HADRON 2023

The CUORE and CUPID double-beta decay experiments

Searching for 0νββ with cryogenic bolometers

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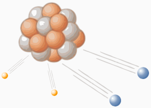
20th International Conference on Hadron Spectroscopy and Structure

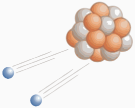
June 5 – 9, 2023 - Genova, Italy

Double Beta Decay: real and virtual neutrinos



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

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



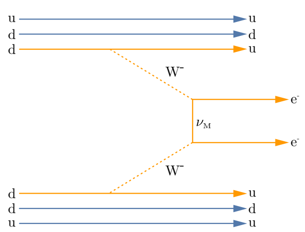
- *L*-violation: creation of a pair of electrons
  - discovery of 0νββ

    ⇒ *L* is not a symmetry of the universe

    ⇒ link to baryon asymmetry in Universe (?)
- assuming the ν mass mechanism

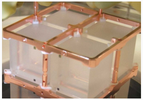
  → 0νββ key tool for studying neutrinos
  - Majorana or Dirac nature
  - mass scale and ordering

A possible diagram

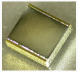


A powerful search aims at optimal **isotope + detector technique** combination

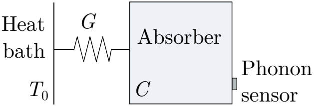
- bolometers detect the **phonon** contribution of the energy release
  - large fraction of the total energy
  - ionization/excitation $\rightarrow \cdots \rightarrow$ phonons
  - measured via **temperature variation**



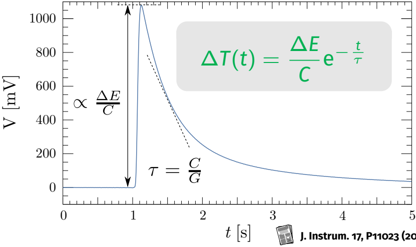
- $\Delta T = \Delta E/C$
  - **low C**: $C \downarrow \;\Rightarrow\; \Delta T \uparrow$
  - **very low T**
    - Debye law: $C \propto (T/\Theta_D)^3$
    - thermal fluctuations $\propto T^2\, C$
- temporal evolution: $\tau = C/G$
- Neutron Transmutation Doped Ge thermistor
  - $R = R_* \; \exp{(T_*/T)^{1/2}}$



Simplified thermal model



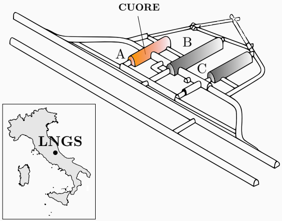
- an absorber with heat capacity C
- (connected to) a heat bath @ constant T_0
- (through) a thermal conductance G



J. Instrum. 17, P11023 (2022)

Cryogenic Underground Observatory for Rare Events

- search for $0\nu\beta\beta$ of ^{130}Te
- largest bolometric detector ever built
    - 19 towers × 13 floors × 4 crystals = 988 bolometers
    - 1 tonne detector mass: 330 kg Cu + 742 kg TeO_2
      → 206 kg of ^{130}Te
- at the Laboratori Nazionali del Gran Sasso
    - $\sim$ 3600 m w. e. (μ: $3 \cdot 10^{-8}$ cm^{-2} s^{-1})
    - 30-year-long history of measurements



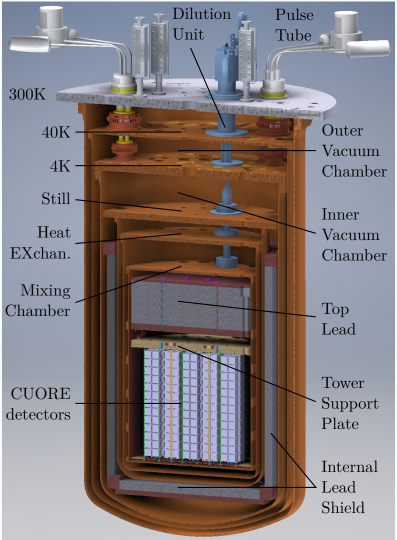
CUORE requires a **dedicated cryogenic system** in order to be operated as a bolometer

CUORE cryostat

- 6+1 thermal stages
  - 300 K @ ambient temperature
  - 40 K @ PT first stage temperature
  - 4 K @ PT second stage temperature
  - Still @ 800 mK
  - HEX @ 50 mK
  - MC @ base $T < 10$ mK
  - TSP @ stabilized working T
- 2 vacuum chambers
- Fast Cooling System +

  5 Pulse Tubes + custom Dilution Unit
- 2 internal lead shields
  - use of ancient **Roman lead**
  - Spanish ingots from I century BCE
  - ^{210}Pb activity $<$ **715 uBq kg^{-1}**

Cryogenics 102, 9 (2019)



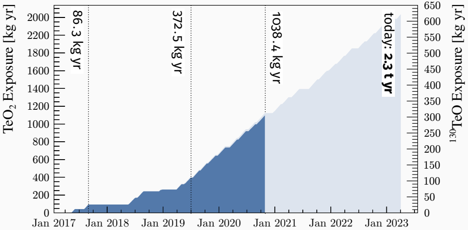
CURE data-taking

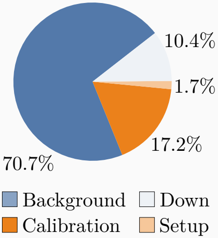
- start of data-taking in April 2017
  - initial period of detector optimization
- *full-speed* data collection since 2019
  - exposure increase of $\sim$ 60 kg yr per month
- goal: 3 t yr of TeO_2 (**1 t yr of ^{130}Te**)

Phys. Rev. Lett. 124, 122501 (2020)

Phys. Rev. Lett. 120, 132501 (2018)

Nature 604, 53 (2022)





Operational performance

- operating $T = 11 - 15$ mK
  - year-long cryogenic stability
- uptime close to 90%
- 99.5% of channels active (984/988)
- energy resolution at $Q_{\beta\beta}$ of **7.8 keV** FWHM
- 0νββ signal efficiency of $\sim$ **80%**

Results on the search for 0νββ

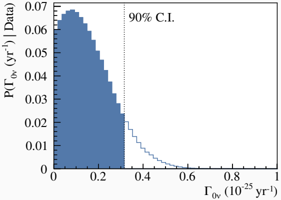
Nature 604, 53 (2022)

- **no peak** found at $Q_{\beta\beta}$ of ^{130}Te
  - 1038.4 kg yr of TeO_2 / 288 kg yr of ^{130}Te
- **bkg index** in line with expectations:

  $(1.49 \pm 0.04) \cdot 10^{-2}$ counts keV^{-1} kg^{-1} yr^{-1}
- **limit** on decay half-life:

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

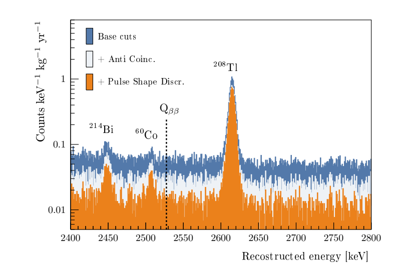
  $t_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr @ 90% C. I.

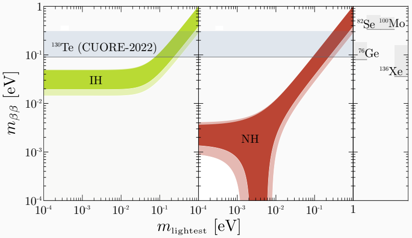


- bound on effective Majorana mass:

  $m_{\beta\beta} > (90 - 305)$ meV

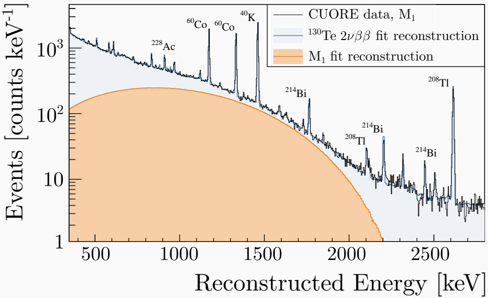
ROI spectrum





Study of the ^{130}Te decay

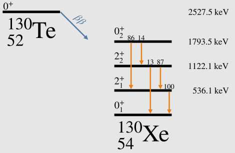
Phys. Rev. Lett. 126, 171801 (2021)



- $2\nu\beta\beta$ spectrum dominates in $(1 - 2)$ MeV range
  - accounts for $\sim 50\%$ of M_1 events
- most precise measurement of $2\nu\beta\beta$ of ^{130}Te
  - TeO_2 exposure: 300.7 kg yr
  - $t_{1/2}^{2\nu} = \left(7.71 \ ^{+0.08}_{-0.06} \text{ (stat.)} \ ^{+0.12}_{-0.15} \text{ (syst.)}\right) \times 10^{20}$ yr

Decay to excited states

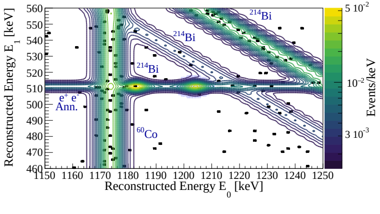
Eur. Phys. J. C 81, 567 (2021)



- search for de-excitation γ's
- multi-site signatures
- no peak was found
- limits @ 90% C. I.
  - TeO_2 exposure: 372.5 kg yr
  - $(t_{1/2})^{0\nu}_{0_2^+} > 5.9 \times 10^{24}$ yr
  - $(t_{1/2})^{2\nu}_{0_2^+} > 1.3 \times 10^{24}$ yr

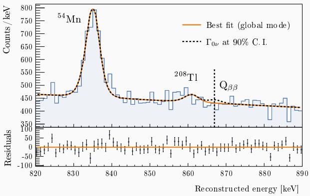
- $0\nu\beta^+$EC of ^{120}Te ($Q_{\beta\beta}$= 1714.8 keV)
  - $^{120}\text{Te} + e_b^- \rightarrow {}^{120}\text{Sn}^* + \beta^+$
    $\rightarrow {}^{120}\text{Sn} + X + \beta^+$
    $\rightarrow {}^{120}\text{Sn} + X + 2\,\gamma_{511}$
  - multiple signatures in M1, M2 and M3
  - limit: $t_{1/2}^{0\nu} > 2.9 \times 10^{22}$ yr @ 90% C. I.
    - 355.7 kg yr of TeO_2 / 0.2405 kg yr of ^{120}Te ($^{120}\text{Te}/^{nat}\text{Te} = 0.09\%$)

Phys. Rev. C 105, 065504 (2022)



- $0\nu\beta\beta$ of ^{128}Te ($Q_{\beta\beta}$= 866.7 keV)
  - limit: $t_{1/2}^{0\nu} > 3.6 \times 10^{24}$ yr @ 90% C. I.
    - 309.33 kg yr of TeO_2 / 78.56 kg yr of ^{120}Te

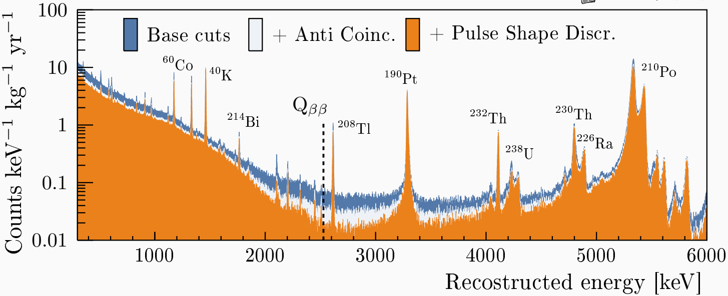
Phys. Rev. Lett. 129, 222501 (2022)



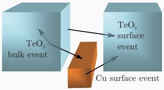
- broad-band investigations
  - low-E search for DM (WIMPS, axions, ...)
  - high-mulitplicity event reconstruction for exotic processes
  - spectral-shape studies of $2\nu\beta\beta$ for CPT violation, Majoron emission, ...

CUORE background

Nature 604, 53 (2022)



- different contributions in different regions of the energy spectrum
  - γ continuum + peaks up to 2.7 MeV
  - degraded α's in $(2.7 - 3.9)$ MeV
  - α region from 4 MeV

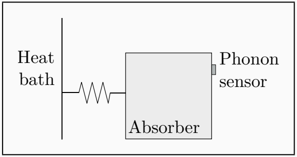


- construction of an extensive **background model**
  - large effort ongoing since predecessors of CUORE
  - ultimate validation by CUORE data

Beyond CUORE

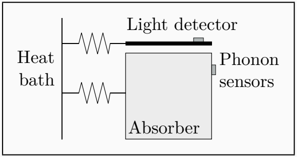
- experimental search for 0νββ: $t^{0\nu}_{1/2} \propto \sqrt{M\,T/B\,\Delta}$
- when $M\,T\,B\,\Delta = \mathcal{O}(1)$, i. e. no event expected in ROI: $t^{0\nu}_{1/2} \propto M\,T$

  $\rightarrow$ crucial to achieve zero background, so that sensitivity scales linearly with exposure



CUORE

- ^{130}Te ($Q_{\beta\beta}$ = 2527.5 keV)
  - below ^{208}Tl @2615 keV
- only heat channel
  - pure thermal detector
  - no particle identification

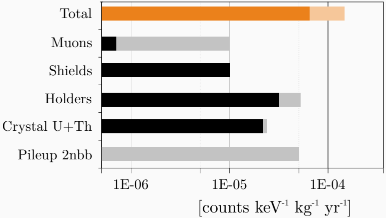


Next generation

- ^{100}Mo ($Q_{\beta\beta}$ = 3034.4 keV)
  - reduced γ contribution
- heat + light
  - scintillating bolometer
  - α vs. β/γ discrimination

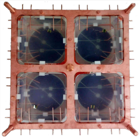
C*UORE* U*pgrade with* P*article* ID*entification*

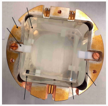
- tonne-scale array of scintillating bolometers for the search of 0νββ of ^{100}Mo
- keep CUORE cryogenic infrastructure
  - cost-effective + low risk
- replace CUORE TeO_2 detector with $Li_2{}^{100}MoO_4$ crystals
  - $>$ 95% enrichment (quite expensive, but available at industrial scale)
- Collaboration extended to $>$ 130 members
  - joined groups from CUORE, CUPID-0 & CUPID-Mo
  - expoiting different expertise
  - optimized R&D program
  - reliable projected background



Where we are

Eur. Phys. J. C 81, 104 (2021)

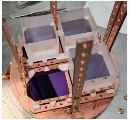


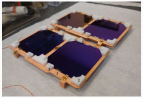


J. Instrum. 16, P02037 (2021)

- rich R&D program
  - simulation of whole detector + facility
  - multiple cryogenic facilies operational (Italy, France, US)
    - $\rightarrow$ benchmark of baseline decisions
    - $\rightarrow$ test of alternative design & technologies
    - $\rightarrow$ background control
- BDPT: first validation of detector baseline design
  - Baseline-Design Prototype Tower
  - 2-floor proof-of-principle successfully deployed
  - runs with 14-floor 'full scale' tower ongoing

Eur. Phys. J. C 82, 810 (2022)

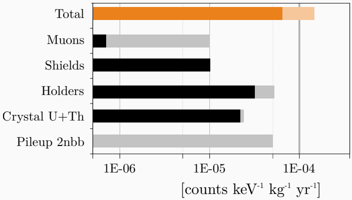


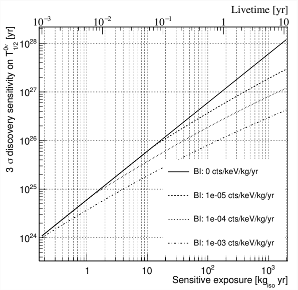


arXiv:2304.04674 [physics.ins-det]

CUPID physics potential

- mass: 450 kg, i. e. $\sim$ 240 kg of ^{100}Mo
  - 1596 $Li_2{}^{100}MoO_4$ crystals
  - 57 towers of 14 floors of 2 crystals
  - each $45 \times 45 \times 45\,mm^3$, with a mass of 280 g
- live time: 10 yr
- resolution: 5 keV at $Q_{\beta\beta}$
- bkg: 10^{-4} counts $keV^{-1}\,kg^{-1}\,yr^{-1}$ in ROI
- sensitivity on 0νββ: $t^{0\nu}_{1/2} > 10^{27}$ yr
  - $m_{\beta\beta} < (15 - 20)$ meV
  - full coverage of Inverted-Hierachy region
- other searches
  - rare decays: 2νββ, excited states
  - spectral-shape study: CPT-violation, Majorons
  - low-E searches: DM, axions, CEνNS

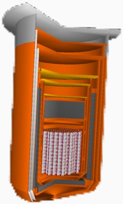




arXiv:1907.09376 [physics.ins-det]

Ultimate goal

CUPID baseline



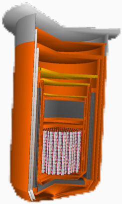
240 kg ^{100}Mo

1×10^{-4} ckky

CUORE cryostat

$t_{1/2}^{0\nu} > 1.4 \times 10^{27}$ yr

CUPID reach



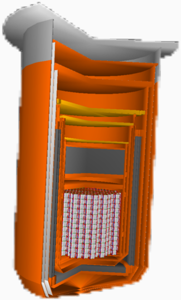
240 kg ^{100}Mo

2×10^{-5} ckky

CUORE cryostat

$t_{1/2}^{0\nu} > 2.2 \times 10^{27}$ yr

CUPID 1T

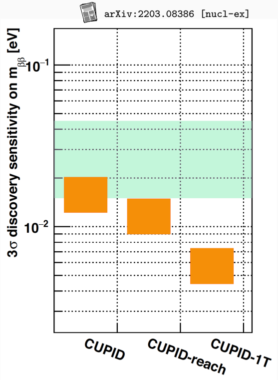


1000 kg ^{100}Mo

5×10^{-6} ckky

new cryostat

$t_{1/2}^{0\nu} > 9.1 \times 10^{27}$ yr



Summary & Outlook

- CUORE has been collecting data since 2017
  - the current limit on the $0\nu\beta\beta$ of ^{130}Te is: $t_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr @ 90% C. I.
  - multiple analyses are ongoing
  - new results on $0\nu\beta\beta$ search & background-model to be released soon
  - the goal is to collect 1 t yr of ^{130}Te
- CUPID will be the successor of CUORE, searching for $0\nu\beta\beta$ of ^{100}Mo
  - the project takes advantage of existing expertise & infrastructures
  - a rich R&D program is ongoing ($\rightarrow$ BDPT)
  - the goal sensitivity is $t_{1/2}^{0\nu} > 10^{25}$ yr, thus probing the IH region
  - a staged approach foresees up to 1t of isotope in a future CUPID-1T experiment

Thank you!

LNGS (Italy), June 2022

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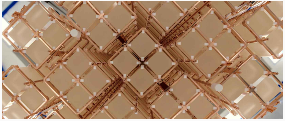
CUORE detector commissioning

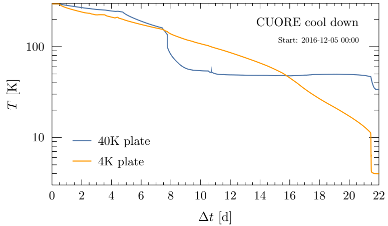
- tower assembly (Sep 2012 – Jul 2014)
- cryostat commissioning

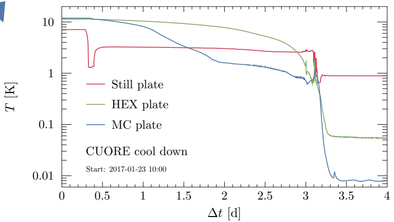
  (Aug 2012 – Mar 2016)
- detector installation (Jul – Aug 2016)



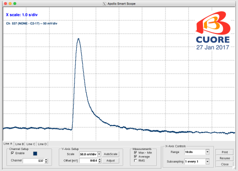
- cool down: T_{MC} = 6.8 mK

CUORE cool down



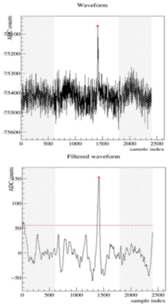


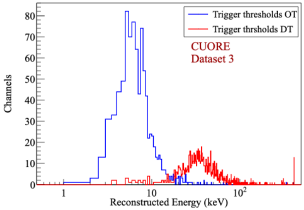
First events @ Jan 2017



Triggering pulses

- Online Derivative Trigger (DT): threshold on the derivative of the data-stream
- Offline Optimal Trigger (OT): identification of pulses in the filtered data-stream (template filter: expected pulse shape wrt to expected noise)



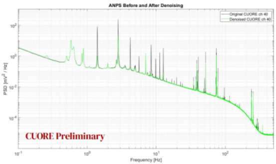


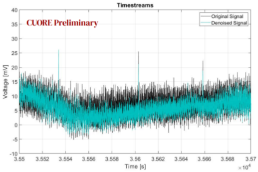
Thresholds: DT ~50 keV, OT <10 keV

CUORE low thresholds

Denoising the continuous data

Remove noise from calorimeter channels utilising diagnostic devices (accelerometers, antennae, microphones) which can identify and measure the noise sources.

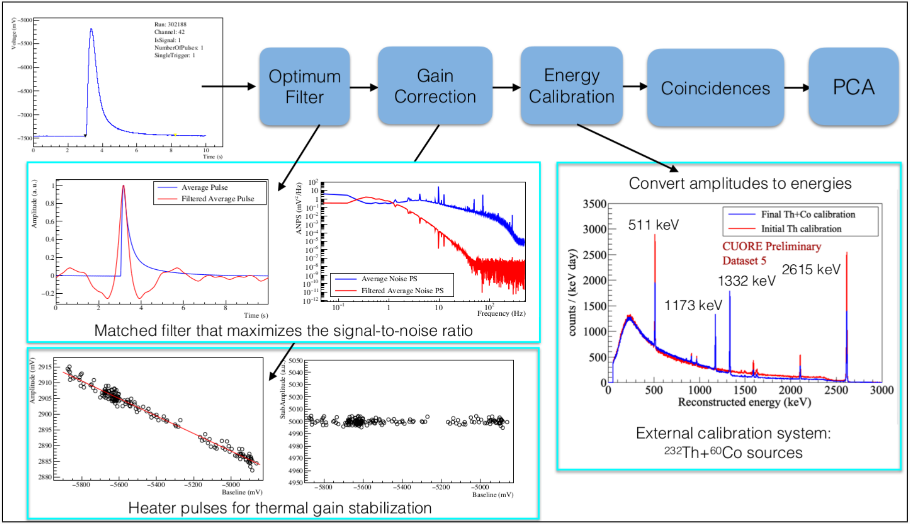




CUORE denoising @DNP 2021

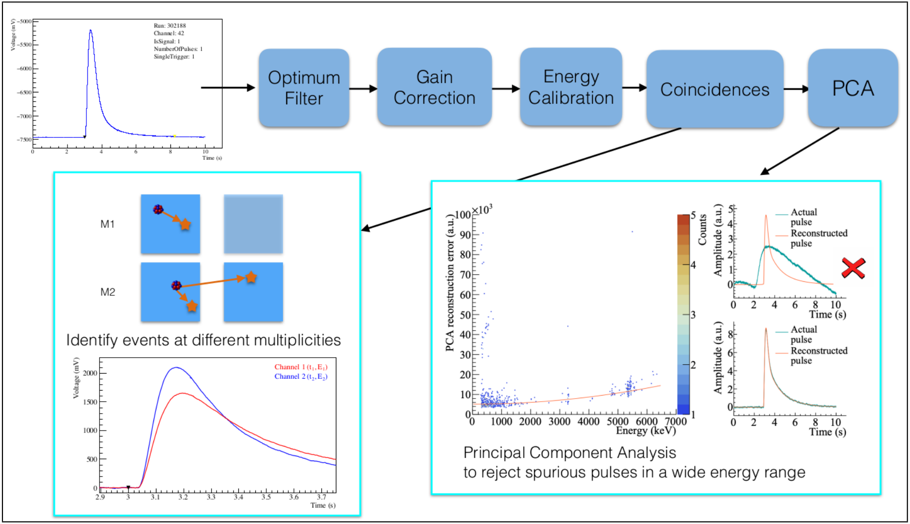
By courtesy of I. Nutini, *CUORE talk @Neutrino2022*

CUORE data processing II



By courtesy of I. Nutini, *CUORE talk @Neutrino2022*

CUORE data processing III

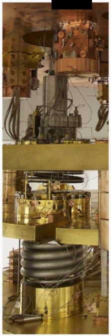


By courtesy of I. Nutini, *CUORE talk @Neutrino2022*

Some pictures from the CUORE cryostat

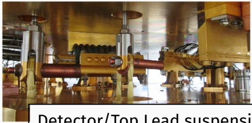
Plates + Top Lead

DU



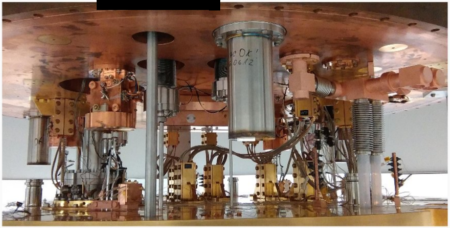
PT

Superinsulation

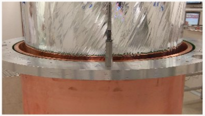


Detector/Top Lead suspensions

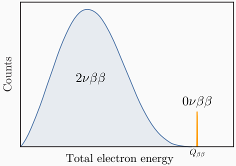
Inside the IVC



Vessels



- the **search** relies on detection of the 2 emitted e^-
  - monochromatic peak at $Q_{\beta\beta}$
  - smearing due to finite energy resolution



- the **observable** is the decay half-life $t^{0\nu}_{1/2}$ of the isotope
  - the experimental sensitivity corresponds to the maximum signal that can be hidden by the background fluctuations $n_B = \sqrt{M\,T\,B\,\Delta}$

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

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

- the **information on the neutrino mass** can be extracted

$$\left[t^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,\frac{m^2_{\beta\beta}}{m^2_e}$$

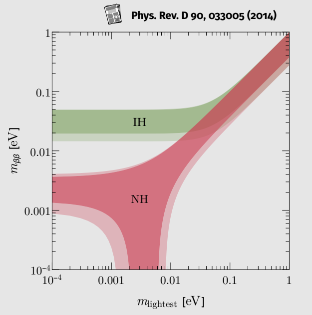
  - $G_{0\nu}$ = **Phase Space Factor** (atomic physics)
  - $\mathcal{M}$ = **Nuclear Matrix Element** (nuclear physics)
  - $m_{\beta\beta}$ = **effective Majorana mass** (particle physics)

$$m_{\beta\beta} \leq \frac{m_e}{\mathcal{M}\sqrt{G_{0\nu}\,t^{0\nu}_{1/2}}}$$

Effective Majorana mass

- $m_{\beta\beta}$ is the key quantity in the 0νββ
  - absolute value of **ee-entry** of ν mass matrix
  - $m_{\beta\beta} \equiv |M_{ee}| = \left| \sum_{i=1,2,3} e^{i\xi_i} \, |U_{ei}^2| \, m_i \right|$
  - $U \equiv U|_{osc.} \cdot \text{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
    - 1 CP-violating + 3 **Majorana phases**
    - U **mixing matrix** of oscillation analysis
  - only two phases play a *physical* role
- $m_{\beta\beta} = \left| e^{i\alpha_1} \cos^2\theta_{12} \cos^2\theta_{13} m_1 + e^{i\alpha_2} \cos^2\theta_{13} \sin^2\theta_{12} m_2 + \sin^2\theta_{13} m_3 \right|$

$m_{\beta\beta}$ vs. m_{lightest}



An **experimental measurement** of the 0νββ half-life corresponds to

a **horizontal band** in the ($m_{\beta\beta}$ vs. m_{lightest}) plot.

The band width is due to **theoretical uncertainties** from atomic and nuclear physics