Cryogenic detectors for rare event searches: an overview

Interdisciplinary Cluster Workshop
"Detectors and Instrumentation"
Garching – June 1, 2016

Federica Petricca
Max-Planck-Institute for Physics Munich
Overview

Cryogenic detectors
- Basics
- Advantages
- Signal formation

Sensors for cryogenic detectors
- Semiconductor Thermistors (ST)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)
- Superconducting Tunnel Junctions (STJ)
- Kinetic Inductance Detectors (KID)

Some selected applications
- Dark matter search
- Neutrinoless double beta decay
- Absolute neutrino mass
Cryogenic detectors

Why cryogenic detectors?

- They originate from the need to have good energy resolution
Cryogenic detectors

Why cryogenic detectors?

- They originate from the need to have good energy resolution

  Energy resolution due to Poisson fluctuations $\propto (\varepsilon)^{1/2}$

  $\varepsilon$ energy to produce an elementary excitation (phonon)
  $N = E/\varepsilon$ number of elementary excitations

  $\Delta E = \varepsilon \Delta N = \varepsilon (N)^{1/2} = (\varepsilon E)^{1/2}$

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Scintillators</th>
<th>Gas detectors</th>
<th>Solid state detectors</th>
<th>Cryogenic detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>100eV</td>
<td>30eV</td>
<td>3eV</td>
<td>$&lt; 0.01$ eV</td>
</tr>
</tbody>
</table>

Low temperatures needed to prevent thermal generation of elementary excitations

Advantage of cryogenic detectors over conventional devices
Cryogenic detectors

Why cryogenic detectors?

- They originate from the need to have good energy resolution

  Energy resolution due to Poisson fluctuations \( \propto (\varepsilon)^{1/2} \)

  \( \varepsilon \) energy to produce an elementary excitation (phonon)
  \( N = \frac{E}{\varepsilon} \) number of elementary excitations
  \( \Delta E = \varepsilon \Delta N = \varepsilon (N)^{1/2} = (\varepsilon E)^{1/2} \)

<table>
<thead>
<tr>
<th></th>
<th>Scintillators</th>
<th>Gas detectors</th>
<th>Solid state detectors</th>
<th>Cryogenic detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>100eV</td>
<td>30eV</td>
<td>3eV</td>
<td>&lt; 0.01 eV</td>
</tr>
</tbody>
</table>

Low temperatures needed to prevent thermal generation of elementary excitations

- Moreover all deposited energy is converted into phonons (non quenched signal)

Advantage of cryogenic detectors over conventional devices
The detection is mediated by elementary excitations in a solid (absorber).

A specific part of the detector is dedicated to the detection of the elementary excitations produced by the interaction (sensor).
Signal formation

In thermal equilibrium $T = T_0$

- **Absorber**
  - Heat capacity $C$
  - Temperature $T$

- **Thermal link**
  - Conductance $G$

- **Heat bath**
  - Temperature $T_0 \sim 10-100\, \text{mK}$

- **Phonons**
  - Temperature $T$
  - Voltage $V$
Signal formation

The interaction deposits **energy** in the absorber \( O(100\text{ps}) \) high frequency acoustic **phonons**

The initial phonon spectrum depends on the original interaction:

- **energy released in the electron branch** - the phonons result from electron-hole recombination non-thermal acoustic phonons with almost monoenergetic distribution of about half the Debye frequency \( \nu_D \)

- **energy released in the nuclear branch** - the phonons result from direct interaction with the lattice non-thermal acoustic phonons with broad frequency distribution
The phonon population is not in equilibrium and starts to decay towards a thermal distribution.
Signal formation

Anharmonic decay, isotope, surface and impurity scattering

\[ \Gamma_{\text{decay}} \propto \left( \frac{\nu}{\nu_D} \right)^5 \quad \Gamma_{\text{isotope}} \propto \nu^4 \]

- rapid initial decrease of the average phonon frequency washes out differences in the initial phonon spectrum
- first fast decay followed by much slower rate of change
  average phonon frequency distribution almost constant for few milliseconds during which phonons spread ballistically over the absorber filling it uniformly
Signal formation

Anharmonic decay, isotope, surface and impurity scattering

\[ \Gamma_{\text{decay}} \propto \left( \frac{\nu}{\nu_D} \right)^5 \quad \Gamma_{\text{isotope}} \propto \nu^4 \]

- rapid initial decrease of the average phonon frequency washes out differences in the initial phonon spectrum
- first fast decay followed by much slower rate of change
  average phonon frequency distribution almost constant for few milliseconds during which phonons spread ballistically over the absorber filling it uniformly

Time development of the average phonon frequency resulting from anharmonic decay of a 7.5THz (~\(\nu_D(Si)/2\)) phonon population in Silicon
Signal formation

Phonons relax on a new equilibrium distribution (temperature increase)

Absorber
Heat capacity C
Temperature T

Thermal link
Conductance G

Heat bath
Temperature $T_0 \sim 10-100$ mK

Phonons

Temperature $T + \Delta T$
The perfect calorimeter

Sensor

Absorber
Heat capacity C
Temperature T

Thermal link
Conductance G

Heat bath
Temperature $T_0 \sim 10-100$ mK

Phonons

$T + \Delta T$
The perfect calorimeter

- **Sensor**
- **Absorber** Heat capacity $C$
- **Temperature** $T$
- **Thermal link** Conductance $G$
- **Heat bath** Temperature $T_0 \sim 10$-$100$ mK

Signal

$$\Delta T = \frac{E}{C}$$

Relaxation time

$$\tau = \frac{C}{G}$$

Irreducible energy fluctuations

$$\langle \Delta E^2 \rangle = k_B T^2 C$$
Heat capacities

Non-magnetic crystalline dielectrics (and pure semiconductors at low temperatures)

Metals

Superconductors in the transition

\[ C = C_{\text{lattice}} \propto \left( \frac{T}{\Theta_D} \right)^3 \]

\[ C = C_{\text{lattice}} + C_{\text{electrons}} \quad C_{\text{electrons}} \propto T \]

\[ C_{\text{op}} \approx C_{\text{electrons}} \left( 2.43 - 1.43 \frac{R_{\text{op}}}{R_{\text{normal}}} \right) \]

- Low temperatures mandatory
- Dielectric or semiconductors preferred absorbers
The **sensor** is a device which converts a temperature signal into any temperature dependent physical parameter.

- Semiconductor Thermistors (ST)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)
- Superconducting Tunnel Junctions (STJ)
- Kinetic Inductance Detectors (KID)

- High technological content
- Often determines the S/N ratio

Extensively employed in astroparticle physics and astronomy

Employed in astroparticle physics and astronomy

Mainly employed in astronomy
Semiconductor Thermistors

Semiconductors doped below (close to) the Metal to Insulator Transition (MIT)

At low temperatures ($\leq 10$ K) the charge transport takes place by phonon-assisted tunneling between impurity sites (Variable Range Hopping with Coulomb gap conduction regime). The resistivity is given by:

$$\rho(T) = \rho_0 \exp \left( \left( \frac{T_0}{T} \right)^n \right)$$

$\rho_0$, $T_0$ and $n$ are material parameters depending on the doping.

- Neutron Transmutation Doped (NTD) Ge thermistors
  - Ge crystal exposed to neutron bombardment
  - Neutron capture and subsequent beta and EC decays produce p and n doping
  - Neutron dose fixes net doping
  - MIT: $6 \times 10^{16}$ cm$^{-3}$

- Si-implanted thermistors
  - Standard microelectronic technology
  - Implantation of P or As (n-doping), B (p-doping)
  - MIT (Si:P): $3 \times 10^{18}$ cm$^{-3}$
Semiconductor Thermistors

- Sensitive over a large temperature range
- High impedance (1 MΩ - 100 MΩ)
  Standard electronics can be used

- Easy to handle (usually glued on the absorber)
- Scarcely sensitive to non-thermal phonons
- Slow response
Transition Edge Sensors

Cryogenic detectors for rare event searches: an overview

F. Petricca

Superconducting thin films kept in the normal to superconducting phase transition

- Steep temperature dependence of the resistance
  \( \Delta T \) \( \rightarrow \) \( \approx \) \( \Delta R \)

- Much higher S/N ratio with respect to ST

- Narrow operating region
- Low impedance \( \mathcal{O}(100 \text{m}\Omega) \)
  - SQUID readout
- Production not easy and not always reproducible
- Sensitive to non-thermal phonons
- Fast response
Paramagnetic alloy in a small magnetic field
The change of temperature leads to a change of the magnetization of the sensor read-out as a change of magnetic flux in a SQUID

The required magnetic field is generated by the current flowing in the SQUID loop

Physical realization of the paramagnetic system: rare earths ions in metals (dilute alloy of erbium $O(300\text{ppm})$ in gold/silver)
Metallic Magnetic Calorimeters

\[ \delta M = \frac{\partial M}{\partial T} \delta T = \frac{\partial M}{\partial T} \frac{\delta E}{C} \]

\[ \delta \Phi_S \propto \frac{\partial M}{\partial T} \frac{1}{C} \delta E \]

- Sensitive over a large temperature range
- No dissipation in the sensor (no Johnson noise)
Superconducting Tunnel Junctions

Two superconductor films separated by an insulating layer (normally a thin oxide film)
Two superconductor films separated by an insulating layer (normally a thin oxide film)

The interaction breaks Cooper pairs in a superconducting film

The excess quasiparticles are counted through a current pulse $i(t)$ developed across the oxide layer by tunneling.
A superconducting film below the critical temperature has a surface inductance proportional to the penetration depth $\lambda (~ 50 \text{ nm})$ of an external magnetic field

$$L_S \propto \lambda$$

$$Z_S = R_S + i \omega L_S$$

The surface impedance depends on the quasiparticle density

An interaction breaks Cooper pairs in the superconducting film changing both $R_S$ and $L_S$ (kinetic inductance effect)

Fractional surface impedance change $\sim$ fraction of broken Cooper pairs
The change can be measured by placing the superconducting inductor in a resonator resonant frequency changes with the absorption of energy.

A probe signal is tuned to the resonant frequency of the resonator. An energy deposition in the inductor can be determined by measuring the changes in phase and amplitude of the probe signal.
Cryogenic detectors - applications

Introduced in rare events physics in the 1980s

Nowadays a consolidated technology

- Threshold frontier - Search for low mass dark matter
- Mass frontier - Search for neutrinoless double beta decay
- Rate frontier - Direct measurement of the neutrino mass
- Background frontier - All rare event searches
Search for dark matter

Particle identifications to suppress background

The partition of the deposited energy among different channels is different between electron recoils and nuclear recoils.

- Phonon – charge technique in semiconductors: CDMS/SuperCDMS (TES), Edelweiss (Ge NTD)
- Phonon – light technique in scintillators: CRESST (TES)

Large mass cryogenic detectors with additional readout to discriminate nuclear recoils from electron recoils.
Phonon – light technique

- Phonon signal
  (independent of the type of particle)
  **Measurement of deposited energy**

- Light signal
  (characteristic of the type of particle)
  **Particle discrimination**

**Two simultaneous signals** from the two transition edge sensors (TES)

300eV nuclear recoil threshold for 300g absorber
Phonon – charge technique

CDMS iZIP detectors

Interleaved charge ionization and phonon sensor design on both faces of the detector. 8 phonon channels (4 on each face) and 4 charge channels (2 on each face).

Discrimination of surface from bulk events with interleaved detectors (z-sensitive).

Pictures courtesy of the CDMS collaboration.
Phonon – charge technique

CDMS iZIP detectors – CDMSlite mode

Charge mediated phonon amplification Neganov-Trofimov-Luke (NTL) Effect

Drifting charges produce large phonon signal proportional to ionization
Electron recoils much more amplified than nuclear recoils

- gain in threshold AND dilute background from electron recoil events

NTL effect mixes charge and phonon signal reducing discrimination

~300eV nuclear recoil threshold for 600g absorber

Pictures courtesy of the CDMS collaboration
Search for neutrinoless double beta decay

Calorimetric technique for the study of DBD proposed by E. Fiorini and T.O. Niinikoski in 1983

Sensitivity
lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$\propto MT$ no background

$\propto (MT)^{1/2}$ with background

Two neutrino DBD continuum with maximum at $\sim 1/3 Q$

Neutrinoless DBD broadening of the peak due to detector resolution

Resolution has to be better than 2% in order to resolve the peak
Search for neutrinoless double beta decay

Calorimetric technique for the study of DBD proposed by E. Fiorini and T.O. Niinikoski in 1983

Two neutrino DBD continuum with maximum at \( \sim 1/3 \) \( Q \)

Neutrinoless DBD broadening of the peak due to detector resolution

Resolution has to be better than 2% in order to resolve the peak

Sensitivity

lifetime corresponding to the minimum detectable number of events over background at a given confidence level

\( \propto MT \) no background

\( \propto (MT)^{1/2} \) with background
Search for neutrinoless double beta decay

Requirements:
• high energy resolution
• high efficiency
• high mass

Calorimetric approach **Source ≡ Detector**

**CUORE**
TeO$_2$ crystals (Ge NTD)

![Image of CUORE detector](image)

- single TeO$_2$ crystal
  - 790 g
  - 5cm x 5cm x 5cm

**Average resolution of 2.2keV at 5407.5keV**

Pictures courtesy of the CUORE collaboration
Search for neutrinoless double beta decay

Cuoricino 2003-2008

Cuore-0 2013-2015

Cuore 2016-2020

39 kg
11 kg of $^{130}$Te

741 kg (988 crystals)
206 kg of $^{130}$Te

Pictures courtesy of the CUORE collaboration
Direct measurement of the neutrino mass

Measure tiny spectral distortions at the end-point of a beta spectrum

![Graph showing beta spectrum with energy resolution and count fraction]

**Tritium as an example**

- The modified part of the beta spectrum is over the range $[Q-M_\nu c^2, Q]$
- The count fraction laying in this range is $\propto (M_\nu/Q)^3$

**Requirements:**

- high energy resolution
- high statistics in a very narrow region of beta spectrum
- well known response of the detector

**Calorimetric approach**  \textbf{Source} $\equiv$ \textbf{Detector}
Direct measurement of the neutrino mass

Electron Capture Spectroscopy of $^{163}$Ho

HOLMES (TES)
ECHo (MMC)
NuMECS (TES)

$Q_{EC} = 2.8$ keV

Counts/0.01eV

Energy / keV

Counts/0.01eV

Energy / keV

$m(v) = 0$ eV

$m(v) = 10$ eV

Pictures courtesy of the ECHo collaboration
Direct measurement of the neutrino mass

Requirements for sub-eV sensitivity in ECHo

- Statistics in the end point region
  \[ N_{ev} > 10^{14} \rightarrow A \approx 1 \text{ MBq} \]
- Unresolved pile-up
  \[ f_{pu} < 10^{-5} \rightarrow 10^5 \text{ pixels} \]
- Precision characterization of the endpoint region
  \[ \Delta E_{\text{FWHM}} < 3 \text{ eV} \]

Pictures courtesy of the ECHo collaboration
Future

Experiments will need to reach more than one frontier
Experiments will need to reach more than one frontier

No direct dark matter signal observed

Signal in the high mass region observed

The ultimate dark matter experiment for low mass dark matter

Unique multi-element target experiment to cross check a possible signal
Future

Experiments will need to reach more than one frontier

Limiting background: surface contaminations (degraded α)
- U and Th surface contaminations of the crystals
- U and Th surface contaminations of the Cu used for the holding structure

Additional light channel possible to discriminate alpha/surface background

AMoRE  CaMoO$_4$ scintillating crystals (MMC)

CUPID (next generation of CUORE)
- TeO$_2$ crystals + Cherenkov light
- Scintillating crystals

Requires the most advanced technology for light detection
Conclusions

Well established technology successfully applied in many fields:

- Astroparticle physics
- Astronomy
- X-ray spectroscopy
- Material analysis and life science
- ...

Brilliant and challenging future