The search of neutrinoless double decay with the CUORE experiment

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on behalf of the CUORE collaboration
Outline

• Bolometric technique for neutrinoless double-beta decay ($\beta\beta 0\nu$)

• Update of Cuoricino results

• From Cuoricino to CUORE
• Background reduction
• Energy calibration system

• Present status and future of CUORE
Calorimetric approach to $\beta\beta 0\nu$

- Several different techniques are being used to search for $\beta\beta 0\nu$
- Calorimetric approach
  - source $\subseteq$ detector
  - large masses
  - all energy measured
  - no event topology

\[\beta\beta 0\nu : (A, Z) \rightarrow (A, Z+2) + 2e^-\]
Bolometric technique

Operated as perfect calorimeters: all energy converted into phonons

\[ \Delta T = \frac{E}{C} \]
\[ \tau = \frac{C}{G} \]

Properties:

- ☺ high energy resolution
- ☀ large choice of absorber materials
- ☹️ only energy and time information
- ☹️ slow response time

Sample bolometer pulse

Deposited energy

Heat sink \(~ 10 \text{ mK}\)

Temperature sensor

Absorber crystal

Thermal coupling

Complete and instantaneous thermalization

Temperatures \(~ 10 \text{ mK}\)

Dielectric and diamagnetic materials

0
0.5
1
1.5
2
2.5
3
3.5
4

0
0.5
1
1.5
2
2.5
3
3.5
4

Time [s]

Arbitrary unit

Unit of arbitrary unit
**TeO$_2$ bolometers**

**Absorber crystal**

The absorber is a 5x5x5 cm$^3$ (790 g) crystal of TeO$_2$ which contains the $\beta\beta 0\nu$ candidate $^{130}$Te.

**Temperature sensor**

The thermal signal is measured by means of an NTD Ge Thermistor

$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

An electrical read-out converts resistance changes into voltage pulses.
Properties of $^{130}$Te

Among the possible $\beta\beta 0\nu$ candidates, $^{130}$Te presents several nice features

- high natural isotopic abundance (I.A. = 33.87 %)
- high transition energy (Q ~ 2527 keV)
- average theoretical calculations of the Nuclear Matrix Elements (NME)
Recent update of $^{130}$Te $Q$-value

\[ Q_{\beta\beta^0\nu}(^{130}\text{Te}) = 2530.30 \pm 1.99 \text{ keV} \quad \text{old value} \]

\[ Q_{\beta\beta^0\nu}(^{130}\text{Te}) = 2527.01 \pm 0.32 \text{ keV} \quad \text{Scielzo et al., nucl-ex/0902.2376} \]

\[ Q_{\beta\beta^0\nu}(^{130}\text{Te}) = 2527.518 \pm 0.013 \text{ keV} \quad \text{Redshaw et al., nucl-ex/0902.2139} \]

![Graph showing recent update of $Q$-value for $^{130}$Te](image-url)
The Cuoricino experiment
Operated at GranSasso Underground Laboratory (Italy) from 2003 to 2008

62 TeO$_2$ crystals
detector mass: 40.7 kg
$^{130}$Te mass: 11 kg $\sim 5 \times 10^{25}$ $^{130}$Te nuclides

11 modules, 4 detectors each
crystal size: 5x5x5 cm$^3$
crystal mass: 790 g

2 modules, 9 detectors each
crystal size: 3x3x6 cm$^3$
crystal mass: 330 g
Cuoricino results

- Use new more accurate Q-value
- Updated statistics through Jan 2008

Cuoricino achievements
- Provides the best limit to date on $^{130}$Te half-life and a competitive limit on the Majorana mass of the neutrino
- Demonstrates the feasibility of a large scale bolometric detector with good energy resolution and background

- Background in $\beta\beta$ region:
  $0.18 \pm 0.01 \text{ c/keV/kg/y}$

- Average resolution @ 2615keV:
  $\sim 8\text{keV}$
  during calibrations, only 5x5x5 cm$^3$ crystals

- Tot exposure $\sim 18$ kg y $^{130}$Te anticoincidence spectrum

- $^{60}$Co

- $\beta\beta$0ν

- $T_{1/2}^{0\nu} \geq 2.9 \times 10^{24} \text{ y (90\%CL)}$
- $m_{\beta\beta} < 0.21 - 0.70 \text{ eV}$

Sensitivity $F^{0\nu}$: Lifetime corresponding to the minimum number of detectable events above background at a given C.L.

- Increase by enrichment
- Increase size and number of crystals
- Improve system reliability and duty cycle
- New procedure for energy calibration

$F^{0\nu} \sim \frac{a}{A \sqrt{b \cdot \Delta E}} \sqrt{M \cdot T}$

Reduce background:
- Material selection & handling
- Shielding
- Surface cleaning
- Avoid recontamination
- Improve detector design
**CUORE**

Cryogenic Underground Observatory for Rare Events will be a tightly packed array of

**988 bolometers** - M ~ 200 kg of $^{130}\text{Te}$

- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator
- Shielded by several lead shields

![Diagram of CUORE](image)
CUORE @ LNGS

Laboratori Nazionali del Gran Sasso, Italy

3200 m.w.e overburden

CUORE R&D

CUORE

Cuoricino
Comparison of Cuoricino data with Monte Carlo simulations

Flat continuum above 2615 keV line

- $^{60}$Co
- $\beta\beta0\nu$

U/Th contamination on surfaces
- Degraded alphas

- 30 ± 5 % $^{232}$Th in cryostat
- 20 ± 5 % TeO$_2$ surface
- 50 ± 10 % Cu surface in the $\beta\beta0\nu$ region
From Cuoricino to CUORE: shielding

- Low radioactivity materials for cryostat parts
- Neutron shielding: Borated polyethylene box
- Sealed and flushed with Nitrogen to eliminate Radon
Prediction of CUORE background

- $^{232}\text{Th}$ from cryostat and environment
  - reduced by use of selected materials
  - improved shielding
- Muons, neutrons, and cosmogenic activation: negligible

- **Surface contaminations**
  R&D activity at LNGS demonstrated:
  - reduction of crystal surface contamination by a factor ~5
  - reduction of continuum background in 3-4 MeV region of a factor ~ 2

- **Monte Carlo projected contaminations in CUORE** based on measured contaminations, and Cuoricino and R&D results: $< 0.04 \text{ c/kg/keV/y}$

  CUORE background goal: $< 0.01 \text{ c/keV/kg/y}$
  still working to improve the background reduction
Background reduction in CUORE

- CUORE dedicated **crystal growth** facility @ SICCAS, China
  - definition of a precise production protocol
  - strict control of all materials, tools and supplies used during all production step
Background reduction in CUORE

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  - definition of a precise production protocol
  - strict control of all materials, tools and supplies used during all production step
- Copper surface cleaning
  - Tumbling, Electrochemical, Chemical, Magnetron sputtering (TECM) + Ultrasonic cleaning
Background reduction in CUORE

- CUORE dedicated *crystal growth* facility @ SICCAS, China
  - definition of a precise production protocol
  - strict control of all materials, tools and supplies used during all production step
- **Copper surface cleaning**
  - Tumbling, Electrochemical, Chemical, Magnetron sputtering (TECM) + Ultrasonic cleaning
  - Three Towers Test currently taking data at LNGS (12 bolometers for each tower)
Projected sensitivity for CUORE

Detector resolution: \( \sim 5 \text{ keV} \)
Live time: 5 years

Background in \( 0\nu\beta\beta \) region
(conservative goal)
0.01 \( c/\text{keV/kg/y} \)

\[ T_{1/2}^{0\nu} (^{130}\text{Te}) > 2.1 \times 10^{26} \text{y} \]
\[ m_{\beta\beta} < 24 - 83 \text{ meV} \]

Background in \( 0\nu\beta\beta \) region
(demonstrated)
0.04 \( c/\text{keV/kg/y} \)

\[ T_{1/2}^{0\nu} (^{130}\text{Te}) > 1.0 \times 10^{26} \text{y} \]
\[ m_{\beta\beta} < 34 - 117 \text{ meV} \]


CUORE aims at probing the region of inverted mass hierarchy

CUORE

\[ 99\% \text{ CL (1 dof)} \]

Lightest neutrino mass in eV


CUORE aims at probing the region of inverted mass hierarchy
From Cuoricino to CUORE: calibration

- For each bolometer, **Voltage vs Energy relationship** need to be experimentally measured on a regular basis.
- Monthly calibration measurements with $\gamma$ sources of known energies ($^{232}\text{Th}$)

- The **calibration uncertainty** is one of the **systematic errors** in the determination of the $\beta\beta 0\nu$ half life.
CUORE calibration requirements

- **Uniform illumination** of all detectors with 5 calibration lines clearly identified in the energy spectrum between 511 keV and 2615 keV

- **Sources can be replaced.** Other source isotopes can be used if necessary (e.g. $^{56}$Co has been studied)

- **Calibration time** does not significantly affect detector live time

- Negligible contribution to radioactive background in the $\beta\beta 0\nu$ region

- Minimize the uncertainty in the energy calibration. Goal: residual calibration uncertainty in $\beta\beta 0\nu$ region < 0.05 keV
Insertion of 12 $\gamma$ sources that are able to move, under their own weight, through a set of guide tubes that route them from the deployment boxes on the 300K flange down into position in the detector region.
Cryogenic considerations

Sources of heat load:
- Conductance of the guide tubes
- Radiation funneled by guide tubes
- Conductivity of source string
- Radiation emitted by the source string

### Scheme of guide tube materials and thermal couplings

- Stainless Steel
- Copper
  - Perfect thermal coupling
  - Weak thermal coupling

### Table

<table>
<thead>
<tr>
<th>Stage</th>
<th>T [K]</th>
<th>Cooling power available to calibration [W]</th>
<th>Static heat load from guide tubes</th>
<th>Radiation from source string at 4K</th>
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<tbody>
<tr>
<td>40K</td>
<td>40 – 50</td>
<td>~ 1</td>
<td>~1</td>
<td>--</td>
</tr>
<tr>
<td>4K</td>
<td>4 – 5</td>
<td>0.3</td>
<td>0.02</td>
<td>--</td>
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<td>0.7K</td>
<td>0.6 – 0.9</td>
<td>0.55m</td>
<td>0.13m</td>
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<td>70mK</td>
<td>0.05 – 0.1</td>
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<td>0.3μ</td>
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<td>1.2μ</td>
<td>1.07μ</td>
<td>0.08μ</td>
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<td>detector</td>
<td>0.01</td>
<td>&lt; 1μ</td>
<td>--</td>
<td>0.25μ</td>
</tr>
</tbody>
</table>
Challenges for calibration

Sources of heat load:

- Conductance of the guide tubes
- Radiation funneled by guide tubes
- Conductivity of source string
- Radiation emitted by the source string
  - sources must be cooled to < 4 K
  - squeezing mechanism
Challenges for calibration

Sources of heat load:

- Conductance of the guide tubes
- Radiation funneled by guide tubes
- Conductivity of source string
- Radiation emitted by the source string
  - cooling mechanism required at 4K
- Friction during insertion/extraction
  - sliding friction + exponential friction at bends
  - low friction materials
  - source staggering
  - speed adjustment
CUORE construction status

- CUORE has a dedicated site in Hall A at LNGS
- CUORE building and cryostat support structure are completed
- The cryostat has been purchased. Delivery of dilution unit and flanges in early 2010
• Production of 1000 crystals started in 2008
• 157 crystals have been already delivered to LNGS and safely stored
• For each shipment, 4 samples are operated as bolometers to check performance and contamination
  – Bulk: $< 10^{-13}$ g/g $^{238}$U and $^{232}$Th
  – Surface: $< 10^{-8}$ Bq/cm$^2$
  – energy resolution $< 5$ keV
The next step: CUORE-zero

- First tower of CUORE (52 crystals)
- Operated in Cuoricino cryostat
- Test of automation and assembly procedure
- Readiness of background reduction facilities
- Check of data acquisition, processing
- Expected sensitivity $T_{1/2}^{0v} > 7 \times 10^{25}$ y in 2 years
CUORE schedule

2009

- 3-tower test
- background R&D

2010

- CUORE-0 construction
- assembly tests
- single tower assembly (in Cuoricino cryostat)

2011

- CUORE-0 data taking

2012

- CUORE data taking

CUORE construction

- utilities
- clean room
- external shielding

CUORE data taking

- cryostat assembly
- calibration system 4k test
- cryostat test cooldown
- detector assembly: 18+1 towers
- ~1000 detectors
- front-end electronics DAQ
Beyond CUORE ...

• Isotopic enrichment of $^{130}$Te
  – up to > 2x more sensitive on $^{130}$Te half-life
  – no change needed to the experimental infrastructure

• Use other isotopes
  – some compounds of Mo, Cd or Ge have been already tested bolometrically with success

• Advanced detectors
  – discriminate surface contamination
  – surface sensitive bolometers
  – scintillating bolometers
Conclusions

• **Cryogenic detectors** represent a well established and competitive technique for $0\nu\beta\beta$ search.

• **Cuoricino** demonstrated the feasibility of a large cryogenic detector with high energy resolution and low background. It also provided the most stringent limit on $^{130}\text{Te} \beta\beta 0\nu$ half life: $T_{1/2}^{0\nu} \geq 2.9 \times 10^{24} \text{ y}$

• **CUORE** is based on the outstanding experience and knowledge gained with Cuoricino and aims at exploring the region of the inverted hierarchy of neutrino masses, with a sensitivity $T_{1/2}^{0\nu} \geq 2.1 \times 10^{26} \text{ y}$

• The CUORE collaboration has made **good progress in reducing the background and developing a calibration system**. With the techniques at hand, we are confident we can reach our goals.

• The construction of CUORE is already started.
CUORE collaboration

18 Institutions

64 European collaborators
32 US collaborators
5 Chinese collaborators