Results from CUORE and CUORE0

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0νββ Experimental signature

- Observable: line at Q-value
  - Measure $E_{\beta\beta} = E_{\beta 1} + E_{\beta 2}$
  - Smeared by energy resolution
  - $Q$ depends on the isotope

If observed:

$$T_{1/2}^{0\nu} = \ln(2) \cdot N_{\beta\beta} \cdot \frac{t}{N_{0\nu\beta\beta}} \cdot \epsilon$$

- $N_{\beta\beta}$: num. of active nuclei
- $t$: exposure time
- $N_{0\nu\beta\beta}$: events in the peak
- $\epsilon$: efficiency
Physics Implications

- Lepton number violation $\Delta L = 2$
- $\nu = \bar{\nu}$ (some kind of Majorana mass contribution)
- $\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}(Q, Z) \left| M_{nucl}^{0\nu} \right|^2 \frac{\langle m_{\beta\beta}^2 \rangle}{m_e^2}$

- Effective Majorana mass

- Half-life (to be measured)
- Phase space (calculated)
- Nuclear matrix element (calculated)

$m_{\beta\beta} = f(\Delta m_{12}, \Delta m_{23}, m_1)$
- perhaps indications about the mass hierarchy
- constraints on absolute mass scale
Bolometric approach: $E \rightarrow \Delta T$

Source = Detector

- $2e^-$ mostly contained in the bulk
- little (no) energy escape
- excellent efficiency
- excellent energy resolution
- hardly discriminate signal from bkg

Arrangement of bolometers in 2x2 arrays

\[ \Delta T = \frac{E}{C(T)} \quad C \propto \left( \frac{T}{\theta_D} \right)^3 \]

Requires low heat capacity
low temperatures
CUORE bolometers: TeO$_2$ crystals

TeO$_2$:
- $^{130}$Te abundance = 34%
- Q = 2528.5 keV

With:
- E = 1 MeV
- C ~ $10^{-9}$ J/K at 10 mK

$\Delta T = 0.1 \frac{mK}{MeV}$
Thermistor Readout: $\Delta T \rightarrow \Delta V$

Crystals are read out by a "Neutron Transmutation Doped" Germanium thermistor (NTD)

$$R_{th} = R_0 e^{\left(\frac{T_0}{T}\right)^\gamma} = \frac{V_{th}}{I_{bias}}$$

Set $I_{bias}$ working point where signal amplitude is maximum

- Readout $\Delta V$
- Maintain a constant current

Typical signal pulse shape
Sensitivity

May be expressed as the half-life that yields a signal hidden by a fluctuation of the background:

For our detector the background approximately scales with the mass and the rate can be assumed to be constant.

Experimental parameters where improvement produces better sensitivity:

\[ S_{T_{1/2}} = n_\sigma \sqrt{B} \]

\[ B = b \cdot M_{tot} \cdot t \cdot \Delta E \]

- Isotopic abundance
- Total mass
- Exposure time
- Efficiency
- Bkg rate
- Energy resolution

31/05/2017
The CUORE phased program

Cuoricino
2003 - 08

Exp = 9.8 kg y of $^{130}$Te
Bkg = 0.058 c/(kg keV y)
$T_{1/2} > 2.7 \times 10^{24}$ y (90% CL)

CUORE-O
2013 - 15

Exp = 19.75 kg y of $^{130}$Te
Bkg = 0.169 c/(kg keV y)
$T_{1/2} > 2.8 \times 10^{24}$ y (90% CL)

CUORE
2017 -

19 towers
13 floors
4 crystals each

988 bolometers
$M = 742$ kg of TeO$_2$
206 kg of $^{130}$Te

Bkg GOAL = 0.01 c/(kg keV y)

First CUORE-like tower

Same cryostat

New cryostat

31/05/2017

Niccolò Moggi – MEDEX17
Radioactive contamination drives the Cuoricino/CUORE-0 bkg in the ROI

- $\gamma$ of $^{208}$Tl from cryostat
- decay products of $^{238}$U and $^{232}$Th from crystal and Cu surface

<table>
<thead>
<tr>
<th>$\text{c/(keV} \cdot \text{kg} \cdot \text{yr)}</th>
<th>0\nu\beta\beta \text{ region}</th>
<th>\alpha \text{ region (2700-3900 keV – Pt peak)}</th>
</tr>
</thead>
<tbody>
<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 ± 0.004</td>
<td>0.016 ± 0.001</td>
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</tbody>
</table>
Parts cleaning and storage

Copper:
1. Pre-cleaning (remove machining residuals)
2. Tumbling (mechanical abrasion \( \sim 1 \, \mu m \))
3. Electropolishing (\( \sim 100 \, \mu m \) abrasion)
4. Chemical etching (\( \sim 10 \, \mu m \))
5. Plasma etching (2 \( \mu m \))
6. Packaging in vacuum

Crystals:
1. Produced by Shanghai Institute of Ceramics
2. Grown from high purity TeO\(_2\) powder and Te metal
3. Shipped to LNGS by sea in vacuum bags + boxes
4. Stored underground in nitrogen-fluxed cabinets
Crystal gluing, bonding and tower assembly

Glove-box for tower assembly. Assembly is done inside a dedicated clean-room. Glove-box flushed with N\textsubscript{2} atmosphere.

Inside the glove-box for tower assembly.

Robotic system for semi-automated bonding.

Gluing robotic arms.
CUORE-0 results

CUORE-0 + Cuoricino $0
\beta\beta$ limit:

$$T_{1/2} > 4.0 \times 10^{24} \text{y (90\%C.L.)}$$

CUORE-0 energy resolution:

$$\Delta E = 5.1 \pm 0.3 \text{keV FWHM}$$

$m_{\beta\beta} < 270 - 760 \text{meV}$

[Physical Review Letters 115, 102502 (2015)]
CUORE0 background model

- 56 sources of background identified and ascribed to parts of the experiment
- Found contamination levels from material screening
- All sources simulated with Geant4 through the experiment → build bkg model
- Bayesian fit to the CUORE-0 spectrum with priors from screening

Excellent agreement of data with model when including $2
\nu\beta\beta$

![Graph showing excellent agreement](image-url)
CUORE-0 2νββ measure

\[ T_{1/2} = [8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \times 10^{20} \text{ y} \]

[European Physical Journal C 77, 13 (2017)]
Background estimates for CUORE

In the bkg model we can separate components by type:
- CUORE-0 = CUORE (crystals, Cu holders)
- CUORE-0 ≠ CUORE (cryo shields & Pb shield)

Shields are the largest contribution observed in CUORE-0 (~74%)
CUORE background projection

- CUORE-0 bkg rate is projected to the 988 CUORE bolometers
- We expect a lower BI in the ROI thanks to:
  - better granularity (anti-coincidence analysis)
  - self-shielding
  - new cryostat
  - more shielding

\[
1.00 \pm 0.03 \text{ (stat.)}^{+0.23}_{-0.10} \text{ (syst.)} \times 10^{-2} \frac{\text{counts}}{\text{kg} \cdot \text{keV} \cdot \text{y}}
\]

CUORE PRELIMINARY

CUORE PRELIMINARY

C/(keV·kg·yr) 0νββ region
CUORICINO 0.169 ± 0.006
CUORE-0 0.058 ± 0.004
CUORE (projection) 0.0100 ± 0.0003
We expect $\alpha$ to dominate the ROI. ("degraded" $\alpha$ from surface of near elements)

CUORE GOAL: 0.01 counts/keV/kg/y

CUORE PRELIMINARY

Projected CUORE-0 model

- Surface of TeO$_2$
- Bulk of TeO$_2$
- Cosmogenic Activation of CuNOSV elements
- Cosmogenic Activation of TeO$_2$
- Far Bulk: CuOFE elements
- Far Bulk: Roman Pb
- Far Bulk: Modern Pb
- Far Bulk: Superinsulation
- Far Bulk: Stainless steel parts
- Environmental muons
- Environmental neutrons
- Environmental gammas

CUORE GOAL: 0.01 counts/keV/kg/y

Value

90% CL limit

[ arXiv:1704:08970 ]

paper in preparation

31/05/2017

Nicolò Moggi – MEDEX17
CUORE cryostat

- T~10 mK stable
- Size ~ 1 m$^3$
- 6 stages
- Wired ~2700
- Contains Pb shields
- Radiopure material only
- Suspensions to dump vibrations
- ~15 tons cooled to 4 K

25 cm thick lead
2 cm H$_3$BO$_3$ panels
18 cm polyethylene
Cryostat commissioning

- Completed March 2016
- 6.3 mK stable base temp on ~month scale
- Successful test of DCS and DAQ
- "Mini-Tower" test: no unaccounted bkg sources

PRELIMINARY (no noise optimization)
CUORE detector installation

- Performed in a radon-free clean room
- Installation completed in August 2016
- Followed (September – November) by cable routing, electronics and DAQ tests, cryostat closure.
CUORE commissioning

- Cooldown started on Dec. 5 2017
- In April 2017 started data taking
- Working on detector optimization

- Electronic noise attenuation
- Vibration reduction
- Base temperature scan
- Working point (find $I_{\text{bias}}$ of max S/N ratio for each thermistor)
- Detector calibration
- Commissioning of analysis software

Phase I:
- fast cooling
- Cryo technical stop
- Electronic optimization stop

27.01.2017 Observation of first pulse
Detector Calibration System

- In-situ calibration with 12 $^{232}$Th $\gamma$-ray sources (239 keV to 2615 keV)
- Sources outside detector during data-taking, lowered into the cryostat for calibration runs
- Correct for variations in detector gain
CUORE expected sensitivity

Assuming \( b_{\text{kbg}} = 0.01 \text{ c/(kg keV } \gamma) \), \( \Delta E = 5 \text{ keV FWHM} \) and 5 years running

\[
S_{T_{1/2}} \propto \sqrt{\frac{M_{\text{tot}} \cdot t}{b \cdot \Delta E}} \quad S_{m_{\beta\beta}} \propto \sqrt{\frac{b \cdot \Delta E}{M_{\text{tot}} \cdot t}}
\]

\( T_{1/2} > 9.5 \times 10^{25} \text{ y (90\% C.L.)} \)

\( m_{\beta\beta} < 50 - 130 \text{ meV} \)

Axial coupling constant \( g_A = 1.269 \)

\( G^{0v} \): Phys. Rev. C 85, 034316 (2012)


CUORE R&D’s

**CUPID** = Cuore Upgrade with Particle IDentification

Please see Enzo Previtali presentation tomorrow
Conclusion

- CUORE-0
  - most stringent limit on $^{130}{\text{Te}}$ half-life
  - most precise measurement of $2\nu\beta\beta$ half-life in $^{130}{\text{Te}}$
  - validation of the CUORE assembly technology and background model

- CUORE: first $0\nu\beta\beta$ cryogenic experiment at ton-scale
  - completed installation
  - successful cooldown
  - NOW TAKING DATA: physics results soon
Backup slides
The roman lead

Lead ingots recovered from an ancient Roman ship sunk in ~50 b.c. offshore the west coast of Sardinia. 270 ingots, 33 kg cad = 7 tons (after removal of the inscriptions) Reduced content of $^{210}\text{Pb}$ due to ancient extraction technique and no cosmic activation.
With our MC background Model we can separate $\gamma$ from $\alpha$ backgrounds. $\alpha$ is $\sim$24%

In CUORE the $\gamma$ bkg is expected to drop thanks to the new cryostat so that capability to distinguish bkg due to $\alpha$ becomes crucial.

[European Physical Journal C 77, 13 (2017)]
Analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit

- General data quality cuts
- Pulse-shape cuts to reject unphysical noise pulses
- Pileup rejection on each channel: no signals 3.1s before or 4.0s after
- Tower-wide $\pm$5 ms anticoincidence cut, as 88% of $0\nu\beta\beta$ decays would be single-site events

Only two signatures distinguish events from bkgs:
1. Energy release
2. Single hit ($0\nu\beta\beta$ signal is confined in a single crystal)

$\rightarrow$ Multi-hit events are very likely background
Bayesian analysis on toy MC

- Generate $10^5$ bkg spectra based on CUORE bkg
- Fit to bkg+$0\nu\beta\beta$ model → likelihood = $P(E|T_{1/2}, H^{0\nu})$ (probability of data given the model)
- Compute the probability

$$P(T_{1/2}|E, H^{0\nu}) = \frac{P(E|T_{1/2}, H^{0\nu})\pi(T_{1/2})}{\int_0^\infty P(E|T_{1/2}, H^{0\nu})\pi(T_{1/2})dT_{1/2}}$$

- Find the $T_{1/2}$ that corresponds to the 90% quantile
- The median of the distribution of the $T_{1/2}$ values is taken to be the median sensitivity

Exclusion sensitivity $>$ Cuoricino+CUORE0 in $\sim$days

In 5 years: $T_{1/2} \sim 9 \times 10^{25}$ y (90% C.I.)

(assuming $B\ell = 0.01c/(\text{keV kg y})$ and $\Delta E = 5 \text{ keV FWHM}$)
Bayesian discovery sensitivity

Bayesian analysis on toy MC

- Generate $10^5$ bkg spectra based on CUORE bkg
- Fit to bkg+$0\nu\beta\beta$ model → likelihood = $P(E|T_{1/2},H^{0\nu})$
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(assuming $B_i = 0.01c/(keV \text{ kg y})$ and $\Delta E = 5$ keV FWHM)
We expect $\alpha$ to dominate the ROI. “Degraded” $\alpha$ from surface of near elements.

CUORE background budget in ROI - overall

Projected CUORE0 model
- $\text{TeO}_2$: natural radioactivity
- CuNOSV: natural radioactivity
- CuNOSV: cosmogenic activation
- $\text{TeO}_2$: cosmogenic activation
- CuOFE: natural radioactivity

CUORE material screening
- RomanPb: natural radioactivity
- ModernPb: natural radioactivity
- Si: natural radioactivity
- Rods and 300KFlan: natural radioactivity

LNGS fluxes
- Environmental $\mu$
- Environmental $n$
- Environmental $\gamma$

+ microphonic vibrations

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