Search for $0\nu\beta\beta$ decay of $^{130}\text{Te}$ with CUORE-0 and CUORE

Fabio Bellini
on behalf of the CUORE Collaboration

25th International Workshop on Weak Interactions and Neutrinos
Heidelberg, 8-13 June 2015
CUORE searches for 0νββ decay of $^{130}$Te in natTeO$_2$ bolometers

- 0.75 Kg natTeO$_2$ crystals
  - $C \sim 10^{-9}$ J/K $\rightarrow \Delta T/\Delta E \sim 100\mu K/MeV$

- NTD-Ge thermistor: $R = R_0 \exp(T_0/T)^{1/2}$
  - $R \sim 100$ MΩ $\rightarrow \Delta R/\Delta E \sim 3$ MΩ/MeV

- Resolution @ 0νββ energy ($\sim 2528$ keV): $\Delta E_{FWHM} = 5$-7 keV
The CUORICINO experience

- 62 TeO$_2$ crystals operated at LNGS
- $^{130}$Te: i.a.~34%, $Q_{\beta\beta}$~2528 keV
- Exposure: 19.75 kg·yr $^{130}$Te
- $T^{0\nu}_{1/2} > 2.8 \cdot 10^{24}$ yr (90% CL) \( m_{\beta\beta} < (300\text{-}710) \text{ meV} \)
- Bkg level: $0.169 \pm 0.006$ c/(keV·kg·yr)

\[ \alpha \sigma + \gamma \]  
from $^{232}$Th in cryostat

\[ 0\nu\beta\beta \]  
\[ \alpha \sigma \] from TeO$_2$ and Cu surface contamination

CUORE at LNGS

Array of 988 TeO₂ crystals, each crystal 5x5x5 cm³ (750 g)

- 19 towers - 13 floors - one 4 crystal module per floor
- 741 kg total mass - 206 kg of ¹³⁰Te (~10²⁷ ¹³⁰Te nuclei)

Bkg goal: 0.01 c/(keV·kg·yr) (~17 lower than CUORICINO)

Energy resolution goal: ΔE_{FWHM} = 5 keV

3.6 km.w.e. average deep

μs: ~3x10⁻⁸/(s cm²)
γs: ~0.73/(s cm²)
neutrons: 4x10⁻⁶ n/(s cm²)
CUORE: main challenges

- **Cleaning**
  - Strict radio-purity control protocol to limit bulk and surface contaminations in crystal production
  - TECM (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) cleaning for copper surfaces

- **Cryostat:**
  - Custom pulse tube dilution refrigerator and cryostat. Technologically challenging: ~1 ton of detectors at 10 mK
  - Stringent radioactivity constraints on materials and clean assembly
  - Independent suspension of the detector array from the dilution unit
CUORE Assembly Line

- All parts cleaned/screened according to CUORE protocol
- Stored underground at LNGS
- Assembly carried in N₂-flushed glove boxes in CUORE clean room
CUORE Assembly Line

Gluing

Assembly

Cabling

Bonding
Status of CUORE: assembly

All 19 towers are complete!

Expect to deploy the array in the cryostat this year
Status of CUORE: cryogenic system

- Cryostat assembled, passed 4 K commissioning test
- Dilution unit able to maintain ~5 mK in standalone commissioning test
- 2 out of 3 planned integration runs already reached ~6 mK base T
- Final integration run (everything except detectors) is ongoing
Size similar to CUORICINO:

- 52x750g crystals
- 13 floor of 4 crystals each

Active mass:

- TeO$_2$: 39 kg
- $^{130}$Te: $\sim$11 kg ($5 \cdot 10^{25}$ nuclei)

Same cryostat as CUORICINO:

$\gamma$ background ($^{232}$Th) not expected to change \(\Rightarrow\) test the $\alpha$ background
Data Taking

- 2 campaigns, divided by major cryostat maintenance
- ~1-month datasets, with 2-3 days of shared calibration at beginning & end
- Total exposure: $35.2 \text{ kg} \cdot \text{yr of } \text{TeO}_2$ (9.8 kg \cdot yr of $^{130}\text{Te}$)

March 1, 2015

CUORE-0 Dataset Run Time Breakdown

- Physics: 50.4%
- Down Time: 1.7%
- Test: 13.4%
- Calibration: 13.1%
- Other: 13.1%
Calibration energy resolution

- Exposure weighted sum of the line-shapes of each bolometer-dataset overlaid $^{208}$Tl-2615 keV calibration data
- Exposure weighted harmonic mean FWHM: $4.9 \pm 2.9$ keV

CUORE goal of 5 keV reached
CUORE-0 full spectrum

Calibration spectrum from Th source normalised to $^{208}\text{TI}$ peak in physics data

Calibration data

Physics data

Use prominent peaks in the physics data to check compatibility of calibration line-shapes
CUORE-0 background

- $^{238}$U $\gamma$ lines reduced by ~2 (better radon control)
- $^{232}$Th $\gamma$ lines not reduced (originate from the cryostat)
- $^{238}$U/$^{232}$Th $\alpha$ lines reduced (detector surface treatment)

<table>
<thead>
<tr>
<th></th>
<th>Avg. flat bkg. [$c/(\text{keV} \cdot \text{kg} \cdot \text{yr})$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0$\nu$\beta$\beta$ region</td>
</tr>
<tr>
<td>CUORICINO $\varepsilon = 83%$</td>
<td>0.169 ± 0.006</td>
</tr>
<tr>
<td>CUORE-0 $\varepsilon = 81%$</td>
<td>0.058 ± 0.04</td>
</tr>
</tbody>
</table>
CUORE-0: $0\nu\beta\beta$ search

- Simultaneous UEML fit to 233 events in ROI [2470-2570 keV].

- Best fit $\Gamma_{0\nu}$:
  \[ \Gamma_{0\nu} = 0.01 \pm 0.12 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \times 10^{-24} \text{yr} \]

- Best fit $\Gamma_{\text{bkg}}$:
  \[ 0.058 \pm 0.004 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \text{ c/keV/kg/yr} \]

- 90\%CL bayesian lower limit: \[ T^{0\nu}_{1/2} > 2.7 \cdot 10^{24} \text{ yr} \]

- Median 90\% C.L. lower limit sensitivity: \[ T^{0\nu}_{1/2} > 2.9 \cdot 10^{24} \text{ yr}, \]
Combine CUORE-0 and CUORICINO limit

\[ T^{0v}_{1/2} > 4.0 \cdot 10^{24} \text{ yr @ 90\%CL} \]

\[ m_{\beta\beta} < (270-650) \text{ meV} \]

---

Conclusions

CUORE-0

- CUORE assembly and cleaning technique validated
- Energy resolution and background goals achieved
- Combined with CUORICINO: most stringent limit on 0νββ decay of $^{130}$Te

\[ T^{0\nu}_{1/2} > 4.0 \cdot 10^{24} \text{ yr} @ 90\% \text{CL} \quad m_{\beta\beta} < (270-650) \text{ meV} \]

CUORE

- Towers assembly complete
- Commissioning of the cryogenic system in advanced phase
- Start operation by end of 2015
- 5 yr sensitivity bkg: 0.01 c/(keV · kg · yr), $\Delta E_{\text{FWHM}}$: 5 keV

\[ T^{0\nu}_{1/2} = 9.5 \cdot 10^{25} \text{ yr} @ 90\% \text{CL} \quad m_{\beta\beta} < (50-130) \text{ meV} \]
BACKUP SLIDES
Event Selection

Pile-up: discard multiple events in the same acquisition window

<table>
<thead>
<tr>
<th>Selection</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger &amp; reconstruction</td>
<td>98.529 ± 0.004</td>
</tr>
<tr>
<td>Pileup &amp; Pulse shape</td>
<td>93.7 ± 0.7</td>
</tr>
<tr>
<td>Anticoincidence (0νββ containment)</td>
<td>88.4 ± 0.09</td>
</tr>
<tr>
<td>Anticoincidence (survive accidental)</td>
<td>99.6 ± 0.1</td>
</tr>
<tr>
<td>Total</td>
<td>81.3 ± 0.6</td>
</tr>
</tbody>
</table>

Pulse shape discrimination: discard events with unexpected shapes

Anti-coincidence: select single crystal energy deposition
Use calibration $^{208}$Tl line @ 2615 keV

Find a small low energy tail, well described by double gaussian:

$$\rho(\mu, \sigma, \delta, \eta, E) = \frac{1}{\sqrt{2\pi}\sigma} \left[ (1 - \eta) \cdot e^{-\frac{(E-\mu)^2}{2\sigma^2}} + \eta \cdot e^{-\frac{(E-\delta \cdot \mu)^2}{2\sigma^2}} \right]$$

- Primary gaussian ~ 95% of intensity
- Common width $\sigma$ for both
- Secondary gaussian:
  - Intensity ($\eta$) ~ 5% of total intensity
  - Mean ($\mu'$) ~ 0.3% lower than $\mu$, $\delta = \mu'/\mu$

Simultaneous UML fit to each bolometer-dataset calibration data to determine the line shape parameters

$$\rho_{b,d} = \rho(\mu_{b,d}, \sigma_{b,d}, \delta_{b,d}, \eta_{b,d})$$

- $b = \{1, 2, \ldots, 51\}$
- $d = \{1, 2, \ldots, 20\}$

Fit includes bolometer-dataset independent parameters to model Compton continuum and background

Line shape used for calibration uncertainty study & for ROI peaks in the fit
Calibration uncertainty

Projection of calibration line-shape to physics data

\( \mu (b,d) \) is allowed to vary around the expected calibrated energy via a global free parameter \( \Delta \mu(E) \)

\( \sigma (b,d) \) are varied relative to the ones calculated from calibration data via a global scaling parameter \( \alpha(E) \)

\( \delta (b,d) \) are varied relative to the ones calculated from calibration data by the ratio of \( E \) to 2615 keV

\( \eta (b,d) \) are fixed relative to the ones calculated from calibration data

\[ (1) \ e^+e^- \text{ annihilation} \ - \ (2) \ ^{214}\text{Bi} \ - \ (3) \ ^{40}\text{K} \ - \ (4) \ ^{208}\text{Tl} \ - \ (5) \ ^{60}\text{Co} \ - \ (6) \ - \ ^{228}\text{Ac} \]
Calibration uncertainty

Projection of calibration line-shape to physics data

- Fit a quadratic function to the physics peak residuals
- Use the resulting best-fit function to estimate the offset at $Q_{\beta\beta}$
- Use the standard deviation of the peak residuals about the best-fit to estimate the systematic uncertainty on $\Delta \mu(Q_{\beta\beta})$

$$\Delta \mu(Q_{\beta\beta}) = 0.05 \pm 0.05 \text{(stat.)} \pm 0.12 \text{(syst.)} \text{ keV}$$

- We estimate the resolution scaling at $Q_{\beta\beta}$ from a fit to the collection of peak resolution scaling parameters

$$\alpha(Q_{\beta\beta}) = 1.05 \pm 0.05 \text{ (stat. + syst.)}$$

(1) $e^+e^-$ annihilation - (2) $^{214}\text{Bi}$ - (3) $^{40}\text{K}$ - (4) $^{208}\text{Tl}$ - (5) $^{60}\text{Co}$ - (6) - $^{228}\text{Ac}$
• Prominent outlier from $^{60}$Co double gamma events
  • ~2507 keV reconstructed vs. ~2505 keV expected

• In a dedicated $^{60}$Co calibration run, the double gamma events reconstruct at ~2507 keV in agreement with our physics data
$^{60}$Co calibration

$^{60}$Co double-gamma events reconstruct at $2507.6 \pm 0.7$ keV,

1.9 $\pm$ 0.7 keV higher than the established value at 2505.6 keV
2615 double escape peak

- Same topology of neutrino-less double beta decay (2 electrons)
- Reconstructs at the correct energy
Fit in the ROI

- We determined the yield of 0νDBD events by performing a simultaneous UEML fit in the energy region 2470-2570 keV.

- The fit has 3 components:
  - A posited peak at the Q-value of $^{130}\text{Te}$.
  - A peak at 2507 keV, attributed to the double gamma events from $^{60}\text{Co}$ in the nearby copper and constrained to follow $^{60}\text{Co}$ half life.
  - A smooth continuum background, attributed to multi scattered Compton events from $^{208}\text{Tl}$ and surface α events.

- The fit has 4 global free parameters:
  - $\Gamma_{0\nu\beta\beta}, N_{60\text{Co}}, \Delta\mu(60\text{Co}), \Gamma_B$

\[ \Delta\mu(Q_{\beta\beta}) = 0.05 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)} \]

\[ \alpha_\sigma(Q_{\beta\beta}) = 1.05 \pm 0.05 \]

Both peaks are modelled using the established line shape.

Use flat background but also consider first- and second-order polynomials.

Used to shift $\mu(b,d)$ from calibration data.

Used to scale $\sigma(b,d)$ from calibration data.
Systematics

- For each systematic, we run toy Monte Carlo to evaluate bias on fitted $0\nu\beta\beta$ decay rate
- Bias is parametrised as $p_0 + p_1 \times \Gamma$, where $p_0$=“additive” and $p_1$=“scaling”
  - **Signal line-shape**: use single and triple gaussian alternatives
  - **Energy resolution**: vary resolution scaling parameter $\alpha(Q_{\beta\beta})$ within its uncertainty(5%)
  - **Energy scale**: vary energy offset $\Delta\mu(Q_{\beta\beta})$ within its uncertainty(0.12 keV)
  - **Fit bias**: Find fit procedure is not biased
  - **Bkg function**: use 1$^{\text{st}}$, 2$^{\text{nd}}$-order polynomial alternatives

<table>
<thead>
<tr>
<th></th>
<th>Signal line shape</th>
<th>Energy resolution</th>
<th>Fit bias</th>
<th>Energy scale</th>
<th>Background function</th>
<th>Efficiency correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$ (additive)</td>
<td>0.007</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>$p_1$ (percentage bias)</td>
<td>1.3%</td>
<td>2.3%</td>
<td>0.15%</td>
<td>0.4%</td>
<td>0.8%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>
**Statistical checks**

- Estimate the significance of fluctuations from a likelihood ratio test.
- Compare hypotheses modelling fluctuations with a peak to our best-fit model.
- None of the fluctuations has a significance $>3\sigma$ C.L.
- Probability to observe the largest fluctuation somewhere in the 100 keV ROI is $\sim 10\%$

- We compared the value of the binned $\chi^2$ with the distribution from a large set of Toy MC.

- The 90% of such experiments return a value of $\chi^2 > 43.9$
ROI: CUORE-0 vs CUORICINO

CUORE-0 Preliminary
Detector stability

- Routinely measure NTD resistances to monitor detector stability

- Spread of NTD resistances across detector within factor of 3

- Resistance of individual NTDs stable to within 3% over a month-long dataset

- It is possible to operate a large bolometer array stably!
• Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from $^{238}\text{U}/^{232}\text{Th}/^{210}\text{Po}$ individually
Crystals

- Radio-purity control protocol to limit bulk & surface contaminations in crystal production


- Benchmarked in dedicated runs at LNGS


<table>
<thead>
<tr>
<th>Isotope</th>
<th>Allowed Contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$&lt; 3 \cdot 10^{-13}$ g/g</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$&lt; 3 \cdot 10^{-13}$ g/g</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$&lt; 1 \cdot 10^{-5}$ Bq/kg</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$&lt; 0.1$ Bq/kg</td>
</tr>
</tbody>
</table>

- CUORE: bkgd $<1.1 \cdot 10^{-4}$ (4.2 $\cdot$ 10$^{-3}$) counts/keV/kg/y from bulk (surface)