Innovative light detectors for background rejection in CUORE and CUPID

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Calorimeters for 0nDBD

CUORE

sets the standard for next generation experiments exploiting calorimeters:

• Hundreds of kg of source ➔ Proved

• Good Energy Resolution ➔ ~0.1% for CUORE-like detectors

• Goal: background of $o(100)$ events in the ROI $\rightarrow T_{1/2}(\beta\beta)\sim 10^{26}$ y
**CUPID**

**CUPID**: Cuore Upgrade with Particle IDentification


Goal: increase sensitivity on 0nDBD from $9 \times 10^{25}$ y to $>10^{27}$ y

- **CUORE cryostat** ➔ useful also for CUPID (ultimate limit in mass)

- Calorimeters: **energy resolution 0.1%** ➔ ideal also for CUPID

- But reduce **background** from $o(100)$ events in the ROI ➔ $~0$ in CUPID!
CUPID: **Cuore Upgrade with Particle IDentification**


Goal: increase sensitivity on 0nDBD from $9 \times 10^{25}$ y to $>10^{27}$ y

**CUORE cryostat** useful also for CUPID (ultimate limit in mass)

Calorimeters: *energy resolution 0.1%* ideal also for CUPID

But reduce *background* from $o(100)$ events in the ROI $\Rightarrow \sim 0$ in CUPID!

- Main background: *alpha particles from detector materials*
- Exploit *light output* for particle ID (alpha rejection)
Particle Identification in TeO$_2$

Couple a light detector to TeO$_2$ to measure the Cherenkov light emitted by e- (not by α’s)

CUORE TeO$_2$ : low light output (~100 eV at 0νββ from Cherenkov emission)

Using a “standard" LD with noise of 80 eV RMS does not permit particle ID

A LD with noise RMS < 20 eV would allow to reject the dominant background (α)
Particle Identification: alternative

Use compounds that, in contrast to TeO₂, emit scintillation light at 10 mK

- ZnSe (⁸²Se)
- ZnMoO₄
- Li₂MoO₄ (¹⁰⁰Mo)
- CdWO₄ (¹¹⁶Cd)

Suggested talks (all the 20th):

- C. Nones: “Scintillating bolometers for the study of double beta decay”
- N. Casali: “CUPID-0 cryogenic calorimeters with particle ID for double beta decay”
- A. Giuliani: “A 100Mo pilot experiment with scintillating bolometers (CUPID activities)
Particle Identification in TeO$_2$

Requirements for a light detector suitable for CUPID:

- Baseline resolution $<20$ eV RMS
- Large active area ($5 \times 5$ cm$^2$)
- High radio-purity
- Ease in fabrication/operation ($\sim 1000$ channels)
  - Reproducible behavior in a rather wide temperature range (5-20 mK)
  - Low heat load for cryogenic system
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But none of the existing technologies fulfills all these requirements (yet)

We propose a new technology
Kinetic Inductance Detectors

- Superconductors operated in AC
- Cooper Pairs acquire kinetic inductance $L$
- It act as a resonator
- Photons break Cooper pairs $\rightarrow$ change $L$ $\rightarrow$ change resonance

\[
 f_0 = \frac{1}{2\pi \sqrt{LC}}
\]

Amplitude [dB]

Frequency [MHz]

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- **Low heat load for cryogenic system**
Phonon mediated approach

**Goal of the CALDER project**

1) Optimize detector geometry, read-out and analysis using Aluminum $\rightarrow$ 80 eV

2) Move to more sensitive superconductors (TiAl, TiN..) and increase surface $\rightarrow$ <20 eV

3) Large-scale test of our light detectors on TeO$_2$ array at LNGS (Italy)

Phase 1

Al KIDs on 2x2 cm² Si substrate (goal: 5x5 cm²)

First test (with 4 KIDs): 150 eV RMS (goal: 80 eV)

Optimize the design of the resonator and our analysis tools to improve the RMS

Two energy estimators: phase/amplitude

Usually phase has better signal-to-noise ratio

We developed tools to combine them accounting for noise correlations

Frequency and width $\rightarrow$ 2 informations

KIDs are characterized by dual-readout
Phase 1

Al KIDs on 2x2 cm$^2$ Si substrate (goal: 5x5 cm$^2$)

First test (with 4 KIDs): 150 eV RMS (goal: 80 eV)

Optimize the design of the resonator and our analysis tools to improve the RMS

Reached noise 82 eV RMS

Resolution constant up to 200 mK

References:


Phonon mediated approach

Goal of the CALDER project

1) Optimize detector geometry, read-out and analysis using Aluminum → 80 eV

2) Move to more sensitive superconductors (TiAl, TiN..) and increase surface → <20 eV

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Phase 2: surface

Al KIDs on 2x2 cm² Si substrate (goal: 5x5 cm²)

1st test with a KID on a 5x5 cm² substrate (last week)

Frequency [Hz]

<table>
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<th>2596</th>
<th>2597</th>
<th>2598</th>
<th>2599</th>
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<td>6</td>
<td>10</td>
<td>10</td>
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Magnitude [dB]

| 8.5÷9 cm |

Ratio: 0.63

Cobalt

Fibers

Graph
Phase 2: new materials

Al does not allow to achieve the necessary sensitivity $\rightarrow$ other superconductors

$$
\Delta E \propto \frac{T_C}{\epsilon \sqrt{Q L}}
$$

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ti-Al</th>
<th>Ti+TiN</th>
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</thead>
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<tr>
<td><strong>Tc [K]</strong></td>
<td>1.2</td>
<td>0.6 - 0.9</td>
<td>0.5 - 0.8</td>
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<tr>
<td><strong>L [pH/square]</strong></td>
<td>0.5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td><strong>producer</strong></td>
<td>INF-CNR</td>
<td>CSNSM-Néel, CNRS</td>
<td>FBK</td>
</tr>
<tr>
<td><strong>status</strong></td>
<td>completed</td>
<td>this result</td>
<td>in production</td>
</tr>
</tbody>
</table>

First tests on Ti-Al and Al-Ti-Al prototypes
Again a 2x2 cm² Si substrate sampled by KIDs made of different materials
Goal: from 80 eV to <20 eV

Phase 2: new materials
Development of sensitive cryogenic LD is fundamental for CUPID

Phonon-mediated KIDs is a viable technology

CALDER Phase-I reached 80 eV with Aluminum KIDs, now in Phase-II (20 eV) with more sensitive superconductors

Preliminary tests already hit 30 eV

http://www.roma1.infn.it/exp/calter

Thank you for the attention
Most of cryogenic calorimeters suffer from the lack of active background rejection

Solution: measure not only energy but also light

Good discrimination power >1 MeV, spoiled at low E because of LD resolution ~80 eV RMS

Not a problem for 0νββ, but a better LD (RMS < 20eV) would provide particle ID also at low energy (below 30 keV) —> dark matter searches “for free”
Sitting in the center of the resonance loop, we can monitor variations in I and Q (or, changing coordinates, in amplitude/phase) produced by interactions.

Since phase is more sensitive, we use this estimator to reconstruct the pulse energy.
KIDs efficiency

\[ \delta \phi = \frac{\alpha S_2(\omega, T)}{N_0 \Delta^2} \cdot \frac{Q}{V} \cdot \frac{\epsilon E}{E} \]

More or less material dependent

Test with LED [400 nm] + optical fiber, but also with $^{55}$Fe/$^{57}$Co X-rays (calibration systematics)

We tested different detector configurations: Al on a 2x2 cm$^2$, 300 µm thick Si substrate:

*Geometry*

- 6 keV pulses from $^{55}$Fe

Efficiency

We varied thickness (t) and active area (A), as we expect $\epsilon$ to scale as (tA)

1. Single pixel t: 25 nm, A: 2.4 mm$^2$ → $\epsilon \sim 2\%$
2. Single pixel t: 40 nm, A: 2.4 mm$^2$ → $\epsilon \sim 7\%$
3. Single pixel t: 40 nm, A: 4.0 mm$^2$ → $\epsilon \sim 11\%$

The efficiency is position dependent, but we can correct this effect exploiting pulses time development
If we are dominated by the amplifier noise (ideal case), we expect the resolution to scale as:

$$\sigma_E = \frac{2N_0 \Delta_0^2}{\alpha S_2(\omega, T)} \frac{V}{Q\epsilon} \sqrt{\frac{kT_N}{Pf\tau_{qp}}}$$

More or less material dependent

Geometry

In the 4-pixel configuration, we measured samples with noise from 150 eV to 90 eV. We changed $V$, $\alpha$, $Q$ and $\epsilon$ of the single KID. The resolution changed from 160 to 90 eV.

Target of phase-I (80 eV) within reach

Low frequency noise, probably ascribable to electronics, always present in our KIDs.

It limits the energy resolution, that could better also with Al films.

Now under investigation.