The status of the CUORE experiment
Cryogenic Underground Observatory for Rare Events

Andrea Giachero

on behalf of CUORE collaboration

April 5th, 2011
Theoretical Aspects

Bolometers

CUORICINO

The CUORE Experiment

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The status of the CUORE experiment

NPA5 2011, April 5th, 2011
Nuclear Double Beta Decay (DBD)

CUORE (Cryogenic Underground Observatory for Rare Events [1, 2]) is a next generation experiment designed to search for the neutrinoless double beta decay of $^{130}\text{Te}$ using the bolometric technique.

$2\nu\beta\beta : (A, Z) \rightarrow (A.Z + 2) + 2e^- + 2\bar{\nu}_e$

- Allowed by Standard Model (second order weak transition);
- Observed for several isotopes.

$0\nu\beta\beta : (A, Z) \rightarrow (A.Z + 2) + 2e^-$

- Forbidden by Standard Model ($\Delta L = 2$);
- Allowed only for Massive Majorana neutrinos;
- Never observed.
0νββ decay rates

Experiments can measure the decay rate $\Gamma_{1/2}^{0\nu}$

$$\Gamma_{1/2}^{0\nu} = \left(\tau_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left| \langle m_\nu \rangle \right|^2,$$

where $\left| \langle m_\nu \rangle \right|^2 = \left| \sum_{i=1}^{n=3} m_i U_{ei}^2 \right|$ is the Effective Majorana Mass.

Observation of 0νββ would prove that

1. lepton number is not conserved ($\Delta L = 2$);
2. neutrinos are Massive Majorana Particles ($\nu = \bar{\nu}$).

It could also give informations on the absolute scale of neutrino masses and on the neutrino mass hierarchy (through $\left| \langle m_\nu \rangle \right|$)
0νββ in Experiments

Experimental Signature:

All the energy is shared between the 2 electrons: monochromatic line at the Q-value of the decay.

Examples ⇒ \[
\begin{align*}
130\text{Te} : & \quad E_Q = 2528 \text{ keV} \ [4, \ 5] \\
76\text{Ge} : & \quad E_Q = 2039 \text{ keV} \ [6]
\end{align*}
\]

Experimental Sensitivity \(S^{0\nu}\):

Defined as the decay time corresponding to the minimum number of detectable events above background (\(B\)).

\[
S^{0\nu} \propto \epsilon \cdot \text{i.a.} \cdot \sqrt{\frac{M \cdot \Gamma}{B \cdot \Gamma}}
\]

- Isotopic Abundance
- Detector Mass
- Live time
- Efficiency
- Background Counts
- Energy Resolution
Bolometric technique

In a bolometer the temperature rise is roughly proportional to the energy deposition ($\Delta E$) and inversely proportional to thermal capacity ($C$) of the material used as absorber [7].

Dielectric and diamagnetic crystals show a low thermal capacity in case of low temperature:

Debye Law $\Rightarrow C(T) \propto \left(\frac{T}{T_D}\right)^3$

Features

- True calorimeter (100% efficiency);
- Large detection volume;
- High intrinsic energy resolution 7 keV FWHM @ 2615 KeV.
TeO₂ Bolometers

CUORICINO/CUORE-0/CUORE use TeO₂ crystals: Source ⊆ Detector

<table>
<thead>
<tr>
<th>ββ Decay Reaction</th>
<th>Isotopic Abundance [atomic %]</th>
<th>Q-value [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁴⁸Ca→⁴⁸Ti</td>
<td>0.2</td>
<td>4274</td>
</tr>
<tr>
<td>⁷⁶Ge→⁷⁶Se</td>
<td>7.6</td>
<td>2039</td>
</tr>
<tr>
<td>⁸²Se→⁸²Kr</td>
<td>8.7</td>
<td>2996</td>
</tr>
<tr>
<td>⁹⁶Zr→⁹⁶Mo</td>
<td>2.8</td>
<td>3348</td>
</tr>
<tr>
<td>¹⁰⁰Mo→¹⁰⁰Ru</td>
<td>9.6</td>
<td>3034</td>
</tr>
<tr>
<td>¹₁⁶Cd→¹¹⁶Sn</td>
<td>7.5</td>
<td>2809</td>
</tr>
<tr>
<td>¹²⁴Sn→¹²⁴Te</td>
<td>5.8</td>
<td>2288</td>
</tr>
<tr>
<td>¹²⁸Te→¹²⁸Xe</td>
<td>31.8</td>
<td>866</td>
</tr>
<tr>
<td>¹³⁰Te→¹³⁰Xe</td>
<td>34.2</td>
<td>2528</td>
</tr>
<tr>
<td>¹³⁶Xe→¹³⁶Ba</td>
<td>8.9</td>
<td>2458</td>
</tr>
<tr>
<td>¹⁵⁰Nd→¹⁵⁰Sm</td>
<td>5.6</td>
<td>3368</td>
</tr>
</tbody>
</table>

Decay: $^{130}\text{Te} \rightarrow ^{130}\text{Xe} + e^{-}$

Why $^{130}\text{Te}$:
- high isotopic abundance: 34.2% [8] ⇒ no need for enrichment;
- Q-value (2528 keV [4, 5]) almost above the natural $\gamma$ background (>2615 eV) and below the natural $\alpha$ background (<4.01 MeV);

Why TeO₂:
- Easy to grow big crystals with low radioactive contaminations [9];
- Good mechanical properties;
- Low heat capacity (dielectric and diamagnetic).
CUORE Program

CUORICINO
2003 - 2008

CUORE-0
2011 - 2014

CUORE
2013 - 2018

1 Tower
44 + 18 = 62 crystals
≈ 11 kg of $^{130}$Te
$B = 0.153$ c/keV/kg/y

1 Tower
52 crystals
≈ 11 kg of $^{130}$Te
$B = (0.05 \div 0.18)$ c/keV/kg/y

19 Towers, 52 crystals each
988 crystals
≈ 206 kg of $^{130}$Te
$B = (0.01 \div 0.001)$ c/keV/kg/y
CUORICINO [10, 11, 12] (2003 - 2008) is still the largest bolometric experiment ever realized.

CUORICINO: 62 TeO$_2$ Crystals

- It took data form April 2003 to June 2008;
- 11 modules of 4 TeO$_2$ crystals $5 \times 5 \times 5$ cm$^3$ (790 g);
  - 2 modules of 9 TeO$_2$ crystals $3 \times 3 \times 6$ cm$^3$ (330 g);
    - 14 crystals of natural $^{130}$Te (34.2% [8])
    - 2 crystals enriched in $^{130}$Te (75% [13]);
    - 2 crystals enriched in $^{128}$Te (82.3%);
- Total mass of TeO$_2$: 40.7 kg
- Total mass of $^{130}$Te: 11.3 kg
There are two main sources of background in the region of interest (ROI: 2474÷2580 keV):

1. $\approx 70\%$: Degraded alphas from $^{238}\text{U}$ and $^{232}\text{Th}$ on copper (predominant) and crystal (minor) surfaces;

2. $\approx 30\%$: Compton events from 2615 keV peak of $^{208}\text{Tl}$, from $^{232}\text{Th}$ cryostat contamination;

The 2505 keV $^{60}\text{Co}$ peak is likely due to cosmic-ray activation of the copper;
Many of the background counts in the ROI are due to multiple-hit events.

- bulk contamination of crystals can be identified;
- surface contaminations on crystals are clearly visible;
- Multi-hit Events reduce background by 15% in the ROI.
Theoretical Aspects

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CUORICINO $0\nu\beta\beta$ results

Total exposure: 19.75 kg·y of $^{130}\text{Te}$ (big crystals alone: 15.8 kg·y of $^{130}\text{Te}$)

Energy [keV]

Counts/1keV

Background: $(0.153 \pm 0.006)$ c/keV/kg/y [18]

Lower Limit, Half-life: $\tau_{1/2}^{0\nu}(^{130}\text{Te}) > 2.8 \cdot 10^{24}$ y (90% C. L.) [18]

Upper Limit, Majorana Mass: $m_{\nu_e} < (300 \div 710)$ meV [18]

NME References

- **R(QRPA):** F. Simkovic et al., PRC 77 (2008) [14];
- **pn(QRPA):** O. Civitarese et al., JoPCS 173 (2009) [15];
- **ISM:** J. Menendez et al., NPA 818 (2009) [16];
- **IBM:** J. Barea and F. Iachello, PRC 79 (2009) [17];
The CUORE experiment

988 TeO$_2$ crystals, $5 \times 5 \times 5$ cm$^3$ (750 g), arranged in 19 towers;

741 kg of TeO$_2$ $\Rightarrow$ 600 Kg of Te $\Rightarrow$ 206 kg of $^{130}\text{Te}$ (i.e $\simeq$ 34.2% [8]);

Energy Resolution 5 keV @ 2615 keV (FWHM);

Background aim: $B = (0.01 \div 0.001)$ c/keV/kg/y.

Main concepts:

$\simeq$20 times the mass of CUORICINO;

stringent controls on radioactivity of materials and assembly;

heavy shielded (Roman lead);

high efficiency in bkg rejection [19]:

- neutron ($n$) by 30;
- muon ($\mu$) by 20;
- from crystals surfaces by 4;

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Theoretical Aspects | Bolometers | CUORICINO | The CUORE Experiment

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Gran Sasso Underground Laboratory

LNGS Environment

- **Average depth**
  \[ \bar{D} \simeq 3650 \text{ m.w.e} \] [20, 21, 22]

- **Muon Flux**
  \[ \Phi_\mu = (2.58 \pm 0.3) \cdot 10^{-8} \frac{\mu}{\text{s cm}^2} \] [22]

- **Neutron Flux**
  \[ \Phi_n \simeq 4 \cdot 10^{-6} \frac{n}{\text{s cm}^2} \] [23, 24]

- **Gamma Flux**
  \[ \Phi_\gamma \simeq 0.73 \frac{\gamma}{\text{s cm}^2} \] [25, 26]

Environmental background is not a problem
CUORE Hut

2nd Level
- Top Flange Access;
- Suspension Access;
- Electronics and DAQ;
- Counting Room;

1st Level
- Cryostat Access;
- Clean Room;

Ground Floor
- Cryostat Equipments (Pumps, Compressors)

Cryostat (Pulse Tube Assisted)

Copper Shields

External Lead Shielding (25 cm thick, 80 tons, placed on a lifting platform)
The 1000 CUORE crystals are produced by SICCAS (Shanghai, China) [9]:
- 560 crystals ordered by INFN (now @LNGS);
- 500 crystal ordered by DoE (91 already in @LNGS, end in Sept. 2012)

For each production batch 2 or more crystals are tested in the Hall C R&D Cryostat:
- Same single module as CUORE;
- New Data Acquisition and online as CUORE;
- All material cleaned CUORE-like;

6 CCVR measurements were analyzed (preliminary results):

- **Bulk**: \[
\begin{align*}
< 6 \cdot 10^{-14} \text{ g/g in } ^{238}\text{U} \\
< 8 \cdot 10^{-14} \text{ g/g in } ^{232}\text{Th}
\end{align*}
\]
  \[\Rightarrow B_{\beta\beta} < 5 \cdot 10^{-5} \text{ c/keV/kg/y}\]

- **Surface**: \[< n\text{Bq/cm}^2 \Rightarrow B_{\beta\beta} < 2 \cdot 10^{-3} \text{ c/keV/kg/y}\]

- **Resolution**: \[\langle \Delta E \rangle_{FWHM} = (4.9 \pm 1.9) \text{ keV}\]
CUORE Radioactivity test: TTT

The Three Tower Test (TTT)

- The test was done in Hall A cryostat (the same as CUORICINO);
- Crystals were dismounted from CUORICINO detector and repolished on surfaces;
- Three different types of copper cleaning were tested to evaluate the surface contribution to background:
  - **T1 Polyethylene Wrapping**: electropolishing, chemical etching, passivation and copper frames covered with 50 µm PET foil;
  - **T2 Chemical Treatment**: electropolishing, chemical etching, passivation;
  - **T3 Legnaro T.E.C.M.**: tumbling, electropolishing, chemical etching, magnetron sputtering.
T1 and T3 are compatible and show a lower background than CUORICINO

<table>
<thead>
<tr>
<th>Tower</th>
<th>2.7-3.9 MeV (excluded $^{190}$Pt line)</th>
<th>4-5 MeV ($^{238}$U/$^{232}$Th peaks)</th>
<th>5-6 MeV ($^{210}$Pb/$^{210}$Po peaks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>value</td>
<td>1σ error</td>
<td>value</td>
</tr>
<tr>
<td>T1</td>
<td>0.068</td>
<td>0.006</td>
<td>0.27</td>
</tr>
<tr>
<td>T2</td>
<td>0.120</td>
<td>0.012</td>
<td>0.36</td>
</tr>
<tr>
<td>T3</td>
<td>0.072</td>
<td>0.008</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table: Rates [c/keV/kg/y] in the α region for the Three Towers Test (TTT). With efficiency correction, no coincidence cuts are applied. The whole statistics have been used.

To be compared with CUORICINO background in the same region:

$$B = (0.136 \pm 0.001) \, \text{c/keV/kg/y}$$

The flat component that contributed for $\approx 70\%$ to CUORICINO background (and that we consider the more important source limiting CUORE background) is reduced by a factor $\approx 2$. 
### CUORE-0

- A single tower (52 TeO$_2$ crystals) realized with the same procedure of CUORE;
  - crystals from the same production line;
  - same copper and PTFE;
  - CUORE-like copper surface cleaning;
  - same assembly line;

- The tower will be installed in Hall A cryostat (the same as CUORICINO);

- Many aspects can be analyzed with CUORE-0;
  - detector performances;
  - radioactive background;

CUORE-0 will be assembled in the next months at LNGS and then put into operation before the end of the year.
Theoretical Aspects

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CUORE-0: a double beta decay experiment

Background of CUORE-0 will be produced by:
- an irriducible contribution from CUORICINO cryostat ($\simeq 0.06$ c/keV/kg/y);
- a surface contribution as observed in the TTT ($\simeq 0.06$ c/keV/kg/y).

Combining these two contributions in the ROI the CUORE-0 background is about $B \simeq 0.12$ c/keV/kg/y (in the case of CUORICINO $B = 0.153$ c/keV/kg/y [18]).

CUORE-0 will be also a new double beta decay experiment:
- $^{130}$Te mass: $\simeq 11$ kg;
- Energy resolution: $\Delta E \simeq (5 \div 6)$ keV.

In one year of live running time CUORE-0 will double the CUORICINO Limit
CUORE Scientific Goal

<table>
<thead>
<tr>
<th>Bkg [c/keV/kg/y]</th>
<th>FWHM [keV]</th>
<th>$\tau_{1/2}^{0\nu}$ @ 68% C.L.</th>
<th>$\langle m_\nu \rangle$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>5</td>
<td>$2.1 \cdot 10^{26}$</td>
<td>35 ÷ 66</td>
</tr>
<tr>
<td>0.001</td>
<td>5</td>
<td>$6.5 \cdot 10^{26}$</td>
<td>20 ÷ 38</td>
</tr>
</tbody>
</table>

After 5 years of live time, CUORE has a $1\sigma$ sensitivity of $\tau_{1/2}^{0\nu} = 1.5 \cdot 10^{26}$ y ⇒ effective Majorana neutrino mass down to $41 \div 82$ meV (bkg = $10^{-2}$ c/keV/kg/y).

- Based on our studies and knowledge we foresee for CUORE a background of 0.01 c/keV/kg/y;
- CUORE will have the capability to explore the inverse hierarchy mass region;

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Conclusion

- Observation of $0\nu\beta\beta$ decay would prove that neutrinos are Majorana particles;

- Bolometers are a powerful technique for the search of Double Beta Decay;

- CUORICINO has demonstrated the feasibility of CUORE;

- CUORE-0 will be the final test before CUORE;

- CUORE data taking is foreseen in 2013.
The status of the CUORE experiment

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References


References (cont.)


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