$0\nu\beta\beta$ Results from the CUORE Experiment

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Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical process that results from possible Majorana nature of the neutrino. A positive detection for this decay will,

- Prove that neutrinos are Majorana particles, and will provide hints about the origins of the matter-antimatter asymmetry
- Conclusively demonstrate lepton number violation and,
- Help determine the effective Majorana mass of the electron neutrino,

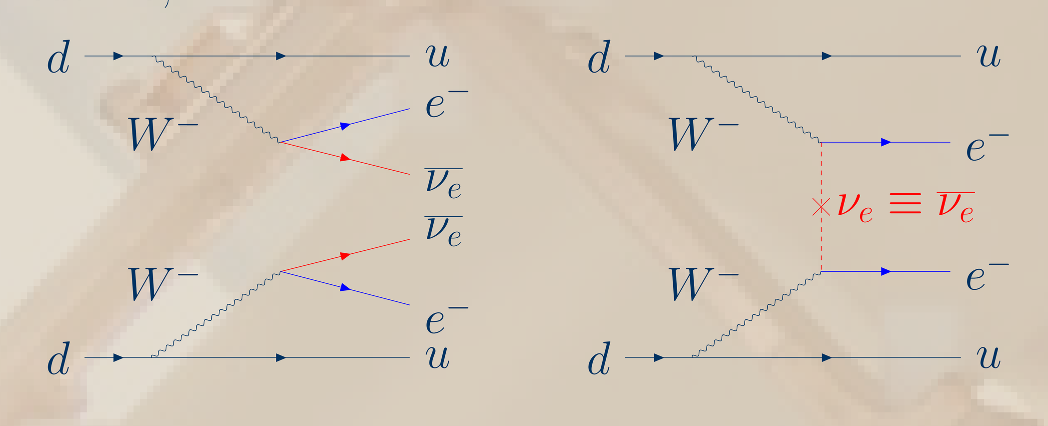

Fig. 1: $2\nu\beta\beta$ and $0\nu\beta\beta$ diagrams

$0\nu\beta\beta$ is detected by looking for the tell-tale bump at the end of the $2\nu\beta\beta$ decay spectrum.

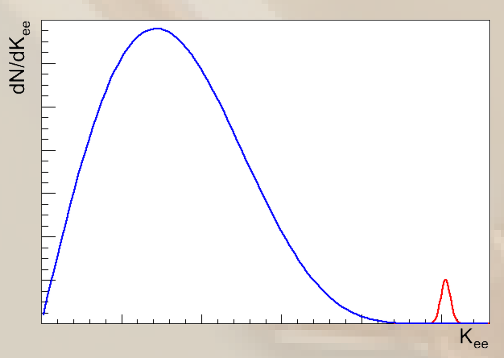

Fig.2: $2\nu\beta\beta$ spectrum with $0\nu\beta\beta$ peak

A decay deposits energy in the detector, which, in bolometers causes a change in temperature that is directly proportional to the released energy.

$$\Delta T_{\mathrm{Event}} = \frac{E_{\mathrm{Event}}}{C_{\mathrm{Crystal}}}$$

Detector

CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents) at Gran Sasso National Lab is a detector array consisting of 988 TeO_2 crystals ($Q_{\beta\beta} = 2527.5$ keV).

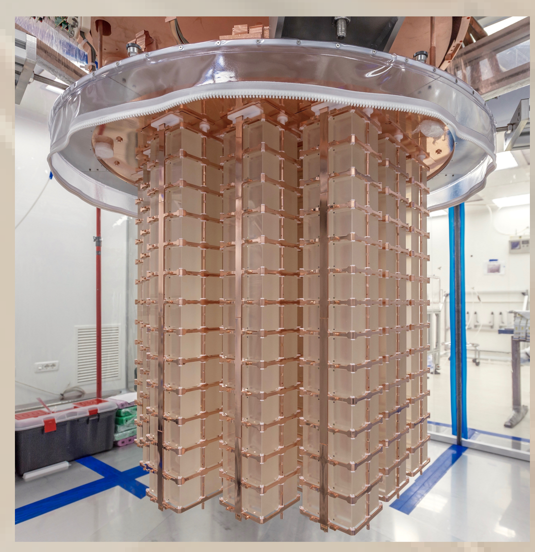

Fig. 3: Fully assembled detector

Detector array: Total mass of 742 kg. Arranged into 19 towers, 13 floors with 4 crystals each.

Crystals: 5 × 5 × 5cm, each instrumented with a NTD thermister and a heater.

NTDs/Heaters: bonded with 25 µm gold wires connecting the Cu strips.

CUORE Cryostat

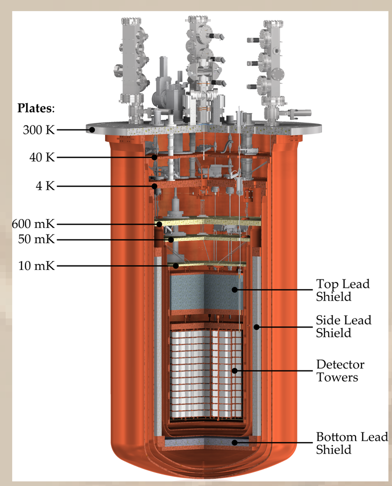

Fig. 4: CUORE Cryostat

- The cryostat has 6 stages and is designed to operate at 10 mK, and uses a custom built dilution unit.
- In the initial cryogenic commissioning run, it reached below 6 mK at the lowest stage.
- About 1 m³ volume and 1.5 t cold mass at 10 mK.

CUORE Program

CUORE is a result of a long running series of TeO_2 bolometric detectors started in 1992 that ranged from 6 g to ~7 kg (TeO_2 mass) before Cuoricino.

Detector	Mass	Year(s)
Cuoricino	41.7 kg	2003-2008
CUORE-0	39 kg	2013-2015
CUORE	742 kg	2017-

Fig. 5 (right): Cuoricino and CUORE-0 detectors arXiv:1801.03580 [hep-ex]

Timeline of CUORE detector

- Aug 2016: Completion of detector assembly and installation
- Jan 2017: First Pulses
- Oct 2017: First published result (shown here)
- After few months of optimizing the detector, currently on the second phase of data taking.

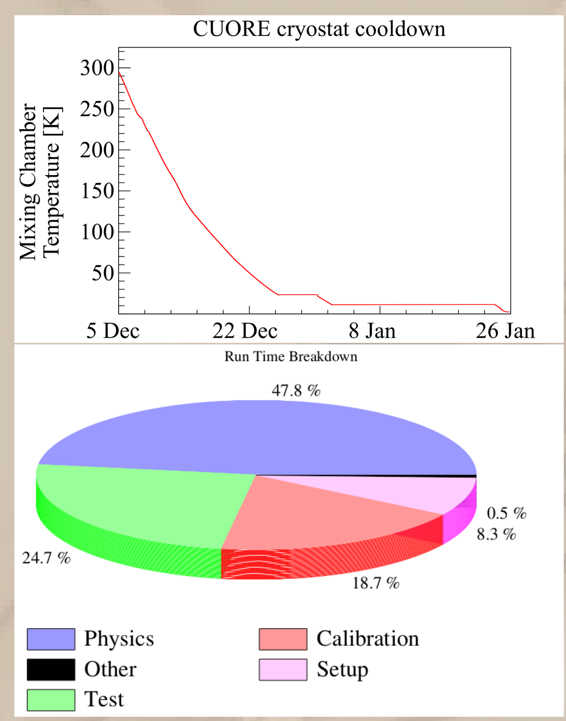

Fig. 6: Timeline

Data Acquisition and Analysis

- **Setting operating conditions:**
  - Temperature scans, select operating temperature,
  - Working point measurements for NTDs,
  - Noise reduction and pulse tube phase scans
- **Data acquisition:**
  - Front-end electronics: Bias and pre-amplifier,
  - Bessel filter: Cutoff frequency at 125 Hz,
  - NI DAQ: Sampling frequency of 1 kHz,
  - Event builder: Write data, Trigger
  - CORC: (CUORE Online Run Check) Web based monitoring of data and flagging rejected intervals.

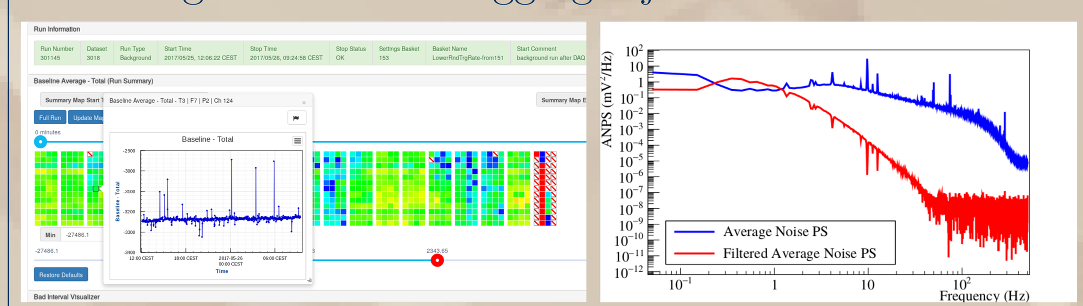

Fig. 7: CORC Monitoring system (left) and Optimal Filter (right)

- **Filter noise** using an Optimal filter
- **Apply thermal gain stabilization** using pulses from Si heaters
- **Energy calibration** Scales the stabilized pulse amplitude to energy
  - Separate calibration runs with 12 strings of ^{232}Th sources lowered into the detector.
  - Uses six high statistics peaks (239 keV, 338 keV, 583 keV, 911 keV, 969 keV and 2615 keV).
- **Blind data** by 'salting' the $Q_{\beta\beta}$ region with rescaled events from 2615 keV ^{208}Tl peak.
- **Apply data quality Cuts,** filter bad events (Stable pre-pulse baseline, No pileup, Pulse shape)
- **Coincidence cuts** to reject multi-site events
- **Calculate efficiency**

Selection Efficiency (%)	Dataset 1	Dataset 2
Base	95.63 ± 0.01	96.69 ± 0.01
Pulse shape	91.1 ± 3.6	98.2 ± 3.0
Anti-coincidence		
Accidentals	99.4 ± 0.5	100.0 ± 0.4
$\beta\beta$ containment	88.35 ± 0.09	

Tab. 1: CUORE selection efficiency

- **Fit for the lineshape** using 2615 keV ^{208}Tl peak, and determine resolution scaling/peak reconstruction offset by fitting to known peaks in the background spectrum.

Unblind data

Results

- CUORE data was unblinded after fixing the fitting procedure and the model.
- The Region of interest (ROI) for $0\nu\beta\beta$, 2465 keV to 2575 keV, is modeled with:
  a. Decay peak for $0\nu\beta\beta$,
  b. A coincident γ peak from ^{60}Co,
  c. And a flat background.
- The ROI was fitted simultaneously for each dataset-bolometer.
- Number of events in ROI: 155
- ^{60}Co fit mean: (2506.4 ± 1.2) keV
- Best fit decay rate: $-1.0^{+0.4}_{-0.3}(\mathrm{stat.}) \pm 0.1(\mathrm{syst.}) \times 10^{-25}\ \mathrm{yr}^{-1}$
- Interpret the data with both Bayesian and Frequentist (Rolke) techniques
- With systematic uncertainties,

	Additive (10^{-25} yr^{-1})	Scaling (%)
Line shape	0.02	2.4
Energy resolution	–	1.5
Fit bias	–	0.2
Energy scale	–	0.2
Background shape	0.5	0.8
Selection efficiency		2.4%

Tab. 2: Systematic uncertainties on $\Gamma_{0\nu}$

Results from: Phys. Rev. Lett. 120, 132501 (2018)

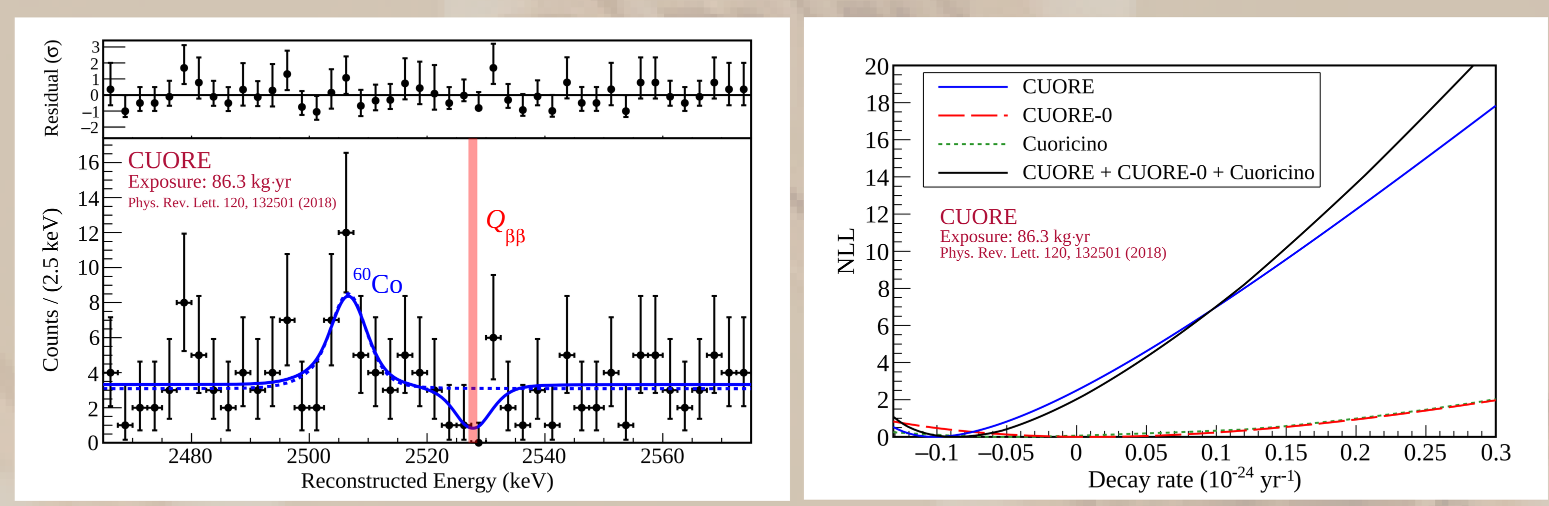

Fig. 8: CUORE ROI fit (left) and Negative log likelihood fit (right)

	Dataset 1	Dataset 2
TeO_2 exposure	37.6 kg · yr	48.7 kg · yr
FWHM @$Q_{\beta\beta}$ (physics)	(8.3 ± 0.4) keV	(7.4 ± 0.5) keV
Exposure weighted FWHM	(7.7 ± 0.5) keV	
ROI Background index	$1.49^{+0.18}_{-0.17} \times 10^{-2}$ ckky	$1.35^{+0.20}_{-0.18} \times 10^{-2}$ ckky
Median expected sensitivity	7.0×10^{24} yr (Bayesian) 7.6×10^{24} yr (Rolke)	
Half life limit (90% C.L)	1.3×10^{25} yr (Bayesian) 2.1×10^{25} yr (Rolke)	
Half life limit (90% C.L) with CUORE-0 and Cuoricino	1.5×10^{25} yr (Bayesian) 2.2×10^{25} yr (Rolke)	

Tab. 3: CUORE Results

We combine CUORE results with that of CUORE-0 and Cuoricino (respectively 9.8 kg · yr and 19.8 kg · yr of ^{130}Te exposure) and report the most stringent limits on $0\nu\beta\beta$ decay of ^{130}Te to date.

Future

- We are optimizing the detector performance and analysis techniques to reach design goals.
- With a target live-time of 5 years, CUORE is expected to reach a 9×10^{25} yr exclusion sensitivity (90% C.L) and 4×10^{25} yr discovery sensitivity(3σ).
- The proposed next generation detector with the ability use particle discrimination and increased isotope mass, **CUPID** (**CU**ORE **U**pgrade with **P**article **ID**), aims to fully cover the inverted hierarchy.

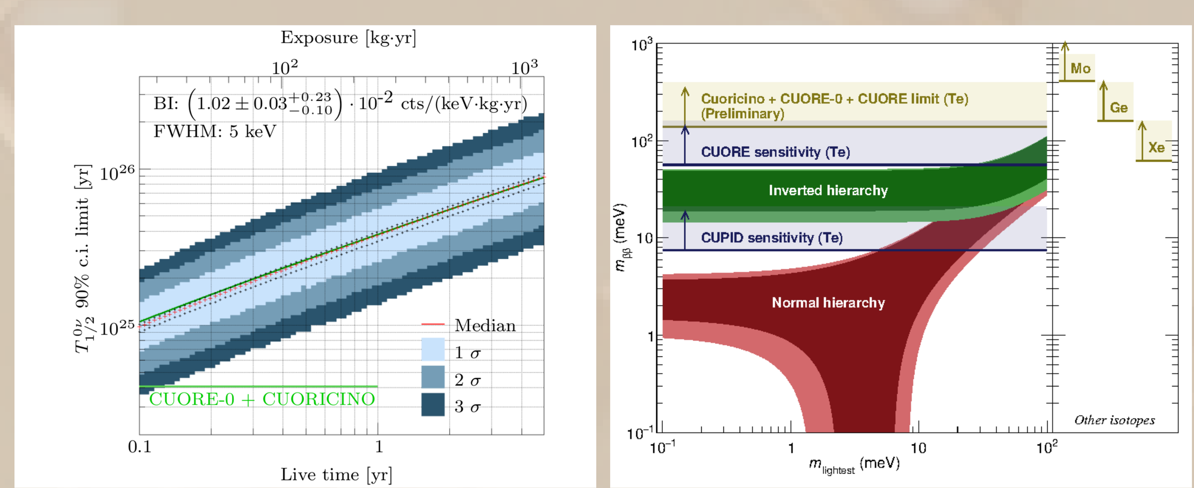

Fig. 9: CUORE and CUPID sensitivity, EPJ C 77, 532 (2017)

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