CUPID: a next generation bolometric 0νββ decay experiment

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0νββ decay

ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ decay
  $\Rightarrow$ Energy peak is the only necessary and sufficient signature to claim a discovery
- Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, daughter tagging, ...

0νββ decay rate

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2
\]

- $T_{1/2}^{0\nu}$ = 0νββ decay half-life
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- $f$ = new physics term
The bolometric technique

- Low heat capacity @ \( T \sim 10 \text{ mK} \)
- Excellent energy resolution (~0.2% FWHM)
- Detector agnostic to origin of energy deposition
- Detector response of O(1) sec if readout with e.g. Neutron Transmutation Doped (NTD) Ge sensors

Simplified thermal model

- Crystal heat capacity: \( C \)
- Conductivity of coupling to thermal bath: \( G \)
- Signal amplitude \( \propto \Delta T = \frac{E_{\text{dep}}}{C} \)
- Decay constant: \( \tau = \frac{G}{C} \)
Isotope choice for bolometric experiment

- High isotopic abundance
- Enrichment possible at reasonable cost?
- $Q_{\beta\beta}$ above end point of $\beta$ or $\gamma$ radiation?
- Scintillating crystal available?
- Large scale crystal production possible?

Advantages of bolometric approach

- Detectors and infrastructure are decoupled. Same cryogenic infrastructure re-usable with different isotopes and/or crystals
- Perfect for test of discovery or precision measurements
The CUORE experiment
The CUORE experiment

CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO₂ crystals with natural Te composition
  → **742 kg total mass**, 206 kg $^{130}$Te mass
- $Q_{\beta\beta}^{(130}\text{Te}) = 2527.5$ keV  → Above most natural γ background
- Located in [Hall A of the Gran Sasso National Lab](https://www.sasso-2000.com/
- Background goal: $10^{-2}$ counts/keV/kg/yr at $Q_{\beta\beta}$
- Sensitivity goal on $T_{1/2}^{0\nu} = 9 \cdot 10^{25}$ yr with 5 yr of live time
CUORE infrastructure

The coldest cubic meter in the known Universe
- Multistage cryogen-free cryostat
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding
- Roman Pb shielding in cryostat
- External Pb shielding
- $\text{H}_3\text{BO}_3$ panels + polyethylene
CUORE results

2νββ decay analysis

- Exposure: 300.7 kg·yr
- Full background model of γ region
- $T_{1/2}^{2ν} = 7.71^{+0.08}_{-0.06} (\text{stat})^{+0.12}_{-0.15} (\text{syst}) \cdot 10^{20}$ yr
  → most precise $^{130}$Te half life measurement!
- Refined background model in progress

0νββ decay analysis

- Exposure: 1038.4 kg·yr
- Fit model: linear bkg + 0νββ + $^{60}$Co peak
- Sensitivity: $T_{1/2}^{0ν} = 2.8 \cdot 10^{25}$ yr
- $T_{1/2}^{0ν} > 2.2 \cdot 10^{25}$ yr @ 90% c.i.
  → $m_{\beta\beta} < 90 - 305$ meV (NME dependent)
- BI: $(1.49\pm0.04) \cdot 10^{-2}$ counts/keV/kg/yr
CUORE background: lessons learned for CUPID

- ~90% of measured background is due to $\alpha$ particles (U/Th close to TeO$_2$ crystals)
  - $\alpha/\beta$ discrimination would suppress the background by one order of magnitude
- A $Q_{\beta\beta} > 2.6$ MeV would automatically reduce the remaining non-$\alpha$ background by one order of magnitude
- Muons are the next dominant contribution
  - Implement active muon veto
Background suppression via Particle IDentification (PID)

- Couple main crystal with secondary bolometer reading the scintillation light
- Exploit different light yield (LY) of $\alpha$ vs $\beta/\gamma$ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)
CUPID-0

Experiment structure

- 26 ZnSe crystals (24 enriched at 95% in $^{82}$Se)
- Light detectors: Ge wafer + NTDs
- Crystals + LDs encapsulated in copper + reflector foil
- 5 towers, located in old Cuoricino cryostat at LNGS
- Total Phase-I exposure: **9.95 kg·yr**
- $\alpha$ rejection through pulse shape of light signal
CUPID-0 results

\[ T^{0\nu}_{1/2} > 3.5 \cdot 10^{24} \text{ yr @ 90\% C.I.} \]

\[ m_{\beta\beta} < 311-638 \text{ meV (depending on NME)} \]

- Background at \( Q_{\beta\beta} \): \( 3.5 \cdot 10^{-3} \text{ counts/keV/kg/yr} \)
  - Lowest ever in bolometric experiment
- Only \( \sim 6\% \) of background from surfaces facing the crystal

\[ T^{2\nu}_{1/2} = [8.6 \pm 0.03\text{(stat)}^{+0.17}_{-0.10}\text{(syst)}] \cdot 10^{19} \text{ yr} \]

- Tested SSD vs HSD for \(^{82}\text{Se} \rightarrow \text{HSD excluded}\)
- Full background model using energy, time, and space information
  - Precise understanding of contaminant locations and intensities
  - Novel technique to reconstruct events from the same U/Th decay chain
CUPID-Mo

Experiment structure

- Located in Edelweiss cryostat @ Modane
- 20 $\text{Li}_2\text{MoO}_4$ crystals of ~210g enriched at 97% in $^{100}\text{Mo}$
- 20 Ge wafers instrumented as light detectors
- Neutron transmutation doped (NTD) thermistors
- Silicon-based resistors used as heaters for pulser events

Data collection

- Physics data: March 2019 - June 2020
- Analysed data: March-2019 - April 2020
→ Analyzed exposure: 2.16 kg·yr

CUPID-Mo, EPJ C80 (2020) A4
CUPID-Mo results

0νββ decay analysis

- Bayesian counting analysis in Q_{ββ} ±50 keV
  \[ T_{1/2}^{0ν} > 1.5 \times 10^{24} \text{ yr} \] @ 90% C.I. → Best result so far in 100Mo!
- \( m_{ββ} < 0.3-0.5\) eV (depending on NME)
- Bi O(10^{-3}) counts/keV/kg/yr
  → Precise evaluation with background model ongoing

CUPID-Mo is a real experiment, not just a demonstrator!
CUPID: CUORE Upgrade with Particle IDentification

- Profits of vast experience from predecessor experiments:
  - isotope choice
  - background suppression and active rejection
  - cryogenic techniques
- Same cryogenic infrastructure of CUORE
- $\text{Li}_2\text{MoO}_4$ scintillating crystals
- $^{100}\text{Mo}$ enrichment $> 95$
- $45 \times 45 \times 45$ mm$^3$ crystals
- New, simpler tower structure (under advanced testing)
- ~1500 crystals $\rightarrow$ ~250 kg of $^{100}\text{Mo}$
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- $\alpha$ rejection via particle identification on light detector
- Goal background: $10^{-4}$ counts/keV/kg/yr

CUPID, arXiv:1907.09376
CUPID, EPJ C 81 (2021) 2, 104
CUPID, JINST 16 (2021) 02, P02037
CUPID background projection and sensitivity

- Crystals
  - U/Th bulk → from CUPID-Mo
  - U/Th surface → from CUORE bkg-model
  - 2νββ pile-up ($T_{1/2}^{2ν} = 7.1 \times 10^{18}$ yr)
- Crystal holders
  - U/Th surface → CUORE-0 bkg-model
- Reflector foil:
  - U/Th → CUPID-0 bkg-model + BiPo3
- Cryogenic infrastructure and shielding
  - U/Th bulk → CUORE bkg-model
- Muons → Cut by muon veto

**Discovery sensitivity**

- $T_{0ν}^{1/2} = 10^{27}$ y
- $m_{ββ} = 12 - 20$ meV

→ Fully cover the inverted ordering region
THANK YOU!