Status of CALDER: Kinetic Inductance light detectors for neutrinoless double beta decay

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http://www.roma1.infn.it/exp/calder/
Detect Cherenkov or scintillation light from large-mass bolometers to search for double beta decay with the CUORE successor.

Sensor R&D by other groups: NTD or TES (w or w/o Luke amplification)

**We investigate a new technology for this field: KIDs**
Cooper pairs (cp) in a superconductor act as an inductance ($L$).

Absorbed photons change cp density and $L$.

High quality factor ($Q$) resonating circuit biased with a microwave (GHz): signal from amplitude and phase shift.
Multiplexed readout of a KID array

Different resonators can be coupled to the same feedline with slightly different resonant frequencies. Resonant frequency modified via the capacitor (C) pattern of the circuit.

132 pixel CMB camera

Multiplexing up to 100-1000 KIDs has been already demonstrated.
Counting Near Infrared Photons with Microwave Kinetic Inductance Detectors

(a) Response [a.u.]
(b) Time [μs]
(c) TiN absorber
(d) Homodyne detection scheme

ΔE = 0.22 eV
CALDER: light detectors with KIDs

GHz operation limits the maximum sensible area of KIDs to few mm$^2$

Scaling to several cm$^2$: indirect detection mediated by phonons

Substrate of silicon (5x5cm$^2$ x 300µm)

Diffused phonons can be absorbed by the KIDs

KIDs (~2mm$^2$ x 60-nm)

Incident photons convert into athermal phonons

Supports

Challenge: collect as many phonons as possible

The smaller the number of pixels the better!

CALDER collaboration

Istituto Nazionale di Fisica Nucleare:

Sapienza University of Rome:
F. Bellini, C. Cosmelli

Consiglio Nazionale delle Ricerche:
M.G. Castellano, G. Pettinari.

Università degli studi di Genova:
S. Di Domizio.

CSNSM - CNRS/IN2P3
H. Le Sueur

Institut Néel - CNRS
M. Calvo, J. Goupy, A. Monfardini

M. Vignati
Aluminum detector (2016)

Film thickness: provides better quality of the superconductor.

Large film area: increases the **phonon absorption efficiency**.

Resonant frequency \( \sim 2.5 \text{ GHz} \).

High resonator Q \( \sim 10^5 \): increases the signal height.
KID signal

1. Frequency sweep to measure the transmission $S_{21}$ past the resonator:

2. Determine the resonant frequency and bias the detector at that frequency.

3. Measure Phase and Amplitude Modulation of the wave transmitted past the resonator

Very fast cryogenic detectors, application to $^{100}$Mo?
Results of the Aluminum detector

- Result obtained by combining phase and amplitude readout with a 2D optimal filter: \( \bar{H}^T(\omega) = k \bar{S}^\dagger(\omega) N^{-1}(\omega) \)

- Temperature independent up to 200 mK.

- Decay time identified as \( \tau_{qp} \), similar behavior with microwave power
Improving the energy resolution

\[ \Delta E \propto \Delta_0 \sqrt{\frac{T_N}{\alpha Q V}} \]

- **Superconductor gap** 
  - [180 \(\mu\)eV for Aluminum]

- **Amplifier noise** 
  - [2-6 K]

- **Superconductor Volume** 
  - [2x2mm\(^2\) x 60nm]

- **Kinetic Inductance fraction** 
  - [3% for Al]

- **Resonator Q** 
  - [10\(^5\)]
Titanium enhances Kinetic Inductance but lowers the internal $Q$. Tested different TiAl and AlTiAl multilayers. Best results from:

Same design as Aluminum films.
AlTiAl performance

Phase signal 3x higher than Aluminum only
Phase RMS = 25 eV @0 eV (4x better than Al)
Amplitude RMS = 80 eV @0eV (similar to Al)
CALDER development

- 04/14 - Aluminum KIDs
  9 pixel
  2x2 cm²
  2-8 keV

- 05/15 - 4 pixel
  150 eV
  APL107
  093508

- 06/16 - 1 pixel
  80 eV
  APL110
  033504

- 07/17 - Ti/Al 1 pixel
  25 eV
  SUST31
  075002

- Final goal - Ti/Al 1-4 pixel
  25 eV
  5x5 cm²

2013
End of 2013 Lab refurbishment

2014
03/14 ERC start
EPJ C75 353

2015
11/16 New lab
New cryostat

2016

2017
05/18 77th cool down

2018
end/18 Final tests at Gran Sasso
Scaling the area to 5x5 cm$^2$

**ISSUE**: resonator quality factor deterioration, low SNR.

We are investigating on it, magnetic fields? Stray radiation? Vibrations?
Athermal phonons characterization

- Built a phonon simulation on top of the CDMS Geant4 Package
- We are able to simulate:
  - Phonon rise time
  - Collection efficiency
- We derived transmission coefficients: Si-Al and Si-Teflon.
Conclusion and outlook

25 eV RMS have been reached by a large area light detector with KID, and we hope to further improve.

We are moving from 2x2 to 5x5 cm². Preliminary results indicate that the phonon loss with a single pixel is < 30%. Problems with quality factor.

➡ Determine whether 4 KID pixels are needed to compensate the loss and reach 25 eV RMS.

We are preparing the update of the LNGS test cryostat for the final test with TeO₂ bolometers.
Backup
Heterodyne readout development

- So far using an electronics able to handle up to 12 KIDs in parallel.
- We are developing a custom FPGA firmware on top of the ROACH2 opensource hardware and software board.
  - Goal: 100 KIDs in parallel.
- Developed by a wide (mostly astro-) community.

**ROACH readout system**

- FPGA board (Virtex6) for signal processing
- On-board PowerPc for FPGA control
- 16-bit 1000Msps dual DAC
- 14-bit 400Msps dual ADC
- 4x 10Gbe interfaces for data streaming
- Up/down conversion w clock-distribution board
High scalability

ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer

The phase noise is substantially lower than Aluminum.
End of 2016: New cryostat, new lab