Results from the CUORE experiment

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CUORE

- Cryogenic Underground Observatory for Rare Events
- Main objective: 0νββ in $^{130}$Te
- 988 TeO$_2$ crystals, 5x5x5 cm$^3$ each
- Total mass: 742 kg TeO$_2$ (natural Te)
- $^{130}$Te mass: 206 kg
- Crystals operated as bolometers in a cryostat capable of reaching T < 10mK
CUORE: sensitivity

\[ T_{1/2}^{0\nu}(n_\sigma) \propto \sqrt{\frac{M \cdot t}{b \cdot \Delta E}} \]

Goals

- \( \Delta E \): 5 keV FWHM @\( Q_{\beta\beta} \)
- \( b \): 0.01 counts/(keV·kg·y)
- \( t \): 5 years livetime

Median expected sensitivity:

\[ T_{1/2}^{0\nu} > 9 \times 10^{25} \text{ yr (90\% C.L.)} \]
TeO₂

- High natural isotopic abundance of source isotope (¹³⁰Te)
- ¹³⁰Te included in the detector: high efficiency
- $Q_{\beta\beta} = 2527.5$ keV, in a region with relatively low $\beta/\gamma$ background
- Excellent energy resolution (5 keV FWHM @ $Q_{\beta\beta}$)
- Reproducible growth of high quality crystals
Detector principle

- Energy deposition converted into a temperature rise: \( A \propto \frac{E}{C(T)} \)
- Need to work at extremely low temperature, as \( C(T) \propto T^3 \)
- Signal readout with an NTD Ge sensor: \( R_{NTD} \propto \exp\left( \frac{1}{T^{1/2}} \right) \)
- Heat dissipated to the Cu holder; base temperature restored in a few seconds
Material selection driven by thermal/mechanical properties and radio-purity

Special surface cleaning procedures for elements close to the detector

Shielding: 25 cm Pb @300K + 6 cm roman Pb @4K

Extremely low vibrations (suspensions)

Stable, ultra-low temperature
Detector installation

The 19 towers were completely installed in August 2016 in a specially constructed, radon-free clean room.
Detector installation

Installation of thermal and radiation shields, electronics and DAQ completed between Sep. and Nov. 2016
Pre-operation

- Gradually turned on all the 988 channels
- Optimization of the DAQ and data analysis software
- Improvement of noise, both from electronics and from vibrations (pulse tubes)
- Determination of the optimal working point for each crystal

First pulses recorded on Jan. 2017

End of commissioning in April 2017

Physics data taking started in May 2017
Calibration system

- The detector calibration system (DCS) consists of 12 strings, loaded in $^{232}\text{Th}$, that can be lowered to detector level.
- The strings are guided through tubes and positioned as to illuminate evenly all 19 towers.
- Calibrations are run at the beginning and end of each dataset.
CUORE data taking

- 86.3 kg·y exposure accumulated in summer 2017
- 99.6% active channels (994/988)
- 92% of channels pass analysis cuts
- 7.7 keV FWHM @Q-value
- 80% signal efficiency
0νββ Results

- Background index: \((1.4 \pm 0.2) \times 10^{-2}\) counts/(keV·kg·y)
- Median expected sensitivity: \(T_{1/2}^{0\nu} = 7.0 \times 10^{24}\) y
- Combined limit with CUORE-0 and CUORICINO:

\[T_{1/2}^{0\nu} > 1.5 \times 10^{25}\) y (90% C.L.)
CUORE Preliminary
Exposure: 86.3 kg yr

Background generally consistent with expectation
γ strongly reduced, α region consistent
210Po excess under investigation, irrelevant in ROI (<1%)
CUORE background model

- Full background reconstruction with a Bayesian fit
- Fit components: 60 contaminations spread across the cryostat
- Each component is simulated with a detailed Geant4 MC simulation

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<tr>
<th>Volume</th>
<th>Type</th>
<th>Components</th>
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| TeO$_2$  | Bulk              | $^{2
\nu}\beta$, $^{210}$Pb, $^{232}$Th, $^{228}$Ra-$^{208}$Pb, $^{238}$U-$^{230}$Th, $^{228}$Ra-$^{210}$Pb, $^{40}$K, $^{60}$Co, $^{125}$Sb, $^{190}$Pt |
| TeO$_2$  | Surface (0.01 µm) | $^{232}$Th, $^{228}$Ra-$^{208}$Pb, $^{238}$U-$^{230}$Th, $^{228}$Ra-$^{210}$Pb |
| TeO$_2$  | Surface (1 µm)    | $^{210}$Pb                                                                   |
| TeO$_2$  | Surface (10 µm)   | $^{210}$Pb, $^{232}$Th, $^{238}$U                                             |
| CuNOSV   | Bulk              | $^{232}$Th, $^{238}$U, $^{40}$K, $^{60}$Co, $^{54}$Mn                       |
| CuNOSV   | Surface (0.01 µm) | $^{210}$Pb                                                                   |
| CuNOSV   | Surface (1 µm)    | $^{210}$Pb, $^{232}$Th, $^{238}$U                                             |
| CuNOSV   | Surface (10 µm)   | $^{210}$Pb, $^{232}$Th, $^{238}$U                                             |
| Roman lead | Bulk         | $^{232}$Th, $^{238}$U, $^{108}$mAg                                           |
| Top lead  | Bulk              | $^{232}$Th, $^{238}$U, $^{210}$Bi                                             |
| Ext. lead | Bulk              | $^{210}$Bi                                                                   |
| CuOFE    | Bulk              | $^{232}$Th, $^{238}$U, $^{60}$Co                                             |
| External | -                 | Cosmic muons                                                                |

- Split the data according to event multiplicity
- Split the detector in two layers, outer (sensitive to cryostat contaminants) and inner (sensitive to towers)
We're able to reconstruct the main features of the observed spectra
In CUORE0, $2\nu\beta\beta$ accounted for about 10% of the events in the 1-2 MeV region...
2νββ Results

In CUORE0, 2νββ accounted for about 10% of the events in the 1-2 MeV region...

...but now, thanks to the improved background, it accounts for almost 100% of events
\[ T^{2\nu}_{1/2} = (7.9 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (syst.)}) \times 10^{20} \text{ y} \] (Preliminary)

\[ T^{2\nu}_{1/2} = (8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}) \times 10^{20} \text{ y} \] (CUORE-0)

\[ T^{2\nu}_{1/2} = (7.0 \pm 0.9 \text{ (stat.)} \pm 1.1 \text{ (syst.)}) \times 10^{20} \text{ y} \] (NEMO-3)
Summary

- With 7 weeks of data CUORE:
  - Set the most stringent limit on $0\nu\beta\beta$ half-life of $^{130}\text{Te}$ to date
  - Made the most precise measurement of $2\nu\beta\beta$ half-life of $^{130}\text{Te}$
- After a period of detector optimization, we restarted data taking in May 2017
- CUORE will continue taking data in the coming years, with an ultimate sensitivity to $0\nu\beta\beta$ half-life in $^{130}\text{Te}$ of $T_{1/2}^{0\nu} > 9 \times 10^{25}$ yr