

Degenerate

Is the neutrino its own antiparticle?

Normal Hierarchy

Inverted Hierarchy

solar $\sim 7 \times 10^{-5} \text{eV}^2$

atmospheric $\sim 2 \times 10^{-3} \text{eV}^2$

$\nu_e$  
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Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE: An array of TeO$_2$ bolometers
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
  - CUORE-0: Detector
  - CUORE-0: Performance and Background
  - CUORE-0: Results
- Summary
Neutrino(less) double-beta decay

**2νββ**
- Allowed in SM
- Observed in several nuclei
  \( T_{1/2}^{2ν} \sim 10^{18} - 10^{21} \text{ yr} \)

**0νββ**
- Beyond SM
- Hypothetical process only if \( ν = \overline{ν} \) and \( m_ν > 0 \)

**Observation of 0νββ**
1. will establish that neutrinos are Majorana Particles (\( ν = \overline{ν} \))
2. demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the \( ν \) mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement
Neutrino(less) double-beta decay

- **2νββ**
  - Allowed in SM
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- **0νββ**
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  - Hypothetical process only if $ν = \bar{ν}$ and $m_ν > 0$

### Observation of 0νββ
1. will establish that neutrinos are Majorana Particles ($ν = \bar{ν}$)
2. demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the $ν$ mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement

$^{48}$Ca, $^{150}$Nd, $^{96}$Zr, $^{100}$Mo, $^{82}$Se, $^{116}$Cd, $^{130}$Te, $^{136}$Xe, $^{76}$Ge
Look for peak in the detector at the Q-value of decay.

Good energy resolution of a detector suppresses intrinsic background from $2\nu\beta\beta$. 

( Assumes BR $0\nu/2\nu = 1\%$ and detector energy resolution is 2\% )
Look for peak in the detector at the Q-value of decay.

Good energy resolution of a detector suppresses intrinsic background from $2\nu\beta\beta$. 

(Assumes BR $0\nu/2\nu = 1\%$ and detector energy resolution is $2\%$)
Search for $0\nu\beta\beta$

Decay rate:

$$\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}(Q, Z) \left| M^{0\nu} \right|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

- Well defined
- Difficult to calculate

$$\langle m_{\beta\beta} \rangle \equiv \sum_{i=1}^{3} U_{ei}^2 m_i$$

<table>
<thead>
<tr>
<th>$T_{1/2}^{0\nu}$</th>
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- Probes absolute mass scale
- Sensitive to hierarchy
Decay rate:

\[(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) \left| M^{0\nu} \right|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}\]

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

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| \(a\) | isotopic abundance of source |
| \(\epsilon\) | detection efficiency |
| \(M\) | total detector mass |
| \(b\) | background rate /mass/energy |
| \(t\) | exposure time |
| \(\delta E\) | energy resolution (spectral width) |
Search for $0\nu\beta\beta$

Decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Source Selection/
Detector Building Strategies

- Large total mass
- Ultra-low background
- Good energy resolution
- High Q-value
- High isotopic abundance
- NME

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- $a$: isotopic abundance of source
- $\epsilon$: detection efficiency
- $M$: total detector mass
- $b$: background rate/mass/energy
- $t$: exposure time
- $\delta E$: energy resolution (spectral width)
Search for $0
\nu\beta\beta$
Search for 0νββ

Majorana
Under construction

EXO
Data Taking

GERDA
Data Taking

CANDLES
Complete

CUORE
Under construction

SuperNEMO
Under construction

SNO+
Under construction

KamLAND-Zen
Data Taking

NEXT
Under construction

L. Winslow, APS 2015
Search for 0νββ: $^{136}$Xe

**KamLAND-Zen**

$T_{1/2} > 1.9 \times 10^{25}$ years

*Phys. Rev. Lett. 111 (2013) 122503*

**EXO-200**

$T_{1/2} > 1.1 \times 10^{25}$ years

*Nature 510 (2014) 229–234*
Search for $0\nu\beta\beta$: $^{76}\text{Ge}$

**GERDA**

Combined $^{76}\text{Ge} T_{1/2} > 3.0 \times 10^{25}$ years

Search for $0\nu \beta\beta$: $^{130}\text{Te}$

Decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle}{m_e^2}.$$ 

$T_{1/2}^{0\nu}$ sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

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Source Selection/ Detector Building Strategies

- Large total mass
- Ultra-low background
- Good energy resolution
- High $Q$-value
- High isotopic abundance
- NME

www.nndc.bnl.gov/chart
High isotopic abundance, low background at the Q-value makes $^{130}\text{Te}$ appealing for $0\nu\beta\beta$ search.
TeO$_2$ Bolometers

- Measure energy deposition through temperature rise.
- Provides excellent energy resolution.

- Crystal absorber: $E \rightarrow \Delta T$
- Biased $T$ sensor: $\Delta T \rightarrow \Delta V$
- Thermal coupling: $T_0 \sim 13$ mK

K. E. Lim (Yale University)
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Summary
The CUORE $0\nu\beta\beta$ Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003-2008)

Achieved (2008)

$T_{1/2}^{0\nu} > 2.8 \times 10^{24}$ yr (90% C.L.)

CUORE-0 (2013-2015)

Achieved (2015)

CUORE (2015-2020)

Projected (2020)

$T_{1/2}^{0\nu} > 9.5 \times 10^{25}$ yr (90% C.L.)

Astroparticle Physics 34 (2011) 822
The CUORE $0
\beta\beta$ Search

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Astroparticle Physics 34 (2011) 822
CUORE Collaboration

21 institutes (USA+Italy)
166 people
CUORE at LNGS
CUORE at LNGS
The CUORE Detector

- Pulse Tube Refrigerator (5)
- Dilution Refrigerator
- Top Shield (6 tons)
- PE + H$_3$BO$_3$ Shield
- Outer Lead Shield
- Side/Inner Shield (Roman Lead)
- 988 TeO$_2$ bolometers (19 towers)
The CUORE Detector

doi:10.1038/news.2010.186 (nature)
Progress towards CUORE

- Dilution Refrigerator reached 5 mK for the commissioning test, has been integrated in the cryostat.
- External shields installation finished.
- CUORE-0, the first tower from CUORE assembly line has been running in the Cuoricino cryostat since March 2013.

Cryostat assembled, commissioning, passed 4 K Test, reached 5.9 mK, wiring with mini-tower tested.

Detector calibration system well underway.

- 19 towers completed.
- Installation in the cryostat is anticipated in this summer.
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CUORE-0

The first CUORE-like tower
Detector Assembly

Crystals are prepared & assembled into towers inside N$_2$-fluxed glove boxes in a Class 1000 clean room.
Detector Assembly

Gluing machine

Mechanical assembly

Cryostat

Storage

Assembly

Gluing

Wire bonding

Tower garage

K. E. Lim (Yale University)
Transported from CUORE cleanroom to Cuoricino cleanroom

After assembly

Attached to Cuoricino dilution refrigerator
The CUORE-0 Experiment

- 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.
- Verified understanding on the background sources. 
  

- Tested DAQ & Analysis framework for CUORE.
- Taking 0νββ data since March 2013 in former Cuoricino cryostat.
Tower Response

Run 201388 Working Resistances

Run 201388 Working Temperatures

Cuoricino RMS: 9%
CUORE-0 RMS: 2%
Neutrinoless double-beta decay ($0\nu\beta\beta$) search

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Summary
Start data taking in March 2013

- Cryogenic maintenance between campaigns
- Acquired 0νββ data till March 2015
- 35.2 kg-yr of $^{nat}\text{TeO}_2$
- 9.8 kg-yr of $^{130}\text{Te}$

Physics data
Calibration data
**Analysis Procedure: Experimental Input**

Data Acquisition

- continuously sample and record the bolometer signal @ 125 S/s

Bolometer Pulse

- Raw Data Processing
  - software trigger thresholds (30-120 keV)
  - signal, noise, pulser events
  - filter pulse to optimize energy resolution
  - signal (thermal) gain correction
  - energy calibration (V $\rightarrow$ keV)

- Event Selection
  - remove low quality events
  - single pulse in 7.1s window
  - require pulse shape to be expected signal
  - no other pulse in coincidence in other bolometers

- Reduced Data

- Experimental Input
  - calibration, 0νββ data
  - background estimation, energy resolution

- Blinding

- ROOT Data Trees

- Analysis efficiency!
Analysis Procedure: Results & Interpretation

Data Acquisition

Experimental Input

Raw Data Processing

Event Selection

Analysis Procedure: Results & Interpretation

CUORE-0 Preliminary Exposure: 18.1 kg \cdot yr

Event Selection

Raw Data Processing

Data Acquisition

Experimental Input

Event Selection

Statistical Treatment

Unbinned likelihood (UEML) fit Bayesian approach

Nuclear Physics

Acknowledgements

K. E. Lim (Yale University)
Reconstructed Energy (keV)

Counts / (0.5 keV)

Summed calibration data
Projected fit

\( \gamma_{208\text{Tl}} \)

\( E(\text{StabAmpl}) = a \cdot \text{StabAmpl} + b \cdot \text{StabAmpl}^2 \)

Energy [keV]

\( 583 \text{ keV} \) (\( ^{208}\text{Tl} \))

\( 965 \text{ keV}, 969 \text{ keV} \) (\( ^{228}\text{Ac} \))

\( 1588 \text{ keV} \) (\( ^{228}\text{Ac} \))

\( + 1592 \text{ keV} \) (\( ^{208}\text{Tl} \) double escape)

\( 2104 \text{ keV} \) (\( ^{208}\text{Tl} \) single escape)

\( 2615 \text{ keV} \) (\( ^{208}\text{Tl} \))

\( 2104 \text{ keV} \) (\( ^{208}\text{Tl} \) single escape)

\( 1592 \text{ keV} \) (\( ^{208}\text{Tl} \) double escape)

\( 511 \text{ keV} \), \( 965 \text{ keV} \)

\( 583 \text{ keV} \) (\( ^{208}\text{Tl} \))

\( 969 \text{ keV} \) (\( ^{228}\text{Ac} \))

\( 1588 \text{ keV} \) (\( ^{228}\text{Ac} \))

\( 2615 \text{ keV} \) (\( ^{208}\text{Tl} \))

\( 2560 \text{ keV} \)

\( 2570 \text{ keV} \)

\( 2580 \text{ keV} \)

\( 2590 \text{ keV} \)

\( 2600 \text{ keV} \)

\( 2610 \text{ keV} \)

\( 2620 \text{ keV} \)

\( 2630 \text{ keV} \)

\( 2640 \text{ keV} \)

\( 2650 \text{ keV} \)
Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from $^{208}\text{TI}$ in the calibration data.

The obtained resolution is < 5 keV, which is the CUORE goal.
Background Spectrum

Counts / (keV \cdot kg \cdot y)

Physics spectrum
Scaled calibration spectrum

CUORE-0 Preliminary

Reconstructed Energy (keV)

(1)e^+e^-, (2)^{214}Bi, (3)^{40}K, (4)^{208}Tl, (5)^{60}Co, (6)^{228}Ac

K. E. Lim (Yale University)
γ background (from $^{232}$Th) was not reduced since the cryostat remained the same.

γ background (from $^{238}$U chain) was reduced by a factor of 2.5 due to better radon control.

α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface treatment.

Demonstrate CUORE sensitivity goal is within reach.

Background paper in preparation!
### Background Rate

#### Energy [keV]

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<tr>
<td>2600</td>
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<tr>
<td>2800</td>
</tr>
<tr>
<td>3000</td>
</tr>
<tr>
<td>3200</td>
</tr>
<tr>
<td>3400</td>
</tr>
<tr>
<td>3600</td>
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<tr>
<td>3800</td>
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</tbody>
</table>

#### Event Rate [counts/keV/kg/y]

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<tbody>
<tr>
<td>-2</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

#### Background Rate

<table>
<thead>
<tr>
<th>Detector</th>
<th>Background Rate [counts/keV/kg/y]</th>
<th>signal eff. [%] (detector+cuts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0νββ region</td>
<td>α region (excl. peak)</td>
<td></td>
</tr>
<tr>
<td>Cuoricino</td>
<td>0.169 ± 0.006</td>
<td>0.110 ± 0.001</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>0.058 ± 0.011</td>
<td>0.016 ± 0.001</td>
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Summary
Region of Interest was blinded by “salting”: A small (and blinded) fraction of the events within ±10 keV in $^{208}$Tl photopeak are exchanged with events within ±10 keV of the $0\nu\beta\beta$ Q-value to produce a fake peak.

Background at ROI can be characterized without biasing $0\nu\beta\beta$ analysis.
CUORE-0 Unblinding

Number of Events per 2 keV

Energy [keV]

spec

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
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<tr>
<td>300</td>
<td>2519</td>
<td>24.54</td>
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K. E. Lim (Yale University)
Simultaneous unbinned extended ML fit to range [2470,2570] keV

Fit function has 3 components:
1. Calibration-derived lineshape modeling posited fixed at 2527.5 keV
2. Calibration-derived lineshape modeling Co peak floated around 2505 keV
3. Continuum background
Fitted background: $0.058 \pm 0.004$ (stat.) $\pm 0.002$ (syst.) counts/keV/kg/yr

Best-fit decay rate: $\Gamma^{0\nu\beta\beta}(^{130}\text{Te}) = 0.01 \pm 0.12$ (stat.) $\pm 0.01$ (syst.) $\times 10^{-24}$ yr$^{-1}$
Fit to the Unblinded ROI

\[ \Gamma^{0\nu\beta\beta}(^{130}\text{Te}) < 0.25 \times 10^{-24} \text{ yr}^{-1} \text{ (90% C.L., statistics only)} \]

\[ T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 2.7 \times 10^{24} \text{ yr} \text{ (90% C.L., statistics only)} \]
For each systematic, we run toy MC exps. to evaluate bias on fitted $0νββ$ rate.

Bias is parameterized as $p0 + p1xΓ$, where $p0$ = “additive” and $p1$ = “scaling”

**Signal lineshape**: Used variety of different line shapes to model signal

**Energy resolution**: Apply $1.05 \pm 0.05$ correction to calibration-derived resolution

**Fit bias**: Effect of using unbanned extended ML fit to extract values

**Energy scale**: Assign 0.12 keV uncertainty derived from peak residuals in physics spectrum

**Bkg function**: Choices of 0-,1-,2- order polynomial.
We find no evidence for $0\nu\beta\beta$ of $^{130}\text{Te}$ (report the Bayesian limits)

\[
\Gamma^{0\nu\beta\beta}(^{130}\text{Te}) < 0.25 \times 10^{-24} \text{ yr}^{-1} \text{ (90\% C.L., stat.+sys.)}
\]
\[
T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 2.7 \times 10^{24} \text{ yr} \text{ (90\% C.L., stat.+sys.)}
\]

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

<table>
<thead>
<tr>
<th></th>
<th>Additive ($10^{-24} \text{ y}^{-1}$)</th>
<th>Scaling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lineshape</td>
<td>0.007</td>
<td>1.3</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>0.006</td>
<td>2.3</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.006</td>
<td>0.15</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.005</td>
<td>0.4</td>
</tr>
<tr>
<td>Bkg function</td>
<td>0.004</td>
<td>0.8</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td></td>
<td>0.7%</td>
</tr>
</tbody>
</table>
Combining the CUORE-0 result with the Cuoricino result from 19.75 kg-yr of $^{130}$Te exposure yields the Bayesian lower limit:

$$T_{1/2}^{0
u\beta\beta}(^{130}\text{Te}) > 4.0 \times 10^{24} \text{ yr (90\% C.L., stat.+sys.)}$$
Limits on Effective Majorana Mass

\[ \langle m_{\beta\beta} \rangle < 270 \text{ – } 650 \text{ meV} \]

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

\[ \langle m_{\beta\beta} \rangle < 270 \text{ – } 760 \text{ meV} \]

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))
CUORE Preliminary

Near Surfaces: TeO$_2$
Near Surfaces: Cu NOSV or PTFE
Near Bulk: TeO$_2$
Near Bulk: Cu NOSV
Cosm. Activ.: TeO$_2$
Cosm Activ.: Cu NOSV
Near Bulk: small parts
Far Bulk: COMETA Pb top
Far Bulk: Inner Roman Pb
Far Bulk: Steel parts
Far Bulk: Cu OFE

Environmental: muons
Environmental: neutrons
Environmental: gammas

Counts/ROI/ton/y

90% CL limit
value

Bkg GOAL: 0.01 c/keV/kg/y
CUORE: Sensitivity

- Assumptions: 5 keV FWHM ROI resolution ($\delta E$), background rate ($b$) of 0.01 counts/(keV·kg·yr)
- 5 years of live time.

$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 9.5 \times 10^{25}$ yr (90% C.L.)

$m_{\beta\beta}$: 50-130 meV

arXiv:1109.0494
Observation of $0\nu\beta\beta$ will establish that neutrinos are Majorana particles.

$\text{TeO}_2$ bolometers offer a well-established and competitive technique to search for $0\nu\beta\beta$.

CUORE-0 and Cuoricino, the experiments on the way to CUORE, did not find evidence of $0\nu\beta\beta$ of $^{130}\text{Te}$.

CUORE-0, the first CUORE-like tower currently operating at LNGS, demonstrated background suppression and resolution improvements, i.e., achieved goals for CUORE.

CUORE, the largest cryogenic detector using $\text{TeO}_2$ bolometers with 206 kg of $^{130}\text{Te}$ mass, completed detector construction and commissioning of the cryogenic system along with infrastructure is well underway.

CUORE is scheduled to start data-taking in late 2015 and various R&D projects are on-going for searches beyond CUORE.