Latest Results from the CUORE Experiment

QNP 2022

Samantha Pagan on behalf of the CUORE Collaboration
Unanswered questions about neutrinos

### # of neutrinos species

| Neutrino Type | Mass Difference |
|---------------|-----------------|
| $\nu_1$       | $\geq 1 \text{eV}^2$ |
| $\nu_2$       | $\simeq 2.5 \times 10^{-3} \text{eV}^2$ |
| $\nu_3$       | $\simeq 7.4 \times 10^{-3} \text{eV}^2$ |

Sterile Neutrinos

[https://www.nevis.columbia.edu/daedalus/motiv/sterile.html](https://www.nevis.columbia.edu/daedalus/motiv/sterile.html)

Cosmological Models

[https://plancksatellite.org.uk/results/first-full-sky-image/](https://plancksatellite.org.uk/results/first-full-sky-image/)

### Neutrino Mass Scale

- $\nu_1$, $\nu_2$, $\nu_3$
- $d$, $s$, $b$
- $u$, $c$, $t$
- $e$, $\mu$, $\tau$

[2013 Snowmass Neutrino report: https://arxiv.org/pdf/1310.4340.pdf](https://arxiv.org/pdf/1310.4340.pdf)

### Majorana or Dirac

- Neutrinoless Double Beta Decay
- Could explain matter anti matter asymmetry

[https://cuore.lngs.infn.it/en/about/physics](https://cuore.lngs.infn.it/en/about/physics)

### Mass Hierarchy

- Normal hierarchy (NH)
- Inverted hierarchy (IH)

[Credit: JUNO Collaboration / JGU-Mainz](https://www.juno-experiment.org/)

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**CUORE**

**S.Pagan**

QNP 2022
Unsolved questions about neutrinos

**# of neutrinos species**

| Species | Mass Difference |
|---------|----------------|
| $\nu_1$ | $\Delta m^2_{12}$ |
| $\nu_2$ | $\Delta m^2_{23}$ |
| $\nu_3$ | $\Delta m^2_{34}$ |
| $\nu_4$ | $\geq 1 \text{ eV}^2$ |

Sterile Neutrinos

[https://www.nevis.columbia.edu/daedalus/motiv/sterile.html](https://www.nevis.columbia.edu/daedalus/motiv/sterile.html)

**Neutrino Mass Scale**

Cosmological Models

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Double Beta Decay (2νββ)

\[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e\]

Standard model process

Precise measurement and spectral shape inform nuclear models

Example Isotopes: $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{128}$Te, $^{130}$Te, $^{136}$Xe (even mass number)

Measured Half-life: $\sim$10$^{17}$-10$^{22}$ yrs
Neutrinoless Double Beta Decay (0νββ)

\[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e\]

Violates the conservation of total lepton number, beyond the SM process.

Implies a Majorana neutrino.

Example Isotopes: $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{100}\text{Mo}$, $^{130}\text{Te}$, $^{136}\text{Xe}$

Half life limits: $\sim 10^{25}$-$10^{26}$ years
Neutrinoless Double Beta Decay: Signal

Image Credit: J. Torres
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}^{0\nu}(Q,Z) \cdot |M_{0\nu}|^2 \cdot |<m_{\beta\beta}>|^2$$

Phase space factor

Effective Majorana mass

Nuclear Matrix element

$$m_{\beta\beta}^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

https://www.particlebites.com/?m=201609
ββ Isotopes

Experiments using various isotopes: $^{76}\text{Ge}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, $^{82}\text{Se}$, $^{100}\text{Mo}$,

**Q-value:**
Higher is preferable

$2\nu\beta\beta$ background $\propto \frac{1}{Q_{\beta\beta}^5}$

**Isotopic abundance:**
Higher is preferable

*Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007*
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![Graph showing isotopic abundances and Q-values](Image credits: J. Torres)

Zuber, J. Phys. Conf. Ser. 578 (2015) 1, 012007

QNP 2022
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Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007
$^{130}\text{Te}$

Q-value: 2528 keV

High isotopic abundance of 33.8% can use natural crystals

$^{130}\text{Te} \rightarrow ^{130}\text{Xe} + 2e$

Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007
We would like to acknowledge support from the U.S. Department of Energy Office of Science contract No. DE-SC0019368 and DE-SC0012654 and the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1752134.
CUORE: The Cryogenic Underground Observatory forRare Events

Source/detector: $^{130}$Te

988 TeO$_2$ crystals

Gran Sasso National Laboratory (LNGS), L’Aquila, Italy
Average depth: ~3600 m.w.e.

Cryogenic calorimeters-bolometers
CUORE: The Cryogenic Underground Observatory for Rare Events

19 towers with 13 floors of 4 crystals each

TeO$_2$ natural abundance crystal
5.00×5.00×5.00 cm$^3$, 750 g each
Total $^{130}$Te mass: 206 kg

Custom dilution refrigerator, nested vessels, and 5 pulse tubes

Operated at ~10 mK

Surrounding lead, and roman lead shielding

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)
Bolometers: Operating Principle

Particle interaction increase crystal temperature

Thermal coupling to 10 mK heat bath

Neutron Transmutation Doped (NTD) Ge thermistors

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

\[ R(T) = R_0 e^{\sqrt{\frac{\Delta E}{C_V}} \frac{T_0}{T}} \]

\[ \Delta T = \frac{\Delta E}{C_V} \approx 100 \frac{\mu K}{MeV} \]

E. E. Haller, J. Appl. Phys. 77, 2857-2878 (1995)
CUORE Sensitivity

\[ S \propto a_I \sqrt{\frac{mt}{B \Delta E}} \]

- Isotopic abundance
- Mass \( m \)
- Time \( t \)
- Backgrounds \( B \)
- Energy Resolution \( \Delta E \)

\( 10^{-2} \text{ cts/(KeV} \cdot \text{kg} \cdot \text{y)} \)

\( \sim 1\% \text{ at } Q_{\beta\beta} \)
Evolution of cryogenic $0
\nu\beta\beta$ bolometers

Running period

$\tau_{0.1/2}$ (90% C.L.) [yr]

Rev. Sci. Instrum. 89, 121502 (2018)
CUORE Construction Photos
CUORE 1 Tonne·Year Results
CUORE Data Taking: 1 Tonne·Year Results

Began data taking in 2017

Stable operations, ~ 50kg·yr/month

Exposure (tonne·yr)

- Total TeO$_2$ exposure
- Analysis exposure (before cuts)
- Cryogenic maintenance

Adams, D.Q. et al. (CUORE Collaboration), Nature 604, 53-58 (2022)
1 Tonne-Year Energy Spectrum

TeO$_2$ exposure: 1038.4 kg·yr

Adams, D.Q. et al. (CUORE Collaboration), *Nature* 604, 53-58 (2022)
## 1 Tonne-Year Backgrounds

![Graph showing physics data with Q_{ββ} highlighted]

- **Physics data**
  - Base cuts
  - Base cuts + AC
  - Base cuts + AC + PSD

### Near sources:
- Crystals, copper holders, foil, 2νββ, crystal impurities, $^{238}\text{U}$ $^{232}\text{Th}$ chains

### Far Sources:
- Shields, Cryostat, Decays in $^{238}\text{U}$ and $^{232}\text{Th}$ chains

### Externals Sources:
- Environmental muons, γs, and neutrons

*Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)*
1 Tonne·Year Background Fit Results

**Nuisance Parameters:** Analysis efficiency, energy bias, energy resolution, $Q_{\beta\beta}$, $^{130}$Te abundance

Best fit to [2490,2575] keV

Unbinned Bayesian analysis using Bayesian Analysis Toolkit (BAT)

No evidence of $0\nu\beta\beta$

Background-only model:

$b = 1.49(4) \times 10^{-2} \text{ counts/(keV⋅kg⋅yr)}$ (90 % C. I.)

Best fit signal-plus-background model:

$\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26} \text{ yr}^{-1}$

**Fit Parameters:** $\Gamma_{0\nu}$, background index, background slope, $^{60}$Co rate

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CUORE
Exposure: 1038 kg.yr

Best fit (global mode)

90% CI limit on $\Gamma_{0\nu}$

Fit without $0\nu\beta\beta$ component
Bayesian Median Exclusion Sensitivity

10^4 toy-MC spectra with background only model

Fit spectra with signal+bkg model and extract 90% C.I. limit

Median exclusion sensitivity

\[ T_{1/2} = 2.8 \times 10^{25} \text{ yr} \ (90\% \ C.I.) \]

72% Probability to get a more stringent limit given current sensitivity

Adams, D.Q. et al. (CUORE Collaboration), *Nature* 604, 53-58 (2022)
CUORE 1 Tonne-Year $0\nu\beta\beta$ Limit

Adams, D.Q. et al. (CUORE Collaboration), *Nature* 604, 53-58 (2022)

$T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr (90\% C.I.)
CUORE 0νββ Limit and Sensitivity

Adams, D.Q. et al. (CUORE Collaboration), Nature 604, 53-58 (2022)

CUORE 1 Tonne Limit:
\[ m_{\beta\beta} < 90-305 \text{ meV} \]

CUORE Sensitivity (5 yrs)
\[ m_{\beta\beta} < 50 - 130 \text{ meV} \]

\[ (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) \cdot |M^{0\nu}|^2 \cdot \frac{|<m_{\beta\beta}|^2}{m_e} \]
Other rare decay searches
**2νββ Decay Measurement**

CUORE Background Model

Geant 4 simulation combined with CUORE detector response

62 simulated sources: Including 2νββ decay in the crystals and contaminants

Produces multiplicity, time resolution, energy dependent trigger efficiencies

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The CUORE Collaboration. *Phys. Rev. Lett.* 126:171801 (2021)
The most precise determination of $^{130}\text{Te} \ 2\nu\beta\beta$ decay half-life

$$T_{1/2}^{2\nu} = 7.71^{+0.08}_{-0.06} \text{(stat.)}^{+0.12}_{-0.15} \text{(syst.)} \times 10^{20} \text{ yr}$$

Bayesian analysis performed on single crystal events using background model and MC. Spectral fit from 350 keV to 2.8 MeV.

The CUORE Collaboration. *Phys. Rev. Lett.* 126:171801 (2021)
Other Recent CUORE Results

All results are the most stringent limits on these searches in Te

Double beta decay of $^{130}$Te to the first $0^+$ excited state of $^{130}$Xe

- $0\nu\beta\beta$: $(T_{1/2})^{0\nu}_{0^+} > 5.9 \times 10^{24}$ yr (90% C.I.)
- $2\nu\beta\beta$: $(T_{1/2})^{2\nu}_{0^+} > 1.3 \times 10^{24}$ yr (90% C.I.)

Adams, D.Q. et al. (CUORE Collaboration) Euro. Phys. J. C 81, 567 (2021) https://doi.org/10.1140/epjc/s10052-021-09317-z

$^{128}$Te $0\nu\beta\beta$

$0\nu\beta\beta$ decay in an additional Te isotope of high isotopic abundance

- $(T_{1/2}) > 3.6 \times 10^{24}$ yr (90% CI).

Adams, D.Q. et al. (CUORE Collaboration) Phys.Rev.C 105 (2022) 065504 https://doi.org/10.1103/PhysRevC.105.065504

$^{120}$Te Neutrinoless $\beta^+/EC$

Additional mechanism of $\beta\beta$

- $^{120}$Te $\beta^+/EC$: $T_{1/2} > 2.9 \times 10^{22}$ yr (90% C.I.)

Adams, D.Q. et al. (CUORE Collaboration) Phys.Rev.C 105 (2022) 065504 https://doi.org/10.1103/PhysRevC.105.065504
What comes after CUORE?
CUPID and $0\nu\beta\beta$

CUPID: CUORE Upgrade with Particle IDentification

LNGS Gran Sasso National Laboratory

Source/detector: $^{100}\text{Mo}$
Signal: Peak at 3035 KeV

Upgraded Technology/Systems:
- Scintillating Bolometers
- Particle Identification
- Muon Veto

Baseline Background: $10^{-4}$ cts/(keV·kg·yr)

Baseline Sensitivity: $m_{\beta\beta} < 10^{-17}$ meV
Baseline projected sensitivity covers the inverted ordering region

CUPID Baseline Sensitivity: \( m_{\beta\beta} < 10^{-17} \text{ MeV} \)
Summary

- CUORE is the first tonne-scale operating cryogenic 0νββ decay experiment
- CUORE is stably operating and aims to collect 5 yr of livetime data
- 1 tonne·yr of CUORE data has been analyzed for 0νββ decay
- CUORE has the leading limit on 2νββ of $^{130}$Te
- CUORE’s science program includes multiple rare events searches
- CUPID will build off of the CUORE technology and infrastructure to reach greater sensitivity and cover the inverted ordering region for the 0νββ
Thank you!

Visit https://cuore.lngs.infn.it/en/about/physics for more information!
Back up slides
# 1 Tonne-Year Parameters and Efficiencies

| Parameter                  | Value          |
|----------------------------|----------------|
| Number of datasets         | 15             |
| Dead channels              | 4              |
| Active channels            | ~934           |
| TeO$_2$ exposure           | 1038.4 kg·yr   |
| $^{130}$Te exposure        | 288 kg·yr      |
| FWHM at Q$_{\beta\beta}$  | 7.8(5) keV     |
| Trigger threshold          | ~10 keV        |
| Analysis threshold         | 40 keV         |

| Efficiency name            | % efficiency   | Description                                                                 |
|----------------------------|----------------|-----------------------------------------------------------------------------|
| o$\nu$ββ containment       | (88.350 ± 0.090)% | Probability for an o$\nu$ββ event to be M1 and fully contained in the ROI. From MC. |
| Trigger and energy         | 96.418(2)%     | Includes: trigger, event reconstruction, and pile up                        |
| reconstruction             |                |                                                                             |
| Multiplicity/              | 99.3(1)%       | Correctly tagging a single crystal event                                     |
| Anticoincidence            |                |                                                                             |
| Pulse shape analysis       | 96.4(2)%       | Efficiency for a good physical pulse to pass pulse shape discrimination cuts |
| All cuts except            | 92.4(2)%       | Products of the terms above, propagated in quadrature                        |
| containment                |                |                                                                             |

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)
Systematics

Implemented as additional nuisance parameters to the fit

| Parameter                        | Dependence | Method/Prior                                      |
|----------------------------------|------------|---------------------------------------------------|
| Analysis efficiency I            | Dataset    | Gaussian                                          |
| Analysis efficiency II           | Global     | Gaussian                                          |
| Energy bias                      | Dataset    | Fit residual peaks in physics spectrum from literature value with 2nd order polynomial |
| Energy resolution                | Dataset    | Fit ratio of FWHM in physics and calibration data with 1st order polynomial |
| Qbb                              | Global     | Gaussian                                          |
| 130Te isotopic fraction          | Global     | Gaussian                                          |