RESULTS FROM THE CUORE EXPERIMENT

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OUTLINE

CUORE:
Cryogenic Underground Observatory for Rare Events

• Double beta decay
• Detector
• Cryostat
• Commissioning
• Detector optimization
• Data analysis
• Results
• Conclusion
Double Beta Decay ($\beta\beta$) is a second order weak interaction, directly observable only for few nuclei.

The isotope of interest for the CUORE experiment is $^{130}\text{Te}$

- high isotopic abundance (34.17%)
- $^{130}\text{Te}$ within the detector absorber of TeO$_2$
- reproducible growth of high quality crystals
- Q-value of 2527.515 ± 0.013 keV
DOUBLE BETA DECAY

Signature:
peak at the Q-value of $^{130}$Te $\beta\beta$ decay
$\beta\beta$ summed $e^-$ energy spectrum in $^{130}$Te

$2\nu\beta\beta$ with neutrinos

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

- Allowed by SM ($\Delta L = 0$)
- Observed in several nuclei

$\tau_{1/2} \sim 10^{19-21}$ years

$0\nu\beta\beta$ neutrinoless

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

- Beyond by SM ($\Delta L = 2$)
- Never observed to date

$\tau_{1/2} > 10^{25-26}$ years

Implication in $0\nu\beta\beta$ decay observation:
- demonstrate lepton number violation
- establish the Majorana nature of neutrinos
- constrain the absolute neutrino mass hierarchy and scale
**CHALLENGES**

**Sensitivity:**

\[ T_{1/2}^{0\nu} \propto \sqrt{\frac{M t}{b \Delta E}} \]

- **big exposure (mass x time)**
  - 988 TeO$_2$ crystal with isotopic abundance of 34.167% for a total mass 206 kg of active material
  - foreseen 5 years of data taking

- **high energy resolution**
  - noise reduction techniques
  - temperature stability
  - fine tuning of detectors parameters to optimize the signal to noise ratio

- **low background**
  - strict radiopurity criteria on material selection and assembly chain
  - passive shields from external and cryostat radioactivity

**Goals:** ~ 1 ton year

- 5 keV FWHM
- 0.01 counts/keV/kg/yr

**Goal:**

\[ T_{1/2} (90\% \text{ C.L.}) > 9 \times 10^{25} \text{ yr} \]

\[ \langle m_{\beta\beta} \rangle \quad 45 - 210 \text{ meV} \]

European Physical Journal C 77.532 (2017)
CUORE DETECTOR
TeO2 cryogenic bolometers

SINGLE TeO2 CRYSTAL
5×5×5 cm³ and 0.75 kg each

FLOOR
4 TeO2 crystals

TOWER
( CUORE-0 like)
52 TeO2 crystals arranged in 13 floors

DETECTOR ARRAY
Closely packed array of 988 TeO2 crystals arranged in 19 towers
A particle interaction in the absorber causes an increase in temperature, measured by the thermistor.

The absorber and the thermistor are optimized to work at 10mK.

\[ R(T) = R_0 e^{\sqrt{T_0/T}} \]

\[ \Delta T = \frac{\Delta E}{C} \sim \frac{100\mu K}{MeV} \]

\[ \tau = \frac{G}{C} \sim 1s \]

\[ C(T) \propto T^3 \]

C: absorber capacity
\( \Delta T \): temperature variation
\( \Delta E \): energy deposition
G: thermal conductance
\( \tau \): signal decay time
WHERE

LNGS - GRAN SASSO UNDERGROUND LABORATORY (ITALY)

The mountain of Gran Sasso naturally protects the experiment from cosmic rays

- 3600 m.w.e. deep
- $\mu$s: $\sim 3 \times 10^{-8}/(s \ cm^2)$ - 10^{6} less than above ground
- $\gamma$s: $\sim 0.73/(s \ cm^2)$
- neutrons: $< 4 \times 10^{-6} \ n/(s \ cm^2)$
The CUORE detector is hosted in a cryogen-free cryostat:
- Mass to be cooled < 4K: ~15 tons (Pb, Cu and TeO$_2$)
- Operating temperature 10 mK
- Designed to guarantee extremely low radioactivity and low vibrations environment
- Biggest dilution cryostat in the world

988 TeO$_2$ crystals
(arranged in 19 towers with 13 floors each, 52 5x5x5 cm$^3$ TeO$_2$ crystals per tower)
CUORE
CRYOGENIC INFRASTRUCTURE

Y-beam
Main Support Plate
Cryostat
Sand-filled columns
H$_3$BO$_3$ panels
Polyethylene
Screwjacks
Movable platform

Minus-K insulators
Concrete beams
Lead
Concrete walls
Seismic insulators
Cryogenic system commissioning completed in March 2016:
- Stable base temperature @ 6.3mK
- Cooling power: > 3µW @10mK

Tower assembly performed in \(N_2\) atmosphere to prevent contamination from Rn

Lateral and bottom shielding with 6cm - thick \(^{210}\text{Pb}\) - depleted roman lead

The ingots stayed under water for centuries, loosing their radioactive components. The ingots have been recasted in a clean environment.

Nuclear Instruments and Methods A 768, 130-140 (2014)
COMMISSIONING

towers installation
July - August 2016

The 19 towers were installed in a radon free clean room.
It took about one month.
Only 4 out of 988 channels were lost during the installation.
In September 2018 we were ready to cool down.
The cool down of the cryostat started in December 2016

First phase with dedicated Fast Cooling System, introduction of He exchange gas prior to the start of Pulse Tubes, then pulse tubes only.

Last phase after the pause dedicated to electronics optimisation was achieved with the dilution unit, down to base temperature (~7mK).

26.01.2017
Base temperature 7 mK

27.01.2017
As soon as we reached base temperature we observed the first pulse!
**DETECTOR OPTIMIZATION**

**Temperature scan:**
Chooses temperature that optimises the signal and at the same time allows to work with the designed thermistor resistance (this analysis @ 15 mK)

**Working point and Load Curves:**
Scan to choose the best bias current to feed to each channel thermistor:
- Linear behaviour for small temperature variations
- Maximisation of signal to noise ratio
- Optimization of pulse amplitude

**Optimization of trigger thresholds:**
Trigger thresholds ranging from 20 to a few hundred keV
DETECTOR OPTIMIZATION

The Cryostat is cool down to 4K by 5 Pulse Tubes that induce vibrations at 1.4 Hz and harmonics.

Attenuation of Pulse tube induced vibrations:
1. Switch to Linear Drives to control PT motor heads -> reduce temperature variations on the Mixing Chamber
2. PT phase scan to find the phase configuration that actively minimize the PT induced vibrations
3. Drive the PT at the minimum noise phase configuration

Base temperature

Noise level on the detector

Single channel NPS comparison

PT phase optimization changes noise by an order of magnitude!

Cryogenics 93 (2018) 56–65
DATA TAKING

- CUORE surpassed CUORE-0 exposure in about 3 weeks of data taking
- Collected 86.3 kg·yr of TeO$_2$ over 7 weeks in summer 2017 (splitted in two datasets)
- 99.6% of channels active (984/988)

- 92% of channels passing analysis cuts
- Energy resolution of 7.7 keV FWHM
- Signal efficiency of ~80%
- Average rates per channel:
  - calibration: ~50 mHz, physics: ~6 mHz
• Amplitude Evaluation
• Thermal gain stabilization
• Energy calibration
• Blinding
• Select events with multiplicity = 1
• Pulse shape analysis selection
• Line shape fit
RESULTS
Search for 0νββ of $^{130}$Te

UEML fit in the ROI (2465 - 2575) keV:

- $^{60}$Co peak position: $(2506.4 \pm 1.2)$ keV
- Background index is consistent with expectations $(1.4 \pm 0.2) \times 10^{-2}$ cnts/(keV·kg·yr)
- Median expected sensitivity $T^{0\nu}_{1/2} = 7.0 \times 10^{24}$ yr
- Signal decay rate best fit: $\Gamma_{0\nu} = (-1.0^{+0.4}_{-0.3} \text{ (stat)} \pm 0.1 \text{ (syst)}) \times 10^{-25}$ yr$^{-1}$

**Combined limit (CUORE+CUORE-0+Cuoricino):**

$T^{0\nu}_{1/2} > 1.5 \times 10^{25}$ yr
$m_{\beta\beta} < 110 - 520$ meV

PRL 120, 132501 (2108)

$\beta\beta$ sensitivity in 5 yr:

$T^{0\nu}_{1/2} > 9.0 \times 10^{25}$ yr
$m_{\beta\beta} < 45 - 210$ meV
RESULTS
Background model

- γ background significantly reduced
- Most α background consistent
- Backgrounds consistent with expectations
- $^{210}$Po excess appears to be from shallow contamination in copper around the detectors
  - Current estimated contribution to ROI at the level of $\sim 10^{-4}$ cnts/(keV kg yr)

The background model is able to reconstruct the major features of the observed spectrum in CUORE
RESULTS

Measurement of the $2\nu\beta\beta$ half life of Te$^{130}$

In CUORE-0, $2\nu\beta\beta$ decay spectrum accounts for ~20% of the signal in the range 1-2 MeV

In CUORE, $2\nu\beta\beta$ decay spectrum accounts for nearly all of the signal in the range 1-2 MeV

$T^{2\nu_{1/2}} = [7.9 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (syst.)}] \times 10^{20} \text{ yr}$

$T^{2\nu_{1/2}} = [8.2 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \times 10^{20} \text{ yr}$

$T^{2\nu_{1/2}} = [7.0 \pm 0.9 \text{ (stat.)} \pm 1.1 \text{ (syst.)}] \times 10^{20} \text{ yr}$
CONCLUSION

The first result from the CUORE experiment
• Published in 2018 on PRL 120, 132501

Scientific:
• Most stringent limit on $0\nu\beta\beta$ decay half-life of $^{130}\text{Te}$ to date
  $T^{0\nu1/2} > 1.5 \times 10^{25} \text{ yr}$  $m_{\beta\beta} < 110 - 520 \text{ meV}$
• Most precise and accurate measurements of $2\nu\beta\beta$ decay
  half-life of $^{130}\text{Te}$ $[7.9 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (syst.)}] \times 10^{20} \text{ yr}$

Technical:
• operation of the world’s first ton-scale bolometric detector
• construction and operation of the world’s largest and most powerful dilution refrigerator

The present:
• Analysis ongoing on the data collected in 2018 at 11mK
• New 2019 dataset is going to start in few weeks

The future:
• 5 years of live time planned
• New analyses (dark matter, axions...)
• CUPID (CUORE Upgrade with Particle Identification)
THANK YOU