FINAL RESULTS OF THE CUPID-0 PHASE I EXPERIMENT

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On behalf of the CUPID-0 collaboration
CUPID-0 FOR CUPID
(CUORE UPGRADE WITH PARTICLE ID)

CUPID is a proposed 0νββ experiment based on scintillating bolometers. Its mission is to discover 0νββ decay if $m_{ββ} > 10$ meV.

TECHNICAL CHALLENGES
- Detector mass in the range of several hundred kg of the ββ isotope
  ➢ Isotopic enrichment
- Background close to zero at the ton×year exposure scale
  ➢ Active background rejection and improved material selection
- Energy resolution of a few keV (FWHM) around 0νββ Q-value

CUPID-0 is the first demonstrator of the new technologies that will be implemented in CUPID and it is also a competitive 0νββ decay search in its own right.
Scintillating bolometers

- A bolometer is a highly sensitive calorimeter operated at cryogenic temperature (~10 mK)
- Energy deposits are measured as temperature variations of the absorber
- If the absorber is also an efficient scintillator the energy is converted into heat + light

Detector Features

- High energy resolution $\mathcal{O}(1/1000)$
- High detection efficiency (source = detector)
- Particle IDentification

A close-to-zero background experiment is feasible:

- $\alpha$ background: identification and rejection
- $\gamma/\beta$ background: $\beta\beta$ isotope with large Q-value
Array of scintillating bolometers for the investigation of $^{82}\text{Se}\, 0\nu\beta\beta$ ($Q = 2997.9 \pm 0.3$ keV).

- 95% enriched Zn$^{82}$Se bolometers
- 10.5 kg of ZnSe, 5.17 kg of $^{82}\text{Se}$ ($3.8\times10^{25}$ $\beta\beta$ nuclei)
- Ge bolometers at top/bottom of crystals to detect scintillation
- NTD thermistors to measure energy depositions
- Reflecting foils to enhance light collection
- High radiopure copper holder structure
CUPID-0 @ LNGS

- Deep underground location at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, 1400 m of rock (~3600 m.w.e.)
- Installed in the cryostat previously used for Cuoricino and CUORE-0 experiments
CUPID-0 DATA TAKING (PHASE I)

- Data taking started on March 17\textsuperscript{th}, 2017
- Data presented here collected between June 2017 and December 2018

\begin{itemize}
  \item \textsuperscript{56}Co Energy Calibration
  \item \textsuperscript{232}Th Energy Calibration
  \item System maintenance
  \item Neutron calibration (characterization of $\beta/\gamma$ shape parameters at RoI)
  \item $\beta\beta$ physics
    - ZnSe exposure: $9.95 \text{ kg}\times\text{yr}$
    - \textsuperscript{82}Se exposure: $5.29 \text{ kg}\times\text{yr}$
\end{itemize}
Detector Calibration with $^{232}$Th

- $^{232}$Th sources are periodically deployed beside the cryostat for calibration of heat and intercalibration of light detectors
**Detector Calibration with $^{56}$Co**

We performed a calibration run with a $^{56}$Co source to:

- check the goodness of energy reconstruction
- evaluate the energy resolution at $^{82}$Se $Q_{\beta\beta}$

The exposure-weighted harmonic mean FWHM energy resolution at $^{82}$Se $Q_{\beta\beta}$ is equal to:

$$(20.05 \pm 0.34) \text{ keV}$$
0νββ SEARCH: HEAT SPECTRUM PRODUCTION

- **Anti-coincidence** → tag & reject events depositing energy in more than one ZnSe crystal within a ±20ms window
- Rejection of **pile-up** (1 sec before and 4 sec after trigger)
- Rejection of “non-particle” events through **pulse shape analysis**

**ββ physics spectrum**

**0νββ RoI**

- **82Se exposure:** 5.29 kg·yr

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0νββ SEARCH: REJECTION OF α PARTICLES

- Rejection of α events based on the shape of the light pulse

- mean value of α particle SP ($\mu_\alpha(E)$)
- acceptance threshold = $\mu_\alpha(E) - 3 \cdot \sigma_\alpha(E)$
- energy below which the PID is not applied

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0νββ SEARCH: REJECTION OF $^{208}\text{Tl}$ EVENTS

Analysis of $\alpha - \beta/\gamma$ delayed coincidences:

- $^{208}\text{Tl}$ $\beta/\gamma$ events are preceded by $^{212}\text{Bi}$ $\alpha$ events
- We veto any event preceded by a primary $^{212}\text{Bi}$ $\alpha$ event within 7 half-life time window
- $^{212}\text{Bi}$ events are selected among $\alpha$ events with energy in the range 2 – 6.5 MeV
0νββ SEARCH: RESULTS

**Background index in the range** [2.8 – 3.2] MeV:

\[(3.5^{+1.0}_{-0.9}) \cdot 10^{-3} \text{ cnts/(keV\cdot kg\cdot yr)}\]

*Lowest background achieved with bolometric experiments.*

No evidence of 0νββ signal

Best half-life limit on \(^{82}\)Se 0νββ

\[T_{1/2}^{0\nu} > 3.5 \cdot 10^{24} \text{ yr (90\% C.I.)}\]

\[m_{\beta\beta} < 311 – 638 \text{ meV}\]

range due to the nuclear matrix element calculations

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<table>
<thead>
<tr>
<th>Event Confined inside a Single Crystal</th>
<th>81.0±0.2 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger Efficiency + Energy Properly Reconstructed</td>
<td>99.5 %</td>
</tr>
<tr>
<td>Heat Pulses Selection Efficiency + Delayed Coincidences</td>
<td>88 %</td>
</tr>
<tr>
<td>Beta/Gamma Selection Efficiency</td>
<td>98 %</td>
</tr>
<tr>
<td><strong>Total Signal Efficiency</strong></td>
<td>70±1 %</td>
</tr>
</tbody>
</table>

82Se exposure: 5.29 kg×yr
BACKGROUND MODEL

**Experimental Data**

*Analysis of background source signatures*

**Monte Carlo Simulations of Background Source Spectra**

**Fit of the Source Spectra to the Experimental Data**

**Activity of Background Sources**

Comprehension of background in $0\nu\beta\beta$ RoI.

Predictions

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arXiv:1904.10397
Experimental data divided according to \textit{multiplicity} and \textit{particle type}

→ we build 4 spectra

- Analysis of $\gamma$ and $\alpha$ lines in the spectra.

\begin{itemize}
  \item \textbf{Multiplicity (M)}
  \end{itemize}

Time-coincidence window: 20ms

- $M_1$: energy in each crystal
- $M_2$: energy in two crystals
- $\Sigma_2$: total energy in two crystals

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BACKGROUND MODEL: MC SIMULATIONS

- Monte Carlo simulations (Geant4) of background sources
- CUPID-0 geometry modelled with high detail
- Reproduction of detector features (coincidences, resolution, particle ID, thresholds, ...)

[Diagram showing CUPID-0 geometry with labels for CryoExt, CryoInt, IntPb, Holder, Crystals & Reflectors]
BACKGROUND MODEL: SOURCES

Background model uses 33 sources:
- different contaminants ($^{232}$Th and $^{238}$U decay chains, $^{40}$K, cosmogenic activation, ...)
- different positions in the experimental setup
- Muons

**BACKGROUND SOURCES**

- **Cryostat**:
  - **CryoInt**: 50mK and 600mK cryostat internal shields & holder bulk
  - **CryoExt**: IVC, OVC, superinsulation, main bath & External Lead shield

- **Internal/near sources to fit M1α spectrum**
  - **Crystals**: bulk / shallow surface $\mathcal{O}(10\text{nm})$ / deep surface $\mathcal{O}(10\mu\text{m})$
  - **Reflectors & Holder surface**: shallow surface $\mathcal{O}(10\text{nm})$ / deep surface $\mathcal{O}(10\mu\text{m})$
  - **Surface**: exponential profile

- **External sources**
  - **CryoInt**: 50mK and 600mK cryostat internal shields & holder bulk
  - **IntPb**: ancient roman lead shield
  - **CryoExt**: IVC, OVC, superinsulation, main bath & External Lead shield
**BACKGROUND MODEL: BAYESIAN FIT**

- We perform a simultaneous **Bayesian fit** to M1\(\alpha\), M1\(\beta/\gamma\), M2, and \(\Sigma 2\) spectra to determine source activities (i.e. MC normalizations)
- We use **Markov Chain MC** to sample the **Joint PDF** of fit parameters
- **Priors** are exploited to include additional information from previous experiments/radioassay measurements and from special analyses of CUPID-0 data:
  - Muons \(\rightarrow\) normalized to M\(>3\) events
  - Analysis of \(\alpha-\alpha\) delayed coincidences to get information about positions of crystal contaminations.

**\(^{238}\text{U CHAIN}\)**

- \(^{222}\text{Rn} \quad \tau_{1/2} = 3.82\text{ d}\)
- \(^{218}\text{Po} \quad \tau_{1/2} = 3.11\text{ m}\)
- \(^{214}\text{Pb} \quad \tau_{1/2} = 26.8\text{ m}\)

**\(^{232}\text{Th CHAIN}\)**

- \(^{224}\text{Rn} \quad \tau_{1/2} = 3.66\text{ d}\)
- \(^{220}\text{Rn} \quad \tau_{1/2} = 55.6\text{ s}\)
- \(^{216}\text{Po} \quad \tau_{1/2} = 0.145\text{ s}\)
- \(^{212}\text{Pb} \quad \tau_{1/2} = 10.64\text{ h}\)

Given a **parent** event @ Q-value (\(P_Q\)), the probability to observe a time-correlated **daughter** event @ Q-value (\(D_Q\)):

\[
P(D_Q | P_Q)\]

depends on source position (bulk vs surface).
BACKGROUND MODEL: FIT RESULT M1 $\beta/\gamma$

**Plot Description:**

The plot illustrates the fit result of the background model $\beta/\gamma$ with the following key features:

- **Counts per keV:** The y-axis represents the number of counts per keV, with a logarithmic scale.
- **Energy (keV):** The x-axis represents the energy in keV.
- **Alpha ($\alpha$) and Beta Gamma ($\beta/\gamma$) Regions:** The plot highlights two regions: $\alpha$ and $\beta/\gamma$.
- **Activity Sources:**
  - $^{65}$Zn
  - $^{40}$K
  - $^{208}$Tl

**Legend:**

- **$M_{1\beta/\gamma}$ - Experimental**
- **$M_{1\beta/\gamma}$ - Fit reconstruction**

**Analysis:**

The fit result shows a comparison between experimental data and the fitted model, indicating a good agreement in the $\beta/\gamma$ region, suggesting that the background model accurately represents the experimental observations.
**Background Model: Fit Result M1 α**

Counts / keV

- **α-only**
- **147Sm**
- **α-decay peaks from natural decay chains**
- **214BiPo**
- **212BiPo**

Counts ratio vs Energy (keV)

- **1 σ**
- **2 σ**
- **3 σ**

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Peaks and continuum are well modelled

Some differences in BiPo pile-up events, due to imperfect energy reconstruction

Distribution of fit residuals compatible with a Gaussian with $\mu = 0$ and $\sigma = 1$. 

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Background sources contributing to the M1β/γ reconstruction, grouped by position and contaminant:

2νββ is the dominant contribution

Possibility to perform detailed study on this decay (paper in preparation)

232Th in Crystals is the main contribution in RoI because rejection of 208Tl events is not applied here

After delayed coincidences cut

Muons give ~44% of residual background rate in RoI

Other background sources in crystals, reflectors, cryostat & shields, contributing to the RoI at a level of a few 10^{-4} counts/(keV kg y)
CUPID-0 PHASE II: UPGRADES

- Muons are main residual background
- No reflective foil
- New cleaner Cu shield

Installation of $\mu$-veto
Sensitivity to M2 $\alpha$ events
Thermalization and additional shielding

Data taking started this week!!!!!
SUMMARY AND FUTURE PERSPECTIVES

- CUPID-0 is the first large array of enriched scintillating bolometers
- CUPID-0 Phase I → ZnSe exposure: 9.95 kg·y
- Excellent background index in the $^{82}$Se 0νββ RoI:
  $$(3.5^{+1.0}_{-0.9}) \cdot 10^{-3} \text{ counts} / (\text{keV} \cdot \text{kg} \cdot \text{yr})$$
- Acquired data allowed to establish the **best half-life limit** on $^{82}$Se 0νββ decay:
  $$T_{1/2}^{0\nu} > 3.5 \cdot 10^{24} \text{ yr (90\% C.I.)}$$
- Background model: information on background sources and best measurement of $^{82}$Se 2νββ decay (paper in preparation)
- CUPID-0 Phase II → better understanding of background sources

Thanks for your attention!!!