Results from CUORE-0, Status of CUORE

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**CUORE Bolometer**

**TeO$_2$ Bolometer: Source = Detector**

- **main candidate isotope:** $^{130}\text{Te}$
- **Q-value:** 2530 keV
- **Isotopic abundance:** 34%

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

- **Signal size:** 1 mV

- **Time constant:** $\tau = C/G = 0.5$ s
- **Energy resolution:** $\sim 5$-10 keV at 2.5 MeV

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**Diagram**

- **Heat sink:** Cu structure (8-10 mK)
- **Thermal coupling:** Teflon ($G = 4$ pW/mK)
- **Thermometer:** NTD Ge-thermistor ($100$ k$\Omega$/µK)
- **Absorber:** TeO$_2$ crystal

$C \approx 2$ nJ/K $\approx 1$ MeV / 0.1 mK

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**Single pulse example**

- **Amplitude (a.u.)**
- **Time (ms)**
Search for 0νββ in $^{130}$Te

Experimental Signature of 0νββ

- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable 2νββ background

Cuoricino summed spectrum in $^{130}$Te
The CUORE 0νββ Search

Cuoricino (2003-2008)

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


CUORE-0 (2013-2015)

$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ yr (90% C.L.)

EPJC 74, 2956 (2014)
arXiv:1504.0245

CUORE (2015-2020)

Projected

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

arXiv:1109.0494
CUORE at LNGS

Average depth ~ 3600 m.w.e.

\[ \mu: 3 \times 10^{-8} \mu/s/cm^2 \]
\[ n < 10 \text{ MeV}: 4 \times 10^{-6} \text{ n/s/cm}^2 \]
\[ \gamma < 3 \text{ MeV}: 0.73 \gamma/s/cm^2 \]
Cryogenic Underground Observatory for Rare Events

- 988 TeO$_2$ crystals run as a bolometer array
  - 5x5x5 cm$^3$ crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total; 206 kg $^{130}$Te
  - $10^{27}$ $^{130}$Te nuclei

- Excellent energy resolution of bolometers
- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background at region of interest (ROI)
Detector Towers

Assembly of all 19+ towers is complete!
CUORE Cryostat

- Suspension
- Dilution unit
- Pulse tubes
- Roman lead ~6 tons
- TeO2
- 300 K
- 40 K
- 4 K
- 600 mK
- 50 mK
- 10 mK
- Motion boxes
- Lead shield
- Detector support plate
- Bolometers @ ~10 mK
- Guide tubes
- Lead shield
- 300 K
- 40 K
- 4 K
- 0.6 K
- 50 mK
- 10 mK
Phased Commissioning

**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
- Integration of test tower
- Detector wiring
- Calibration system

**Preparing for Phase III: integrated cryogenic test**
- with lead shields
- wiring
- full calibration system

6mK stable base temperature achieved in October 2014
The CUORE 0νββ Search

Cuoricino (2003-2008)

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CUORE-0 (2013-2015)

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CUORE (2015-2020)

Projected

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

arXiv:1109.0494
CUORE-0

**first tower of CUORE installed in Cuoricino cryostat**

**PURPOSE**

validate cleaning and assembly procedures for CUORE
TeO$_2$ crystal contaminations
Cu holder surface contamination

**stand-alone 0νββ experiment**
phase I data *EPJC 74. 2956 (2014)*
Today’s result: arXiv:1504.0245
CUORE-like Detector Assembly

Gluing machine

Mechanical assembly

Gluing

Assembly

Cryostat

Storage

Tower garage

Wire bonding
Lowering Background: Crystals & Copper

Ultra-pure TeO2 crystal array

**Bulk activity** 90% C.L. upper limits:
8.4 \cdot 10^{-7} \text{ Bq/kg } (^{232}\text{Th}), 6.7 \cdot 10^{-7} \text{ Bq/kg } (^{238}\text{U}), 3.3 \cdot 10^{-6} \text{ Bq/kg } (^{210}\text{Po})

**Surface activity** 90% C.L. upper limits:
2 \cdot 10^{-9} \text{ Bq/cm}^2 (^{232}\text{Th}), 1 \cdot 10^{-8} \text{ Bq/cm}^2 (^{238}\text{U}), 1 \cdot 10^{-6} \text{ Bq/cm}^2 (^{210}\text{Po})

- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching
- Benchmarked in dedicated bolometer run at LNGS
  - Residual $^{232}\text{Th} / ^{238}\text{U}$ surface contamination of Cu: < 7 \cdot 10^{-8} \text{ Bq/cm}^2
- Validated by CUORE-0
- All parts stored underground, under nitrogen after cleaning
Tower Installation

Built in CUORE Cleanroom, transported to Cuoricino cleanroom
Data Run: 2013 – 2015

- March 2013 – March 2015
- Cryogenic maintenance between campaigns
  - 35.2 kg-yr of $^{nat}\text{TeO}_2$
  - 9.8 kg-yr of $^{130}\text{Te}$

Physics data

Calibration data

March 1, 2015
### Calibration

#### Representative CUORE-0 calibration function

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

CUORE-0 Preliminary

Data Set 2079
Channel 15

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**Energy [keV]**
- 511 keV ($e^+e^-$)
- 583 keV ($^{208}\text{Tl}$)
- 965 keV, 969 keV ($^{228}\text{Ac}$)
- 1588 keV ($^{228}\text{Ac}$)
- 1592 keV ($^{208}\text{Tl}$ double escape)
- 2104 keV ($^{208}\text{Tl}$ single escape)
- 2615 keV

**Counts / (0.5 keV)**
- 0
- 5000
- 10000
- 15000
- 20000
- 25000
- 30000
- 35000
- 40000
- 45000

**Summed calibration data**

**Projected fit**

$\gamma^{208}\text{Tl}$

CUORE-0 Preliminary
Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from $^{208}$Tl in the calibration data.

The obtained resolution is < 5 keV, which is the CUORE goal.
Energy spectra and Peak Residuals

- Two outliers are:
  - $^{60}$Co, which reconstruct at 2507±0.6 keV, 2.0±0.6 keV higher than the nominal value
  - $^{208}$Tl single-escape line, which reconstructs 0.84±0.22 w.r.t the nominal value at 2103.51 keV.
- Double escape from $^{208}$Tl at 1592 keV in line with other peaks.

- We determined a global calibration offset function, by performing a parabolic fit to the peak residual (excluding the two outliers).
- We take the standard deviation of the fit residuals (0.12 keV) as a global systematic uncertainty on the reconstructed energy.
CUORE-0 Background Measurement

- γ background (from $^{232}\text{Th}$) was not reduced since the cryostat remained the same.
- γ background (from $^{238}\text{U}$ 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.

$Q_{\beta\beta}=2528$ keV

Background paper in preparation!
Background Rate & Reduction

<table>
<thead>
<tr>
<th>Source</th>
<th>Background rate [counts/keV/kg/y]</th>
<th>signal eff. [%] (detector+cuts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0νββ region</td>
<td>α region (excl. peak)</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>0.169 ± 0.006</td>
<td>0.110 ± 0.001</td>
</tr>
<tr>
<td><strong>CUORE-0</strong></td>
<td>0.058 ± 0.011</td>
<td><strong>0.016 ± 0.001</strong></td>
</tr>
</tbody>
</table>
Blind Analysis

- 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 characterized without biasing $0\nu\beta\beta$ analysis.
Unblinded Spectrum & Fit

- Simultaneous unbinned extended ML fit to range [2470,2570] keV
- Fit function has 3 components:
  - Calibration-derived lineshape modeling posited fixed at 2527.5 keV
  - Calibration-derived lineshape modeling Co peak floated around 2505 keV
  - Continuum background
Unblinded Spectrum & Fit

Fitted background: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) counts/keV/kg/yr

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

CUORE-0 result combined with Cuoricino result from 19.75 kg-yr of $^{130}$Te exposure yields the Bayesian lower limit:

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

$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 2.7 \times 10^{24} \text{ yr}$ (90% C.L., statistics only)

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

arXiv:1504.02454
Submitted to PRL
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))
Projected CUORE Background

- **CUORE-0** - provides benchmark for remaining background with new assembly & crystal/Cu cleaning protocols
- **CUORE** - results of CUORE-0 + screening campaign results -> CUORE MC

**CUORE Preliminary**

- Near Surfaces: TeO₂
- Near Surfaces: Cu NOSV or PTFE
- Near Bulk: TeO₂
- Near Bulk: Cu NOSV
- Cosm. Activ.: TeO₂
- 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

Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from $^{238}\text{U}/^{232}\text{Th}/^{210}\text{Po}$ individually.
CUORE Sensitivity

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

arXiv:1109.0494
Beyond CUORE: $^{130}$Te Enrichment

**Enrichment**

- **Natural next step for CUORE**
  - Increase # of parent nuclei, not the detector mass (# of background events)
- $^{130}$Te enrichment is relatively cheap at $17k/kg$
  - Compared to $^{76}$Ge enrichment at $100k/kg$
- 500 gram of enriched $^{130}$Te metal is sent to SICCAS for enriched crystal growth.

\[
\begin{align*}
\beta \beta & \sim \frac{m_e}{\sqrt{F_N \cdot \epsilon \cdot \eta \sqrt{\frac{M \cdot t}{b \cdot \delta E}}}} \\
\end{align*}
\]

- $F_N$: Nuclear figure of merit: nuclear matrix element x phase space factor
- $\epsilon$: Detection efficiency
- $\eta$: Isotopic abundance
- $M$: Detector total mass [kg]
- $t$: Live time [year]
- $b$: Background [$< 0.01$ kg/keV/yr]
- $\delta E$: Energy resolution [keV]

Current gen. goal of next gen. experiments

$^{76}$Ge claim

- $^{76}$Cuoricino exclusion 90% C.L.
- $^{76}$Ge sensitivity
  - $^{136}$Xe 90% exclusion $(\text{EXO-200/KamLAND-Zen})$
  - $^{130}$Te 90% exclusion $^{130}$CUORE0+Cuoricino
- $^{76}$Ge 90% exclusion $(\text{GERDA+HDM+IGEX})$
R&D for Future Bolometric 0νββ Searches

**Increase mass** enrich in $^{130}$Te

**Reduce background**
- via particle ID
- cleaner detectors,
- tag backgrounds,
- active veto

**Explore other/multiple isotopes**

**Bolometer R&D:**
- CALDER
- Cherenkov/TeO$_2$
- LUCIFER
- LUMINEU
Beyond CUORE: Particle ID with Light Detectors

• Cherenkov light or scintillation to distinguish $\alpha$ from $\beta/\gamma$
  ($^{130}\text{TeO}_2$, $^{82}\text{ZnSe}$, $^{116}\text{CdWO}_4$, and $^{100}\text{ZnMoO}_4$)

• More rejection power needed: 99.9% $\alpha$ background suppression. Light detector R&D for better resolution.

• Background free search.

$$m_{\beta\beta} \sim (M \cdot t)^{-1/2}, \text{ not } (M \cdot t)^{-1/4}$$
Conclusions

*Neutrinoless double beta (0νββ) is the only method for probing the Majorana nature neutrinos. Observation would establish lepton number violation and physics beyond Standard Model.*

**CUORE program builds on the success of CUORICINO and predecessors**

- **CUORE-0 (2013 - 2015)**
  - confirms successful background mitigation and Cuoricino background model
  - energy resolution of < 5 keV FWHM for ROI reached
  - provides the most sensitive limit for (0νββ) in $^{130}$Te to date.

- **CUORE**
  - tower assembly is complete and cryogenic system commissioning underway.
  - Start operation in late 2015.
  - with 206 kg of $^{130}$Te and 5 keV energy resolution, is able to reach 51-133 meV effective Majorana mass.

- **Beyond CUORE**: R&D effort is underway. Large bolometers offer path towards exploring the inverted hierarchy.

*Stay tuned!*