First Cuoricino results and the CUORE project

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on behalf of the CUORE collaboration

Outline

1. From Mi-DBD to CUORICINO and CUORE
2. The CUORE project
3. CUORICINO
4. CUORICINO construction
5. CUORICINO detector performances
6. CUORICINO background
7. CUORICINO results
8. perspectives for CUORE
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From Mi-DBD to CUORICINO and CUORE

**Omogeneous (source = detector)**
approach with bolometers

- Wide choice of materials
- Detectors with an energy resolution comparable with that of Ge diodes

$^{130}$Te nice features

- High natural isotopic abundance (i.a. = 33.87 %)
- High transition energy ($Q = (2528.8 \pm 1.3) \text{ keV}$)
- Encouraging theoretical calculations for $0\nu$-DBD lifetime
- Already observed with geo-chemical techniques ($\tau = (0.7 - 2.7) \times 10^{21}$ yr)

Excellent feature for future reasonable-cost expansion of Double Beta Decay experiments

Large phase space, lower background (clean window between full energy Compton edge of $^{208}$Tl photons)

$\text{m}_{\text{ee}} \approx 0.1 \text{ eV} \iff \tau \approx 1\text{C}$

Study new DBD candidates
Low Temperature Detectors (LTD's)

Temperature signal: \( \Delta T = \frac{E}{C} \approx 0.1 \text{ mK} \) for \( E = 1 \text{ MeV} \)

Bias: \( I \approx 0.1 \text{ nA} \) \( \Rightarrow \) Joule power \( \approx 1 \text{ pW} \) \( \Rightarrow \) Temperature rise \( \approx 0.25 \text{ mK} \)

Voltage signal: \( \Delta V = I \times \frac{dR}{dT} \times \Delta T \Rightarrow \Delta V = 1 \text{ mV} \) for \( E = 1 \text{ MeV} \)

Signal recovery time: \( \tau = \frac{C}{G} \approx 0.5 \text{ s} \)

Noise over signal bandwidth (a few Hz): \( V_{\text{rms}} = 0.2 \mu \text{V} \)

Energy resolution (FWHM): \( 1 \text{ keV} \)

Te dominates in mass the compound
Excellent mechanical and thermal properties

Energy absorber
TeO\(_2\) crystal
\( C \approx 2 \text{ nJ/K} \approx 1 \text{ MeV / 0.1 mK} \)

Heat sink
\( T \approx 10 \text{ mK} \)

Thermal coupling
\( G \approx 4 \text{ nW / K} = 4 \text{ pW / mK} \)

Thermometer
NTD Ge-thermistor
\( R \approx 100 \text{ M\Omega} \)
\( \frac{dR}{dT} \approx 100 \text{ k\Omega/\muK} \)

Calorimetric approach
Good energy resolution
No limit to material choice

In real life signal about a factor 2 - 3 smaller

Te dominates in mass the compound
Excellent mechanical and thermal properties

Energy absorber
TeO\(_2\) crystal
\( C \approx 2 \text{ nJ/K} \approx 1 \text{ MeV / 0.1 mK} \)

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Thermal coupling
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Thermometer
NTD Ge-thermistor
\( R \approx 100 \text{ M\Omega} \)
\( \frac{dR}{dT} \approx 100 \text{ k\Omega/\muK} \)
From Mi-DBD to CUORICINO and CUORE

1990: the first $\text{TeO}_2$ bolometer
1993: the first experiment with a 334 g $\text{TeO}_2$ detector
1997: the 20 (340 g) crystal array (Mi-DBD I)
1998-2002: tests on 750 g $\text{TeO}_2$ crystals

2001: the 20 crystal array is rebuild with a new structure and with cleaner materials (Mi-DBD II)

FWHM 15 keV
$(0.33 \pm 0.11) \text{ c/keV/kg/y}$
$\tau_{1/2} > 2.1 \times 10^{23} \text{ y at 90\% C.L}$
The Mi DBD - II: experimental set-up

... a general test for the CUORICINO set-up

5 modules, 4 detector each
(3x3x6 cm³ TeO₂ crystals, 340 g)
are arranged in a tower-like compact structure (6.8 kg)

the tower is mounted inside
a dilution refrigerator

the tower is surrounded by
an inner Roman lead shield,

and all the refrigerator
by a 20 cm thick outer lead shield + borated PET shield
Mi DBD: limits on $0\nu$DBD

Total statistics:
4.3 kg y

$\text{Bkg} \sim 0.3 \text{ c/keV/kg/y}$

$\tau > 2.08 \times 10^{23} \text{ y} @ 90\% \text{ c.l.}$

$\langle m_\nu \rangle < 1.09 - 2.64 \text{ eV}$

DBD Q-value
CUORE is an array of \(~1000\) bolometers

\[0.75 \text{ kg} \times 1000 = 750 \text{ kg TeO}_2\]

\[= 600 \text{ kg Te} = 203 \text{ kg}^{130}\text{Te}\]

crystals are grouped in 250 modules of 4 crystals each, the modules are arranged in 25 towers assembled in a 5x5 matrix

bolometers placed (in a single dilution refrigerator at \(~10\) mK) as close possible with a minimum amount of material among them

**A SINGLE HIGH GRANULARITY DETECTOR**
a 4-crystal unit ("plane") is a mechanically independent module made of 4 crystals

Various 4-crystal planes have been tested with good results on both reproducibility and reliability (... before CUORICINO)

Energy resolution $\sim 1$ keV at threshold
$\sim 5 - 10$ keV at 3 MeV

nuclear recoil quenching factor $\sim 1$
TheCUORE detector

The tower ...

A tower contains 10 modules, as in the case of the 4-crystal modules also towers are independent structures.

A single tower of CUORE has been already built and is installed in Hall A.

The array

The 25 towers are organized in a square structure (a 5x5 matrix), the towers will be suspended from a large square copper plate suspended with a vertical spring.
The CUORE experimental set-up

The CUORE array:

- closed inside a cubic copper box
- surrounded by 3 cm of **roman lead**
- an additional 20 cm layer of **low activity lead** will be used to shield the array from the refrigerator dilution unit
- a **lead shield** and a **borated PET neutron shield** will surround completely the cryostat
CUORICINO

44 TeO$_2$ crystals 5x5x5 cm$^3$ + 18 TeO$_2$ crystals 3x3x6 cm$^3$

array with a tower-like structure similar to the single tower of CUORE
(the only difference is that it contains 2 planes of 3x3x6 crystals)

mounted inside the Hall A refrigerator
where the Mi-DBD 20 array worked

CUORICINO is a self-consistent experiment
and will give significant results concerning
Double Beta Decay and Dark Matter
CUORE experiment will be installed in the 
Underground National Laboratory of Gran Sasso
L'Aquila – ITALY

the mountain providing a 3500 m.w.e. shield against cosmic rays

Two dilution refrigerators: Hall A (CUORICINO) Hall C (R&D final tests for CUORE)
CUORICINO setup

CUORICINO (and all previous experiments) is carried out in the cryostat located in hall A of Gran Sasso National Laboratory.
CUORICINO (2)

11 modules, 4 detector each, crystal dimension 5x5x5 cm$^3$ crystal mass 790 g

\[ 4 \times 11 \times 0.79 = 34.76 \text{ kg of TeO}_2 \]

This detector is completely surrounded by active materials. substantial improvement in BKG reduction

2 modules, 9 detector each, crystal dimension 3x3x6 cm$^3$ crystal mass 330 g

\[ 9 \times 2 \times 0.33 = 5.94 \text{ kg of TeO}_2 \]

CUORICINO TOTAL ACTIVE MASS = 40.7 kg of TeO$_2$
Assembling the detectors

All operations done in nitrogen atmosphere
Assembling the tower

Almost completely done in nitrogen atmosphere
The CUORICINO Tower
CUORICINO: inner shield and suspension
CUORICINO: Final Assembly
CUORICINO results/statistics

Cool down: february 2003

Detectors: some electrical connection were lost during the cooling of the tower, as a result some detectors cannot be read-out (to recover the electrical connections it is necessary to warm up the cryostat)

4x11 = 44 large size crystals (~5x5x5 cm\(^3\) av. mass = 790 g) 32 working
9x2 = 18 small size crystals (~3x3x6 cm\(^3\) av. mass = 330 g) 16 working

Active mass during this run: 10.4 kg \(^{130}\)Te

\[
\begin{align*}
32 \times 0.790 &= 25.28 \text{ kg} \\
12 \times 0.330 &= 3.96 \text{ kg} \\
\end{align*}
\]
\[
29.24 \text{ kg} = 9.9 \text{ kg} \^{130}\text{Te} - 72\%
\]

\[
\begin{align*}
2 \times ^{130}\text{Te-enriched} \times 0.330 &= 0.660 \text{ kg} = 0.495 \text{ kg} \^{130}\text{Te} \\
2 \times ^{128}\text{Te-enriched} \times 0.330 &= 0.660 \text{ kg} = 0.543 \text{ kg} \^{128}\text{Te} \\
\end{align*}
\]

Start date: 19 April 2003
Stop date: 23 June 2003

Live time: 72%
Background measurement: 57% (891.27 h)
Detector performances: pulse height

average pulse height for 5x5x5 crystals = 340 $\mu$V/MeV
average pulse height for 3x3x6 crystals = 440 $\mu$V/MeV

Pulse height distribution $\mu$V/MeV (normalized to 1 kg of TeO$_2$)
Detector performances: energy resolution

FWHM [keV] of the 2615 keV gamma line of $^{208}$Tl (calibration with a $^{232}$Th source ~ 3 days)

average 5x5x5 cm$^3$ crystals ~ 7 keV
average 3x3x6 cm$^3$ crystals ~ 9 keV
$^{232}$Th calibration: 5x5x5 cm$^3$ crystals

- 2615 keV $^{208}$Tl
- Single escape $^{208}$Tl
- Double escape $^{208}$Tl
CUORICINO background

- CUORICINO
- Mi-DBD II
### Observed γ lines

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>123mTe + 127mTe</td>
<td>1.85E-003</td>
<td>1.16E-003</td>
<td>9.17E-003</td>
<td>2.43E-003</td>
<td>1.91E-001</td>
<td>8.04E-003</td>
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<td>122</td>
<td>57Co</td>
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<td>1.16E-003</td>
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<td>145</td>
<td>125mTe</td>
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<td>1.07E-003</td>
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<td>123mTe</td>
<td>8.25E-002</td>
<td>6.17E-003</td>
<td>6.39E-003</td>
<td>1.07E-003</td>
<td>5.36E-003</td>
<td>9.13E-004</td>
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<td>351</td>
<td>214Pb</td>
<td>4.93E-003</td>
<td>8.94E-004</td>
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<td>3.79E-003</td>
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<tr>
<td>568</td>
<td>207Bi</td>
<td>5.98E-003</td>
<td>5.91E-004</td>
<td>&lt; 4E-3</td>
<td></td>
<td>1.17E-002</td>
<td>9.18E-004</td>
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<td>835</td>
<td>54Mn</td>
<td>9.95E-004</td>
<td>3.03E-004</td>
<td>5.80E-003</td>
<td>1.68E-003</td>
<td>5.14E-003</td>
<td>7.96E-004</td>
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<td>911</td>
<td>228Ac</td>
<td>4.71E-003</td>
<td>4.32E-004</td>
<td>&lt; 2.3E-3</td>
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<td>3.27E-003</td>
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<td>1060</td>
<td>207Bi</td>
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<td>1120</td>
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<td>1173</td>
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<td>9.18E-004</td>
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<td>60Co</td>
<td>7.51E-003</td>
<td>6.49E-004</td>
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<td>1.51E-002</td>
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<td>5.98E-003</td>
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<td>3.17E-002</td>
<td>1.18E-003</td>
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<td>2615</td>
<td>208Tl</td>
<td>5.06E-003</td>
<td>4.61E-004</td>
<td>1.68E-003</td>
<td>7.45E-004</td>
<td>6.97E-003</td>
<td>5.43E-004</td>
</tr>
</tbody>
</table>

**Gamma peaks** of $^{60}$Co, $^{40}$K, $^{208}$Tl have a higher intensity in CUORICINO but the internal roman lead shield has a lateral thickness much reduced (2 cm less).

**Copper activation gamma lines** have a higher intensity in CUORICINO (more copper between the roman lead shield and the tower)

**Tellurium activation gamma lines** have a smaller intensity in CUORICINO

**Amount of internal roman lead shield:**
- **Array OLD:** 1 cm (600 mK) + 10 cm above the tower
- **Array NEW:** 2 cm (50 mK) + 10 cm above the tower
Hard to see it in the 20 crystal array; the background was higher; the peak...

2505 keV line: $^{60}$Co

2505 keV counting rate: $(0.28 \pm 0.13) \times 10^{-3}$ c/h
2505 keV line: $^{60}$Co MC simulations

Spectra normalized at the 1173 keV line

- Measured spectrum
- Contamination of Co60 in the crystal's bulk
- Contamination of Co60 in the copper box's bulk

Main contribution from crystals bulk excluded
Good agreement with a bulk contamination of the copper (c.r. activation)
CUORICINO: Alpha region

Heater lines

- Array new
- Cuoricino

3250keV
3250 keV line: $^{190}\text{Pt}$

Alpha decay from $^{190}\text{Pt}$ to $^{186}\text{Os}(6.5 \times 10^{11} \text{ y})$: $E_{\alpha} + E_{\text{nuclear recoil}} = Q = ...

The crystals were grown in a Pt crucible!!!
We have identified 4 possible sources for the residual BKG in the DBD region:

- Neutrons
- Degraded alphas from TeO$_2$ surface
- Degraded alphas from Cu frame and plate surface
- Energy degraded 2615 keV environmental photons

Excluded @ MiDBD & CUORICINO level since adding B-polyethilene shield had no effect.

The alpha continuum extends down to the DBD region.

A Montecarlo simulation shows that the alpha BKG is determined mainly by a superficial contamination of U-Th in Cu plates and frames. This contamination explains the alpha region BKG, the DBD region BKG and the $^{208}$Tl peak.

Experimental spectrum

Montecarlo

Straight lines correspond to full energy shared by two detectors.

Coincidences between adjacent detectors show that crystal surfaces emit alphas belonging to $^{238}$U and $^{232}$Th series. Crystal contamination determines peaks more than continuum.
Evidence for contributions to the BKG in the DBD region from degraded alpha particles (*surface effect*):

Clear correlation between:

- BKG in the DBD region ⇔ BKG in the region 3-4 MeV

<table>
<thead>
<tr>
<th>Energy Range (keV)</th>
<th>Mi DBD - I</th>
<th>Mi DBD - II</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500-2556 keV</td>
<td>0.59±0.06</td>
<td>0.33±0.11</td>
</tr>
<tr>
<td>3000-4000 keV</td>
<td>0.66±0.01</td>
<td>0.27±0.03</td>
</tr>
</tbody>
</table>

free from alpha and gamma peaks
Experiment/Montecarlo comparison:
- reliability
- quantitative contributions from different sources

Reliable estimate of experimental sensitivity

GEANT4

Mi DBD I
Mi DBD II
Cuoricino
Cuore

Counts

Experimental

MC: bulk
Mounting box
Crystals

MC: Surface
(crystals+mounting box)

Energy (keV)
Background: MC estimates

Geant4
Gendec

Mibeta I

3x3x6 TeO$_2$ crystals

CUORE

Mibeta II

5x5x5 TeO$_2$ crystals
Background: MC estimates (2)

Cryostat, shields and detector details
Background: MiDBD II vs CUORICINO

<table>
<thead>
<tr>
<th>Energy range [keV]</th>
<th>MiDBD</th>
<th>Cuoricino 5x5x5</th>
<th>Cuoricino 3x3x6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2470-2585</td>
<td>4.03e-01 +/- 8.80e-02</td>
<td>2.46e-01 +/- 3.07e-02</td>
<td>2.58e-01 +/- 9.75e-02</td>
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<tr>
<td>2750-3250</td>
<td>2.21e-01 +/- 3.12e-02</td>
<td>1.08e-01 +/- 9.75e-03</td>
<td>1.61e-01 +/- 3.69e-02</td>
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<tr>
<td>3450-3900</td>
<td>2.31e-01 +/- 3.36e-02</td>
<td>1.39e-01 +/- 1.17e-02</td>
<td>1.79e-01 +/- 4.10e-02</td>
</tr>
<tr>
<td>3000-4000</td>
<td>2.80e-01 +/- 2.49e-02</td>
<td>2.16e-01 +/- 9.77e-03</td>
<td>2.37e-01 +/- 3.17e-02</td>
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<tr>
<td>4000-5000</td>
<td>1.83e+00 +/- 6.35e-02</td>
<td>5.52e-01 +/- 1.56e-02</td>
<td>8.05e-01 +/- 5.84e-02</td>
</tr>
</tbody>
</table>

- **Continuous background** in the 3-4 MeV region (cutting off the 3.3MeV peak) is reduced
  - cleaning operation of the copper surfaces
- **Alpha peaks** due to surface contamination of the crystals are reduced
  - cleaning operation of the TeO₂ crystal surfaces

Is the flat continuum actually due to the Copper surface contamination?

Comparison between the central and the lateral 3x3x6 crystals, but we need more statistics.
CUORICINO: new limits on $^{130}$Te $bb(0n)$

anticoincidence spectrum, only 5x5x5 crystals,
19846 h x kg
$\tau_{1/2} > 5 \times 10^{23}$ years at 90% C.L.
CUORICINO: $m_{\text{ee}}$ lower limits

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$T_{1/2}(m = 50 \text{ meV}) \ [10^{26} \text{ years}]$</th>
<th>$m_\nu$ l.l. CUORIC</th>
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<tr>
<td>Engel et al. (1988)</td>
<td>2.72</td>
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<td>Engel et al. (1989)</td>
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<td>Barbero et al. (1999)</td>
<td>1.4</td>
<td>0.84</td>
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<td>Klapdor-Kleingrothaus and Stoica (2001)</td>
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<td>1.45</td>
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<td>Staudt, Muto and Klapdor-Kleingrothaus (1990)</td>
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<td>1.0</td>
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<tr>
<td>Pantis, Vergados, Simkovic and Faessler (1996)</td>
<td>3.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Faessler and Simkovic (2001)</td>
<td>5.68</td>
<td>1.7</td>
</tr>
</tbody>
</table>
2480-2600 keV (ββ $^{130}$Te transition energy = 2528.8 keV) anticoincidence spectrum, only 5x5x5 crystals

\[ b = 0.23 \pm 0.04 \text{ c/keV/kg/y} \]

3 year sensitivity CUORICINO (full mass): b=0.23 G=8 keV

\[ F^{0\nu}_{\text{3 years}} = 1 \times 10^{25} \quad \langle m_\nu \rangle \sim 0.15 - 0.38 \text{ eV} \]
CUORICINO:

- **apparatus**: proves the feasibility of a large bolometric array with the tower-like structure.
- **detectors**: shows that detector performances are not affected by the increase in crystal size (from 340 g to 790 g).

CUORE:

- **apparatus**: it will contain 25 towers similar to the CUORICINO one, R&D will be dedicated to cryostat and mechanical apparatus design.
- **detectors**: R&D to guarantee detector reproducibility and uniformity (pulse shape and resolution).
CUORICINO:

- **background achievements**: MiDBD-II was used as a test bench to verify surface cleaning techniques, the improvement in bkg obtained in Cuoricino (despite the reduced shield) proves the reproducibility of cleaning and handling procedures.

- **background study**: Cuoricino data will be used to further study bkg sources in view of Cuore.
a completely new set-up will allow the optimization of shielding

CUORE is specifically designed to reduce as far as possible amount of materials interposed between the crystals.

the high granularity of the CUORE detector will allow to use high efficiency the coincidence/anticoincidence technique to identify and reject background events

the real challenge of CUORE will be the control and reduction of background

only low radioactivity materials will be employed to build the refrigerator and entire mechanical set up for CUORE

special techniques for surface cleaning will be applied.
MC simulation for BKG contributions:

- **Bulk contamination** is not a problem \(< 0.004 \text{ counts/keV/kg/y}\)

  *MC simulation with MEASURED 90% upper limits on material contaminations*

- **Surface contamination** from passive materials is potentially dangerous, but there will be the possibility to reduce by a factor 10 -100 the amount of Cu facing the detector and/or improve the materials surface treatment \(~ 0.01 – 0.001 \text{ counts/keV/kg/y}~\)

- **Environmental radioactivity** contribution is reduced to a minimum thanks to the lead and neutron shields

- **Cosmogenic** activation of Cu and Te will be reduced to a minimum by the underground storage of materials

- **Two neutrino double beta decay** contribution \(< 0.0001 \text{ counts/keV/kg/y}\)
CUORE $\beta\beta$ sensitivity

$0\nu$ sensitivity

\[ 0\nu \text{ sensitivity} = \ln 2 \, N_A \frac{a.i.}{A} \sqrt{\frac{M t}{b \Gamma}} \epsilon = 2.1 \times 10^{25} \sqrt{\frac{t}{b \Gamma}} \]

Pessimistic estimation: $b = 0.01 - \Gamma = 5$ keV

\[ F^{0\nu} = 9.4 \times 10^{25} \times (T[y])^{1/2} \]

\[ m_{ee} < 49 - 124 \text{ meV} \times (T[y])^{1/4} \]

(33-83 meV in 5 years)

Optimistic estimation: $b = 0.001 - \Gamma = 5$ keV

\[ F^{0\nu} = 2.96 \times 10^{26} \times (T[y])^{1/2} \]

\[ m_{ee} < 27 - 70 \text{ meV} \times (T[y])^{1/4} \]
Long term stability:
  • Cryogenics
  • Detector optimization

Large number of detectors:
  • reproducibility
  • read-out & calibration

Background suppression:
  • materials selection
    • setup materials
    • cleaning/preparation materials
  • surface treatment improvement
  • radiation shields improvement
### CUORE Tentative Time Schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
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<tbody>
<tr>
<td><strong>Proposal</strong></td>
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<tr>
<td><strong>Detector</strong></td>
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<tr>
<td>Crystals</td>
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<tr>
<td>Materials selection</td>
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<tr>
<td>Procedures settling</td>
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<tr>
<td>Growth/Preparation</td>
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<tr>
<td>Sample test</td>
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<tr>
<td>(technical + radiopurity)</td>
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<td>Thermistors &amp; heaters</td>
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<td>Design</td>
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<tr>
<td>Order &amp; construction</td>
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<td>Installation and test</td>
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<td>Item</td>
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Conclusions

- CUORICINO is running (February 2003)
- Some channels lost during cool down of the detector
- Energy resolution is good and even better than in MiDBD
- Efforts to lower energy threshold are in progress
- Background shows a reduction in $\alpha$ energy region
- Background at low energy is comparable with MiDBD
- Background in DBD energy region in good agreement with expectations
- New (improved) limit on neutrinoless DBD of $^{130}$Te and $m_{ee}$
- Future:
  - New setup to solve wiring problem
  - Reduction of energy threshold at level of MiDBD (DM)
  - Complete definition of the CUORE project
  - Formal CUORE proposal
  - Start of the required CUORE R&D
CUORICINO: criostat & wiring
CUORICINO: thermistors and heaters
CUORICINO: anti-Rn

Lapping machine

Gluing box
CUORICINO: 4 crystal plane

Copper surface treatment

TeO$_2$ crystal surface treatment

New improved mounting design