CUORE: a 0νββ experiment at LNGS

Overview and current status
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Outline

• Status of $\nu$ Physics and motivations for $0\nu\beta\beta$ experiments
• Neutrinoless double beta decay ($0\nu\beta\beta$) and the goal of the next generation experiments
• The bolometric approach to $0\nu\beta\beta$ search
• Results of CUORICINO experiment
• CUORE design and expected performances
Status of $\nu$ Physics

Neutrino oscillation experiments proved that neutrinos are mixed and massive

Open questions:

- Absolute mass scale and the hierarchy pattern
- Type of fermion: Dirac or a Majorana?
- $\theta_{13}$ and values of the CP phases
Status of neutrino Physics

Neutrino oscillation experiments proved that neutrinos are **mixed** and **massive**

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Motivations for \( 0\nu\beta\beta \)
Neutrinoless double beta decay

$$(N, Z) \rightarrow (N - 2, Z + 2) + 2e^-$$

- Not allowed by SM ($\Delta L = 2$)
- Claim of observation in $^{76}\text{Ge}$: $\tau = 1.2 \times 10^{25}$ y
- A part from the claim only lower limits on $\tau^{1/2}$
  - $\tau^{(76}\text{Ge}) > 1.6 \times 10^{25}$ y
- Possible only if neutrinos are Majorana particles (Schetcher, Valle Phys. Rev. D25 2951 1982)
0νββ decay and effective mass

In the (standard) hypothesis that the process is mediated by the exchange of a light Majorana ν the half-life for 0νββ is:

\[
\left( \tau_{1/2}^{0\nu\beta\beta} \right) = G(Q, Z) \left| M_{\text{nucl}} \right|^2 \left| m_{\beta\beta} \right|^2
\]

Phase space factor, ~ Q^5, can be computed exactly

Effective neutrino mass

Nuclear matrix element, main source of uncertainty when deriving \( m_{\beta\beta} \) from \( \tau \)
$0\nu\beta\beta$ and mass hierarchy patterns

$$m_{\beta\beta} = \left| \sum m_{\nu_k} U_{ek}^2 \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \vartheta_{12} + m_2 e^{2i\alpha} \sin^2 \vartheta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|$$

The results from oscillation experiments can be used to constraint $m_{\beta\beta}$ and $m_{\text{min}}$, the mass of the lightest eigenstate (Strumia-Vissani, hep/ph 0606054)
$0\nu\beta\beta$ and mass hierarchy patterns

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- Degeneracy: $m_1 \sim m_2 \sim m_3$
- Inverse hierarchy: $m_3 << m_2 \sim m_1$
- Normal hierarchy: $m_1 < m_2 << m_3$
- 1$\sigma$ errors for oscillation parameters

![Graph showing mass hierarchy patterns](image)
$0\nu\beta\beta$ and mass hierarchy patterns

\[
m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = |\cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13}|\]

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![Diagram showing the relationship between $m_{\beta\beta}$, $m_{\text{min}}$, and the oscillation parameters.](image)

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1σ errors for oscillation parameters

Disfavoured by cosmology

Effective mass $m_{\beta\beta}$ (eV)

Minimum neutrino mass $m_{\text{min}}$ (eV)
$0\nu\beta\beta$ and mass hierarchy patterns

$$m_{\beta\beta} = \left| \sum m_{\nu_k} U_{ek}^2 \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|$$

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Best values of oscillation parameters

Disfavoured by $0\nu\beta\beta$ experiments

Disfavoured by cosmology
$0\nu\beta\beta$ and mass hierarchy patterns

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- **Inverse hierarchy**: $m_3 \ll m_2 \sim m_1$
- **Normal hierarchy**: $m_1 \sim m_2 \sim m_3$
- **1σ errors for oscillation parameters**
- **Disfavoured by cosmology**
- **Next generation $0\nu\beta\beta$ experiments**
- **Disfavoured by $0\nu\beta\beta$ experiments**

Minimum neutrino mass $m_{\text{min}}$(eV) vs. effective mass $m_{\beta\beta}$(eV)
The bolometric technique

- Principles of operation
  - $\Delta T = E/C$
  - $C$ (heat capacity) low for dielectrics @ low temperatures ($T<<1\ K$) $C \sim T^3$ (Debye)
  - appreciable $\Delta T$

- Very good energy resolution
Bolometric approach: signature

- $2\nu\beta\beta$ with maximum at $E \approx 1/3 \, Q$: uneliminable background

- $0\nu\beta\beta$ peak at $Q_{\beta\beta} = M_f - M_i$
  - $M_{\text{nuc}} \gg m_e$
    - nuclear recoil can be neglected
    - peak width due only to detector finite resolution
  \[ \delta = \frac{\Delta E_{FWMH}}{Q_{\beta\beta}} \]
  \[ S \approx \frac{m_e}{7Q_{\beta\beta}} \]
  \[ T_{1/2}^{2\nu} \approx T_{1/2}^{0\nu} \]

- A good energy resolution is fundamental!

Measured: sum of electrons kinetic energy

$A_{0\nu} = A_{2\nu}/100$

sum electron energy / Q
Why $^{130}$Te?

- One of the nuclei for which $\beta$ decay is forbidden ($^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{136}$Xe, $^{150}$Nd).
- High \textit{transition energy}: $Q_{\beta\beta} = 2530 \pm 1.9 \text{ keV}$
  - Low background region (highest natural $\gamma$ line: 2615 keV $^{208}$Tl)
  - Few counts from $2\nu\beta\beta$
- High \textit{natural isotopic abundance}: $\eta = 33.87\%$

Isotopic abundance (%)

Transition energy (MeV)

$0\nu\beta\beta$ half-life (y) for $m_{\beta\beta} = 0.1 \text{ eV}$(different nuclear matrix elements)
**Sensitivity of a 0νββ experiment**

**Sensitivity**: half life corresponding to the minimal number of detectable events above the background, for a given C.L.

With the calorimetric approach, pursued either by $^{76}\text{Ge}$ diodes or by bolometers, highest sensitivities have been achieved.
CUORE at LNGS

Underground National Laboratory of Gran Sasso
L'Aquila – ITALY

3500 m.w.e. shield against cosmic rays
CUORE at LNGS

3500 m.w.e. shield against cosmic rays

Cuoricino (Hall A)

CUORE R&D (Hall C)

Underground National Laboratory of Gran Sasso
L'Aquila – ITALY
The prototype: Cuoricino

Cuoricino tower: 62 TeO$_2$ crystals

- mixing chamber $T \approx 6$ mK
- Active mass:
  - TeO$_2$ 40.7 kg
  - $^{130}$Te 14.1 kg

roman Pb shielding (1 cm lateral)
- external shields:
  - 10 cm Pb + 10 cm low act Pb
  - neutron shield: B-polyethylene
  - nitrogen flushed anti-radon box
  - Faraday cage
Cuoricino performances: resolution

232Th $\gamma$-source external to the cryostat: 3 days measurement every month

FWHM at 2615 keV $^{208}$Tl $\gamma$-line
- 5x5x5 cm$^3$ crystals: $7.5 \pm 2.9$ keV
- 3x3x6 cm$^3$ crystals: $9.6 \pm 3.5$ keV
Cuoricino performances: background

**γ region**, dominated by γ and β events. Highest γ line: 2615 keV $^{208}$Tl (from $^{232}$Th chain)

**α region**, dominated by α peaks (internal or surface contamination): $E_{\text{int}} = E_\alpha + E_{\text{rec}}$ $E_{\text{surf}} = E_\alpha - \Delta$

*in the 0νββ region: $0.18 \pm 0.01 \text{ c/keV/kg/γ}$*
Cuoricino results

- Total exposure: \(8.38 \text{ kg }^{130}\text{Te}\cdot\text{y}\)
- Detector efficiency: 86.4%
- Fit in the 2475-2550 keV region
- Flat bkgd + 2505 keV peak
- Peak shape = N gaussians

\[\tau_{1/2}^{0\nu\beta\beta} > 2.4 \cdot 10^{24} \text{ y} \quad @ \quad 90\% \text{ CL} \quad \Rightarrow \quad m_{\beta\beta} < [0.18 \div 0.95] \text{eV}\]

Various NME calculations:
- Staudt, Kuo & Klapdor-Kleingrothaus, PRC 46 871 (1992)
Cuore setup

- 988 TeO$_2$ crystals
- 19 towers of 52 crystals each
- 741 kg TeO$_2$
- 203 kg $^{130}$Te

19 times Cuoricino
Cuore setup

- **TeO₂ detectors**
- **Lead shields**
- **Thermal shields**

Single dilution refrigerator: ~ 10 mK
Cuore expected performances

- Minimum neutrino mass: $m_{\text{min}}$ (eV)
- Effective mass: $m_{\beta\beta}$ (eV)
- Degeneracy: $m_1 \sim m_2 \sim m_3$
- Inverse hierarchy: $m_3 \ll m_2 \sim m_1$
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Diagram showing the expected performances of the Cuore experiment with regions for inverse and normal hierarchies, and degenerate cases.

Disfavoured by cosmology.
Cuore expected performances

Possible evidence (best value 0.39 eV) (with the same matrix element the Cuoricino limit is 0.53 eV)

degeneracy: $m_1 \sim m_2 \sim m_3$

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Present Cuoricino result

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minimum neutrino mass $m_{\text{min}}$ (eV)

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\[ T_{\text{meas}} = 5 \text{ y} \]

<table>
<thead>
<tr>
<th>( B(\text{c/keV/kg/y}) )</th>
<th>( \Delta E(\text{keV}) )</th>
<th>( \tau_{1/2}(\text{y}) )</th>
<th>( m_{\beta\beta}(\text{meV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-2} )</td>
<td>5</td>
<td>( 2.1 \cdot 10^{26} )</td>
<td>19-100</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>5</td>
<td>( 6.5 \cdot 10^{26} )</td>
<td>11-57</td>
</tr>
</tbody>
</table>
Background reduction

- **Cuoricino** bkgd \((0\nu\beta\beta) = 0.18\text{ c/keV/kg/y}\) (main contributions from contaminations in the construction materials)
  
  1. Cryostat internal Cu shields (bulk) - 0.072 c/keV/kg/y
  2. TeO\(_2\) surfaces – 0.018 c/keV/kg/y
  3. Cu surfaces – 0.09 c/keV/kg/y
     negligible contribution from neutrons

- **CUORE** bkgd \((0\nu\beta\beta) = 0.01\text{ c/keV/kg/y}\)
  
  cleaner Cu shields and a thicker internal Pb shield reduces (1) to 0.004 c/keV/kg/y
  etching and polishing crystals reduces (2) to 0.004 c/keV/kg/y
  clean or wrap Cu surfaces reduces (3) to 0.034 c/keV/kg/y
  reduce Cu surface area by ~ 2 reduces (3) to 0.017 c/keV/kg/y
  Total bkgd \(\sim 2.5 \times 10^{-2}\) c/keV/kg/y

- Still a factor 2.5 to go
  - Most experimental efforts are now focused on the reduction of surface impurities
Conclusions

• Whether neutrinos are Dirac or Majorana particles is a fundamental question we need to answer.

• $0\nu\beta\beta$ might be the only chance to probe the absolute neutrino mass scale.

• Cuoricino, the most sensitive running $0\nu\beta\beta$ decay experiment proved the feasibility of CUORE.

• CUORE hut construction has already started.

• DOE CD-I scheduled for the fall of 2007.

• Intense R&D activity to reduce the background and optimize the construction.

• Data taking is scheduled to start in 2011.