New results from the CUORE experiment

Andrea Giachero

University & INFN of Milano-Bicocca

CUORE

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

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Nuclear Double Beta Decay

Very rare radioactive decay where the charge of the nucleus changes by two units

- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e \qquad (2\nu\beta\beta)$

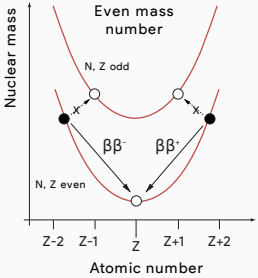
  Allowed in the Standard Model for even-even nuclei and already observed with $T_{1/2} > 10^{18}$ y

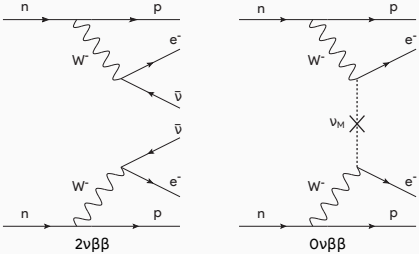
- $(A, Z) \rightarrow (A, Z+2) + 2e^- \qquad (0\nu\beta\beta)$

  Forbidden by Standard Model ($\Delta L = 2$), expected with $T_{1/2} > 10^{25}$ y

- L-violation, i. e. creation of a pair of electrons
  - the discovery of $0\nu\beta\beta$ decay would imply the violation of the SM predicted accidental simmetries

- Key tool to study neutrinos
  - Majorana or Dirac nature ($\nu = \bar{\nu}$ or $\nu \neq \bar{\nu}$))
  - ν mass scale and ordering (inverted or normal hierarchy)
  - CP-violation in the lepton sector





$0\nu\beta\beta$ half-life time

- $0\nu\beta\beta$ is a nuclear process:
  - 2nd order transition: $(A, Z) \rightarrow (A, Z+2)$
  - even-even nuclei: β-decay is forbidden
- half-life expression can be factorized as:

$$\left[t_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,F$$

  - $G_{0\nu}$: Phase Space Factor (PSF, atomic physics)
  - $\mathcal{M}$: Nuclear Matrix Element (NME, nuclear physics)
  - F : New Physics Term

  $\Rightarrow$ in case of 3 light neutrino exchange:

$$F = |m_{\beta\beta}|^2$$

  where $m_{\beta\beta}$ is the Majorana mass

- $m_{\beta\beta}$ is the key quantity in the $0\nu\beta\beta$
  - Absolute value of the ee-entry of the neutrino mass matrix
  - $|m_{\beta\beta}| = \left|\sum_{i=1,2,3} e^{i\xi_i}\,|U_{ei}^2|\,m_i\right|$
  - U can be identified with the mixing matrix of the oscillation analysis

    F. Capozzi, *et al.*, arXiv:1804.09678 [hep-ph]

    F. Capozzi, *et al.*, Phys. Rev. D 95 (2017) 096014
  - $U \equiv U|_{\text{osc.}} \cdot \text{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
  - 1 CP-violating + 3 Majorana phases
  - Only two phases play a *physical* role

$$|m_{\beta\beta}| = \left|e^{i\alpha_1}\cos^2\theta_{12}\cos^2\theta_{13}m_1 + e^{i\alpha_2}\cos^2\theta_{13}\sin^2\theta_{12}m_2 + \sin^2\theta_{13}m_3\right|$$

Experimental search for $0\nu\beta\beta$

- Detection: energy (track) of the 2 emitted e^-
  - monochromatic peak at the Q-value of the decay ($Q_{\beta\beta}$)
  - smearing due to finite energy resolution

- Observable: decay half-life of the isotope, $t^{0\nu}_{1/2}$
  - in the case of a peak in the energy spectrum

$$t^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{N_{\beta\beta}}{N_{\text{peak}}} \qquad \left(\frac{\delta t^{0\nu}_{1/2}}{t^{0\nu}_{1/2}} = \frac{\delta N_{\text{peak}}}{N_{\text{peak}}} \right)$$

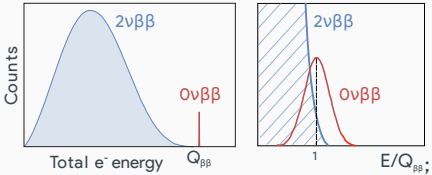
  - if no peak is detected, the sensitivity corresponds to the maximum signal that can be hidden by the background fluctuations $n_B = \sqrt{M\,T\,B\,\Delta E}$

$$S^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n}{n_\sigma \cdot \sigma_B} = \ln 2 \cdot \frac{1}{n_\sigma} \cdot \frac{x\,N_A}{\mathcal{M}_A} \cdot \eta \cdot \varepsilon \sqrt{\frac{M\,T}{B\,\Delta E}}$$

($M\,T$ is the total exposure)

M = detector mass T = measuring time B = background level ΔE = energy resolution

ε = detection efficiency η = candidate isotopic abundance



- Good energy resolution ΔE
  - only protection against $2\nu\beta\beta$ spectrum tail
  - $R_{0\nu/2\nu} \propto \left(\frac{Q_{\beta\beta}}{\Delta}\right)^6 \frac{t^{2\nu}_{1/2}}{t^{0\nu}_{1/2}}$

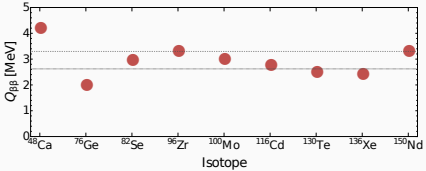
- Very low background B
  - underground location + shielding
  - radio-pure materials for detector and surrounding parts
  - analysis rejection techniques

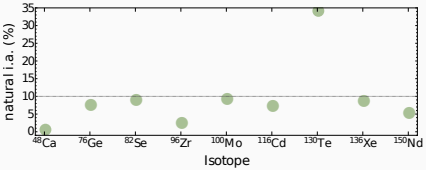
- Large isotope mass M
  - present: some tens up to hundreds of kg
  - tonnes required to cover the IH region

Choice of the isotope

- Value of $Q_{\beta\beta}$ $\rightarrow$ influences the backgroud
  - $>$ 2.6 ($>$ 3.3) MeV end-point of main γs (βs)
  - avoid radioactivity peak position
  - $<$ 4.01 MeV starting point of main αs
- High isotopic abundance
  - ease of material enrichment (technologically + economically)
- Availability of the isotope
  - tonnes required for future $0\nu\beta\beta$ experiments
    $\rightarrow$ high cost + large procurement time
- Compatibility with a detection technique

Most suitable isotope + detector combination





Promising isotopes

^{48}Ca	^{76}Ge	^{82}Se
^{96}Zr	^{100}Mo	^{116}Cd
^{130}Te	^{136}Xe	^{150}Nd

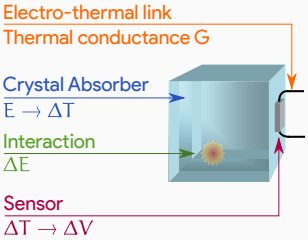
Low Temperature Detectors as Calorimeters

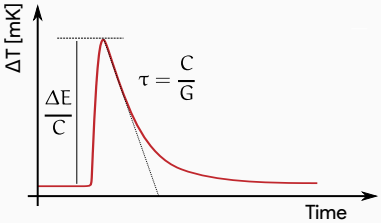
- Complete energy thermalization:
  ionization, excitation $\Rightarrow$ heat $\Rightarrow$ calorimetry;

- $\Delta T = \Delta E / C$ where ΔE is the released energy and C the total thermal capacity;
  - Absorber with very low thermal capacity: $C \downarrow \quad \Rightarrow \quad \Delta T \uparrow$;
  - Debye law for superconductors below T_C and dielectric: $C \propto (T/\Theta_D)^3$;
  - A very low temperature is needed:
    $T \downarrow \Rightarrow C \downarrow \Rightarrow \Delta T \uparrow \Rightarrow (T = 10 \div 100\ \text{mK})$;

- Limit to energy resolution $\Rightarrow$ statistical fluctuation of internal energy $\Delta E_{rms} = \sqrt{k_B T^2 C}$;

- $\Delta T(t) = \dfrac{\Delta E}{C} e^{-t/\tau}$ with $\tau = \dfrac{C}{G}$ and G thermal conductance.





TeO_2 Low Temperature Calorimeters

Decay under study: $^{130}Te \rightarrow {}^{130}Xe + e^-$

Absorber

Why ^{130}Te:

- High isotopic abundance: 34.167% $\Rightarrow$ no need for enrichment;
- Q-value (2527.5 keV)
  almost above the natural γ background (>2615 eV)
  below the natural α background (<4.01 MeV);

Why TeO_2:

- Easy to grow big crystals with low radioactive contaminations;
- Good mechanical properties;
- Low heat capacity (dielectric and diamagnetic).

Sensor

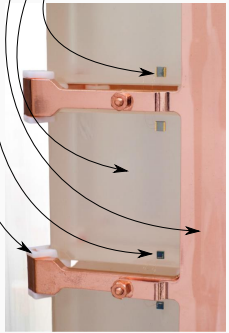
NTD-Ge thermistor:

- Germanium crystal doped by thermal neutrons;
- Operate in VRH (Variable Range Hopping) regime;

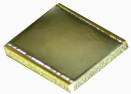
$$R(T) = R_0 e^{\left(\frac{T_0}{T}\right)^{\frac{1}{2}}}$$

$$R_0 = 1\,\Omega \quad , \quad T_0 = 4\,\mathrm{K}$$

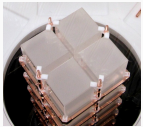
Thermal link: PTFE holders and gold wires
Joule heater: for thermal gain calibration
Thermal bath: Cu structure (cryostat)
Absorber: 5×5×5 cm3 TeO2 crystal
Thermistor: NTD Ge semiconductor



NTD-Ge Thermistor



TeO_2 crystals



Operating at 10 mK
with C ~ nJ/K

$$\frac{\Delta T}{E} \sim \frac{100\,\mu\mathrm{K}}{\mathrm{MeV}}$$

CUORE Experiment

Cryogenic Underground Observatory for Rare Events

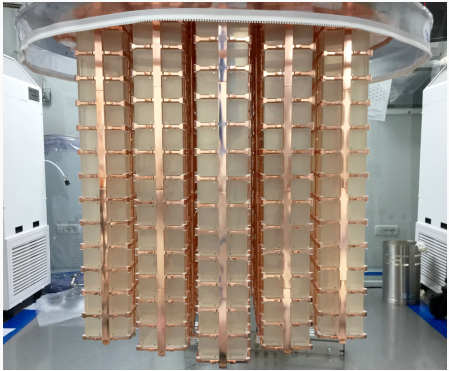
The larger thermal detector array ever built

CUORE Detector:

- Custom Cryostat to reach $T_0 \simeq 10$ mK;
- Array of 988 TeO_2 crystals;
- Total mass of 742 kg;
- 19 towers, 13 floors, 4 crystal for each floor;
- TeO_2 absorber $5 \times 5 \times 5\,cm^3$ (750 g each);
- Stringent radiopurity control on materials and assembly;
- Target energy resolution: 5 keV @ 2615 (FWHM);
- Background aim: 10^{-2} count/keV/kg/yr;
- $t_{1/2}^{0\nu}$ sensitivity in 5 years:

$$t_{1/2} \geq 9.0 \cdot 10^{25} \text{ yr @ } 90\% \text{ C.L}$$

$$m_{\beta\beta} \leq (45 - 211) \text{ meV}$$

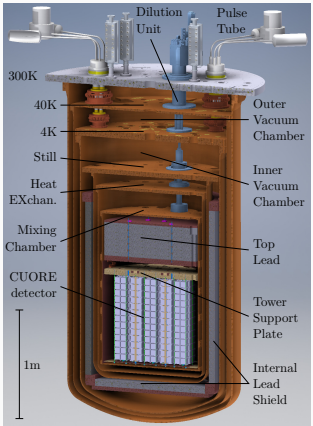


- All 19 towers installed between July-August 2016;
- First cool down in December 2016;
- Base temperature 7 mK in 26/01/2017;

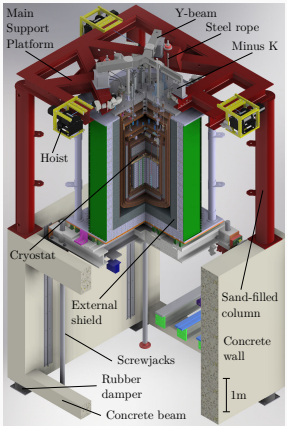
first event observed the same day;

CUORE infrastructure

Rendering of the CUORE cryostat



Rendering of the cryostat support structure

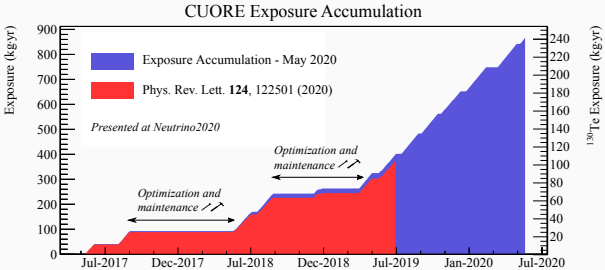


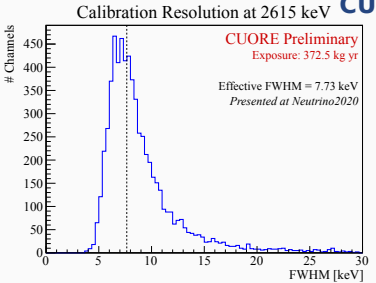
Cryogenics 102 (2019) 9-21
Cryogenics 93 (2018) 56-65

The coldest cubic meter in the known Universe

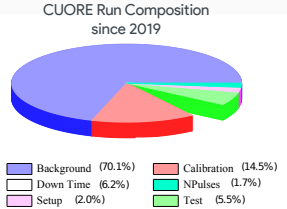
- Powerful multistage cryogen-free cryostat
  - Precooled by a fast cooling system;
  - Pulse Tubes (PTs),
  - ^{3}He/^{4}He dilution refrigerator
- cooling power: 5 μW at 10 mK
- Cooldown time around 1 month;
- Cryogenic vessels and shielding:
  - 13 tonnes < 4 K
  - 5 tonnes < 50 mK
  - 1500 kg @ 10 mK (detectors + materials)
- External Shielding:
  - 30 cm lead
  - 18 cm polyethylene + 2 cm borated material
- Mechanical vibration isolation;
- Active noise cancellation;

CUORE data taking





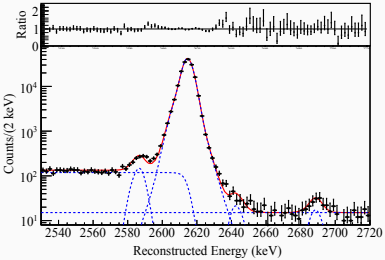
- 7 dataset from April 14, 2017;
- 900(min)-950(max) (over 988) valid calorimeters;
- 7.73 keV FWHM @ 2615 keV;
- 7.0 keV FWHM @ Q-value;
- 372.5 kg·yr of TeO_2 exposure accumulated;
- $\sim$ 10 keV of trigger thresold;
- 40 keV of analysis thresold;



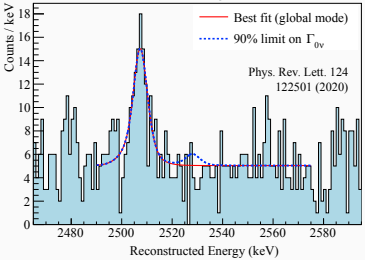
Stable conditions allowed continued data taking with minimal onsite activity during recent lockdowns

CUORE $0\nu\beta\beta$ results

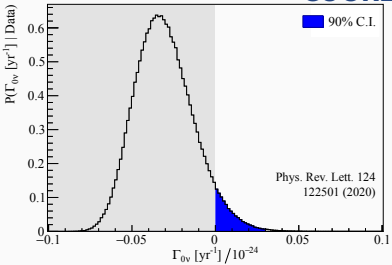
Combined Calibration Fit (DS2)



CUORE ROI Spectrum



Posterior distribution



- Bayesian Analysis (with BAT)
- Likelihood model: flat continuum (BI), and posited peak for $0\nu\beta\beta$ (rate), peak for ^{60}Co (rate+position)
- Unbinned fit on physical range (rates non negative), unifor prior om $\Gamma_{0\nu}$;
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

- No evidence for $0\nu\beta\beta$ decay of 130Te;
- Background index in the ROI:

$$B = (0.0138 \pm 0.0007)\ \text{cnts/keV/kg/yr}$$

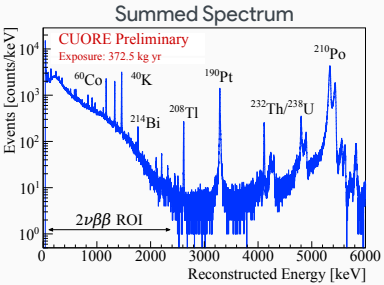
- $t^{0\nu}_{1/2}$ sensitivity (90% CL):

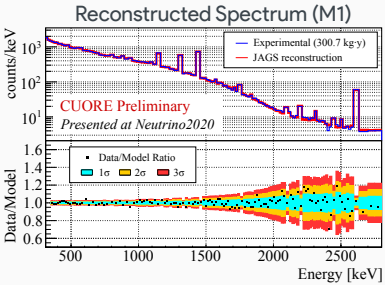
$$t^{0\nu}_{1/2} > 3.2 \cdot 10^{25}\ \text{yr}$$

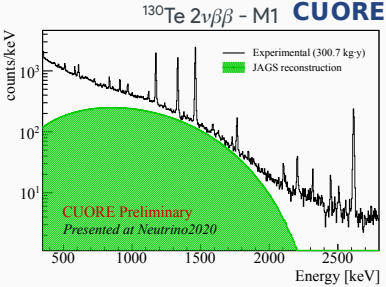
- Limit on the neutrino mass:

$$m_{\beta\beta} < (75 - 350)\ \text{meV}$$

CUORE $2\nu\beta\beta$ preliminary results







- Reconstruct CUORE continuum background;
- GEANT4 simulation + measured detector response function to produce expected spectra;
- 62 sources considered, Bayesian fit with flat priors (except for muons);
- Exploit coincidences and detector self-shielding to constrain location of sources

- CUORE-0 (Eur. Phys. J. C77 (2017) 1, 13)

$$t^{2\nu}_{1/2} = [8.2 \pm 0.2_{(\text{stat})} \pm 0.6_{(\text{sys})}] \cdot 10^{20}\ \text{yr}$$

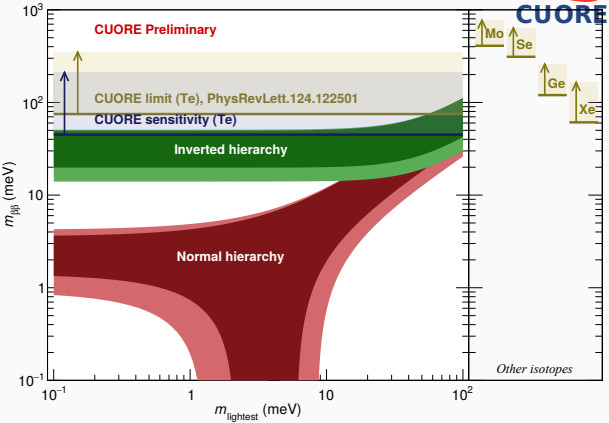
- CUORE (preliminary)

$$t^{2\nu}_{1/2} = \left[7.71^{-0.08\ \ -0.17}_{-0.06\ (\text{stat})\ -0.15\ (\text{stat})}\right] \cdot 10^{20}\ \text{yr}$$

- reduction of a factor 3 on both statistical and systematic uncertainties

CUORE Sensitivity

CUORE Collaboration



- CUORE data taking continues smoothly
  ⇒ stable conditions allowed continued data taking with minimal onsite activity during recent lockdowns;
- CUORE will reach the target sensitivity in a few years, approaching the Inverted Hierarchy Region
  ⇒ next unblinding is foreseen at 1 tonne· year

Conclusion

- The study of frontier subjects in neutrino physics require the use of frontier detectors;
- Observation of $0\nu\beta\beta$ decay would prove that neutrinos are Majorana particle
- CUORE accumulated over 400 kg·yr exposure, new data is being acquired;
- ... and will approach the Inverted Hierarchy Region in a few years;
- Successfull performance of CUORE justifies future developments of cryogenics calorimeters;

$\Rightarrow$ CUPID program: Cuore Upgrade with Particle IDentinficaion
(see Davide Chiesa's talk just after this)