The CUORE and CUORE-0 experiments

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Present knowledge about neutrinos

- neutrinos are massive fermions
- there are 3 active neutrino flavors ($\nu_\alpha$)
- neutrino flavor states are mixtures of mass states ($\nu_k$)

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$$

- Atmospheric / Accelerator
- Reactor / Accelerator
- Solar / Reactor

Measurements of neutrino parameters from:
- neutrino oscillations
- single beta decay
- cosmology
- neutrinoless double beta decay
Neutrinos are important probes of the Standard Model limits

0ν-ββ can give an answer to three open questions:

- Are neutrinos Dirac or Majorana particles?
- What is the absolute neutrino mass scale? mass of the lightest ν
- What is the neutrino mass hierarchy? (m1 < m2 ≪ m3 or m3 ≪ m1 < m2)

Oscillation experiments can determine the hierarchy but are blind to the other two questions
Double beta decay

\[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}\]

\(2\nu\)-DBD

- 2\text{nd} order process allowed in the SM
- observed in several nuclei with \(\tau^{2\nu} \sim 10^{19}-10^{21}\) y

\[(A, Z) \rightarrow (A, Z + 2) + 2e^-\]

\(0\nu\)-DBD (implies physics beyond SM)

- lepton number violating process
- \(\tau^{0\nu} > 10^{24}-10^{25}\) y
- exists if neutrino is a Majorana particle and \(m_\nu \neq 0\)

\(\beta\beta\) summed \(e^-\) energy spectrum
The CUORE and CUORE-0 experiments
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Thermal Detectors

• wide choice of detector materials
  low heat capacity @ $T_{\text{work}}$
• excellent energy resolution ($\sim 1\%$ FWHM)
  huge number of energy carriers (phonons)
• equal detector response for different particles
  true calorimeters
• slowness
  in rare event search doesn’t matter

\[ \Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}} \]
\[ \tau = \frac{C}{G} \]
Not really free, in many cases driven by the detector characteristics.

The advantage of thermal detectors:
first choose the isotope then build the detector having always a good energy resolution

- Isotopic abundance as high as possible
  - money issue
- Q-value as high as possible
  - background
- 2ν-DBD half-life as high as possible
  - energy resolution
Operate a huge thermal detector array in a extremely low radioactivity and low vibrations environment

- Closely packed array of 988 TeO$_2$ crystals (19 towers of 52 crystals $5\times5\times5$ cm$^3$, 0.75 kg each)
- Mass of TeO$_2$: 741 kg (~206 kg of $^{130}$Te)
- Energy resolution: 5 keV @ 2615 keV (FWHM)
- Stringent radiopurity controls on materials and assembly
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tons (lead, copper and TeO$_2$)
- Background aim: $10^{-2}$ c/keV/kg/year
- $T_{1/2}$ sensitivity in 5 years (90% C.L.): ~ $9.5 \times 10^{25}$ yr
CUORE @ LNGS

- ~3600 m.w.e. deep
- $\mu_S$: $\sim 3 \times 10^{-8}/(s \text{ cm}^2)$
- $\gamma_S$: $\sim 0.73/(s \text{ cm}^2)$
- neutrons: $4 \times 10^{-6} \text{ n/(s cm}^2)$
### Cuoricino background

The Cuoricino experiment focuses on the measurement of 0νββ decay, which is a decay process where two beta particles and two antineutrinos are emitted simultaneously. This process is of particular interest in the search for Majorana neutrinos, as it is one of the few direct methods to observe them.

#### Cuoricino final energy spectrum

- **αs + γs from 232Th in cryostat**
- **αs from TeO₂ and Cu surface contamination**
- **0νββ**

#### Background @ 0νDBD Q-value:

- $0.161 \text{ c keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$

#### Background Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>$^{208}$Tl</th>
<th>$\beta\beta(0\nu)$ region</th>
<th>3-4 MeV region</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO₂ $^{238}$U and $^{232}$Th surface contamination</td>
<td>-</td>
<td>$10 \pm 5%$</td>
<td>$20 \pm 10%$</td>
</tr>
<tr>
<td>Cu $^{238}$U and $^{232}$Th surface contamination</td>
<td>$\sim 15%$</td>
<td>$50 \pm 20%$</td>
<td>$80 \pm 10%$</td>
</tr>
<tr>
<td>$^{232}$Th contamination of cryostat Cu shields</td>
<td>$\sim 85%$</td>
<td>$30 \pm 10%$</td>
<td>-</td>
</tr>
</tbody>
</table>
From Cuoricino to CUORE

- Strict material selection
- New lighter detector design structure
- Reduced overall copper surfaces by a factor ~2
- New surface cleaning technique
- Strict production protocols for TeO$_2$ surface contamination
- Minimization of Rn exposure (N$_2$ glove box assembly)
Thermistors & Heaters coupling

Features:

- new semi-automatic system
- highly-reproducible
- fully performed under N$_2$ atmosphere to minimize radioactive recontamination.
CUORE-0 is the first tower produced out of the CUORE assembly line.

- 52 TeO\(_2\) 5x5x5 cm\(^3\) crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO\(_2\) (10.9 kg of \(^{130}\)Te)

CUORE-0 has been taking data since March 2013 in the 25 year old Cuoricino cryostat.

- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Check of the radioactive background reduction
- Sensitive 0vDBD experiment
We determined the yield of $0\nu\beta\beta$ events by performing a simultaneous UEML fit in the energy region 2470-2570 keV. The fit has 3 components:

- a peak at the Q-value of $^{130}$Te
- a peak floating around 2505 keV, attributed to the sum gamma events from $^{60}$Co in the nearby copper
- a flat continuum background, attributed to multi scatter Compton events from $^{208}$Tl and surface alpha events

Background index: $0.058 \pm 0.004$ (stat.) $\pm 0.002$ (syst.) $c$ keV$^{-1}$ kg$^{-1}$ yr$^{-1}$

$0\nu\beta\beta$ $^{130}$Te Bayesian 90% C.L. limit: $T_{1/2} > 2.7 \times 10^{24}$ yr

Exposure: 9.8 kg yr $^{130}$Te
Combining CUORE-0 and Cuoricino

- Combination of the CUORE-0 result with the existing 19.75 kg · yr of $^{130}$Te exposure from Cuoricino
- The combined 90% C.L. limit is $T_{1/2} > 4.0 \times 10^{24}$ yr.

![Graph](image_url)

Phys. Rev. Lett. 115, 102502
The combined result gives a limit on the effective Majorana neutrino mass:

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

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CUORE-0 calibration resolution

The 5 keV CUORE goal has been reached

Physics-exposure-weighted harmonic mean

<table>
<thead>
<tr>
<th></th>
<th>Average FWHM [keV]</th>
<th>RMS of FWHM [keV]</th>
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<tbody>
<tr>
<td>Cuoricino</td>
<td>5.8</td>
<td>2.1</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>4.9</td>
<td>2.9</td>
</tr>
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Distribution of energy resolution @ 2615 keV
The CUORE and CUORE-0 experiments

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CUORE-0 background

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>2600</th>
<th>2800</th>
<th>3000</th>
<th>3200</th>
<th>3400</th>
<th>3600</th>
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<td>Event Rate [counts/keV/kg/y]</td>
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<td></td>
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<td>Cuoricino</td>
<td>10^2</td>
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<td>10^0</td>
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<td>10^{-4}</td>
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<th>2.7-3.9 MeV</th>
<th>ROI</th>
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<tr>
<td>CUORE-0</td>
<td>0.016 ± 0.001</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>0.110 ± 0.001</td>
</tr>
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• ~ factor 6 reduction in the alpha continuum region
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Based on
- Cuoricino & CUORE-0 data
- HPGe, NAA and ICPMS measurements
- Montecarlo

**CUORE background budget**

![Bar chart showing background budget](chart)

- **Near Surfaces**: TeO₂
- **Near Surfaces**: Cu NOSV or PTFE
- **Near Bulk**: TeO₂
- **Near Bulk**: Cu NOSV
- **Cost. Activ.**: TeO₂ (Cosmic Activation)
- **Cosmic 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

**Bkg GOAL**: 0.01 c/keV/kg/y

Counts/ROI/ton/y

90% CL limit

- **90% CL limit**
- **Value**

Counts/ROI/ton/y
The CUORE and CUORE-0 experiments

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CUORE Towers Assembly

• Assembly of all the 19 CUORE towers completed in 2014

Assembly line improved after CUORE-0

CUORE-0
51/52 NTD connected
51/52 heaters connected

CUORE
988/988 NTD connected
988/988 heaters connected

• Also a mockup tower for the Detector installation phase and a minitower to be used during the cryostat commissioning runs were produced
Cryogenic system commissioning

Phased commissioning adding complexity at each step

- Phase I: individual systems test
  - Outer/Inner vacuum chamber
  - Cryostat
    Final temperatures:
    - 32 K at the 40K stage
    - 3.3 K at the 4K stage
  - Dilution Unit
    Lowest temperature: 4.95 mK

- Phase II: system integration
Cryogenic system commissioning: phase 2

- Cryostat + Dilution Unit
- Wiring
- Insertion of few TeO₂ detectors
- Top Pb shield
  - Detector Calibration System
  - Towers support plate
  - Fast Cooling System
- side roman Pb shield

see poster by V. Singh
CUORE: The Coldest Heart in the Known Universe

The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 8 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.
Conclusions

CUORE-0

• Achieved its energy resolution and background level objectives
• Did not find evidence of $0\nu$DBD decay.
• Indicated CUORE sensitivity goal is within reach.
• Results published by PRL
• Two additional papers in preparation (detector and background)

CUORE

• Assembly of the 19 CUORE towers is complete.
• CUORE cryostat reached base temperature of ~ 6 mK in Run 1
• The completion of the cryogenic system commissioning is close and will be followed by the detector installation
• CUORE operation expected early in 2016