Final results of the CUPID-0 Phase I experiment

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Outline

- $0\nu\beta\beta$ motivations
- The cryogenic calorimetric technique
- CUPID-0
  - Detector design and construction
  - Detector performance
- Results
$0\nu\beta\beta$ implications

$0\nu\beta\beta$ at the level of nucleons:

\[ 2n \rightarrow 2p + 2e^- \]

- need lepton-number-violating physics beyond the SM ($\Delta L=2$)
- 2 leptons are produced out of energy: matter creation ("leptogenesis")

Fundamental process (strong implications):

- Baryo/Leptogenesis requires the violation of baryon number and lepton number ($B-L$ is the only conserved quantity)

$0\nu\beta\beta \leftrightarrow$ proton decay
Expected signal

- Signal: peak at the sum-energy (Q) of the two electrons (2-3 MeV depending on the isotope)
- Backgrounds: natural radioactivity in the detector proximity, cosmic rays, ...
- $0\nu\beta\beta$ Half-life: limits in the range of $>10^{26}$ y

Computed energy spectrum

Energy spectrum from natural radioactivity
The Gran Sasso underground facility

Laboratori Nazionali del Gran Sasso
INFN, Italy

Unique site for low background physics

Experimental location:
- Average depth 3600 m w.e.
- Muon flux $2.6 \times 10^{-8} \, \mu/s/cm^2$
- Neutrons < 10 MeV: $<10^{-6} \, n/s/cm^2$
Scintillating bolometers

A bolometer is a highly sensitive calorimeter operated @ 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

↓ Fully active detectors
↓ Slow thermal signal O(5 seconds)
↑ High energy resolution O(1/1000)
↑ High detection efficiency (source = detector)
↑ Particle ID

The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

A **background-free experiment** is possible: α-background: identification and rejection
CUPID-0

CUPID-0 is the first array of scintillating bolometers for the investigation of $^{82}\text{Se} 0\nu\beta\beta$

- $^{82}\text{Se}$ Q-value 2998 keV
- 95% enriched Zn$^{82}\text{Se}$ bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
  - 10.5 kg of ZnSe
  - 5.17 kg of $^{82}\text{Se} \rightarrow N_{\beta\beta} = 3.8 \times 10^{25} \beta\beta$ nuclei
- Light Detector: Ge wafer operated as cryogenic detector
- Simplest modular detector $\Rightarrow$ scale up
  - Copper structure (ElectroToughPitch)
  - PTFE holders
  - Light Reflector (VIKUITI 3M)
Data taking

• Data taking started on March 17th, 2017
• Data presented here collected between June 2017 and December 2018

- $^{56}$Co Energy Calibration
- $^{232}$Th Energy Calibration
- System maintenance

74%
12%
10%
3%
1%

ZnSe exposure: 9.95 kg*\( y \)
$^{82}$Se exposure: 5.29 kg*\( y \)

Neutron calibration (characterization of $\beta/\gamma$ shape parameters at RoI)
Detector energy calibration

Detector energy calibration using $^{232}$Th and $^{56}$Co gamma-radioactive sources:

- Evaluation of the energy resolution at $^{82}$Se $Q_{\beta\beta}$ (2998 keV)
- Study on the energy reconstruction

The exposure-weighted harmonic mean **FWHM energy resolution** at $^{82}$Se $Q_{\beta\beta}$ 

$\text{(20.05±0.34) keV}$
$0\nu\beta\beta$ search: heat spectrum

Single energy deposition at 3 MeV in 1 crystal

DATA SELECTION:

- **Rejection of Non-particle** events through **Pulse Shape Analysis**
- **Anti-coincidence**: reject energy deposit in more than one ZnSe crystal within a ±20ms window
- Rejection of **pile-up** (1 sec before and 4 sec after trigger)

![Energy Spectrum Graph](image)

**$0\nu\beta\beta$ Region of interest**

Background in the RoI: $3.2 \times 10^{-2} \text{ c/keV/kg/yr}$
0νββ search: alpha particle rejection

Rejection of α particle interactions: **Pulse shape analysis of light channel**

**ββ total energy scatter plot**

![Total energy scatter plot](image)

- alpha
- beta/gamma

**0νββ Region of interest**

![Region of interest](image)

- Final Heat Spectrum
- + α Rejection

**Background in the RoI:** \(1.3 \times 10^{-2} \text{ c/keV/kg/y}\)

- mean value for alpha particles \(\text{SP}(\mu_\alpha(E))\)
- acceptance threshold = \(\mu_\alpha(E) - 3\sigma_\alpha(E)\)
- energy below which the PID is not applied
0νββ search: high energy β rejection

Rejection of α-related events:
Delayed alpha coincidence $^{212}\text{Bi} - 208\text{Tl}$

$^{212}\text{Bi} \alpha$ event are selected in a range of (2.5-6) MeV

For each $^{212}\text{Bi} \alpha$ event the detector is disabled for $7\tau_{1/2}$ (21 min).

Rejection of high energy $\gamma$ from $^{208}\text{Tl}$.

$^{208}\text{Tl}$ t = 3.05 m

$b+g$ 100%

Q = 5001 keV

$^{212}\text{Bi}$ t = 60.6 m

a 36%

Q = 6207 keV

$b+g$ 64%

Q = 2254 keV

$^{212}\text{Po}$ t = 299 ns

a 100%

Q = 8954 keV

$^{208}\text{Po}$ stable

$^{212}\text{Bi} - 208\text{Tl}$

0νββ Region of interest

Background in the RoI: $3.5 \times 10^{-3}$ c/keV/kg/y

Lowest background ever achieved with cryogenic detectors
Background model

Development of Monte Carlo simulation code (based on Geant4) for background sources studies
- Highly detailed model of CUPID-0 detector geometry
- Reproduction of detector features (coincidences, resolution, particle ID, thresholds, …)

Background model uses >30 sources:
- different contaminants (\(^{232}\)Th and \(^{238}\)U decay chains, \(^{40}\)K, cosmogenic activation, …)
- different positions in the experimental setup
- Muons

\(^{232}\)Th in Crystals is the main contribution (delayed coincidence of \(^{208}\)Tl is not applied)

After delayed coincidences cut
44\% of residual background rate in RoI are muons
Results on $0\nu\beta\beta$ search

$0\nu\beta\beta$ Region of interest (9.95 kg ZnSe $\times$ y)

UEML Simultaneous fit over the datasets
No evidence of $0\nu\beta\beta$

Best half-life limit on $^{82}$Se:
$T^{0\nu} > 3.5 \times 10^{24}$ yr (90% C.I.)

Corresponding to a neutrino mass limit

$m_{\beta\beta} < 311 - 638 \text{ meV}^*$

* depending on the Nuclear Matrix Element adopted

<table>
<thead>
<tr>
<th>Probability 0vDBD event confined inside a single crystal</th>
<th>81.0±0.2 %</th>
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<tbody>
<tr>
<td>Trigger efficiency + energy properly reconstructed</td>
<td>99.5 %</td>
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<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>Total signal efficiency</td>
<td>70±1 %</td>
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Inverted Ordering ($\Delta m^2 < 0$)

Normal Ordering ($\Delta m^2 > 0$)
The future: CUPID
Cuore Upgrade with Particle ID

• Goal: explore the entire inverted ordering neutrino mass region down to 10 meV
• How: merge the **Cuore cryogenic infrastructure** with **CUPID-0 particle ID technique**

• Highly enriched Li$_2$MoO$_4$ crystals
• Large array of 1500 Li$_2$MoO$_4$ crystals + LDs
• Total detector mass about 250 kg of $^{100}$Mo
• Operation in almost null-background conditions: $10^{-4}$ c/keV/kg/y

TDR and construction readiness by 2021

Conservative, Mature, Data Driven Baseline Design
Conclusions

- 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 $^{82}\text{Se}$ $0\nu\beta\beta$ RoI: $3.5 \times 10^{-3}$ c/keV/kg/y
- Best half-life limit on $^{82}\text{Se}$ $0\nu\beta\beta$ decay: $T_{0\nu} > 3.5 \times 10^{24}$ yr (90%C.I.)
- CUPID-0 Phase II → validation of current background model
- We are currently shaping CUPID collaboration and project