Cryogenics and cryogenic detectors

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CRYOGENICS: Science and technology of very low temperatures (common definition <120 K)

It’s a very wide field with a large variety of applications.

In this talk I will focus on ultra-cryogenic temperatures, which spans from few mK to hundreds of mK.

Cryogenics below 1K underwent huge progresses in the last decades becoming extremely relevant in different particle and astroparticle physics applications and projects.
Cryogenic detectors (aka LTDs)

History of cryogenic detectors is relatively short

They started as a niche technology but today are vastly employed in a wide range of applications, both in fundamental science and technology

• Cosmology and astrophysics
• Beta decay, neutrinoless double beta decay, dark matter (WIMPs), CNNS
• Nuclear and atomic physics
• Quantum technologies
• Material and life science, cultural heritage, homeland security

Main advantages of cryogenic detectors are: excellent energy resolution, low energy threshold, ample choice of detector material
Cryogenic detectors

- Ample choice of detector materials
  - low heat capacity @ $T_{\text{work}}$
- excellent energy resolution (<1 ‰ FWHM)
  - huge number of energy carriers (phonons)
- equal detector response for different particles
  - true calorimeters
- slow respect to other particle detectors

Several temperature sensors
- Semiconducting thermistors (Si o Ge-NTD)
- Superconducting Transition Edge Sensors (TES)
- Magnetic Metallic Calorimeters (MMC)
- Microwave Kinetic Inductance Detector (MKID)
- …

\[ \Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}} \]

\[ \tau = \frac{C}{G} \]
T sensors @ mK

Nuclear Transmutation Doped Germanium: high resistivity thermistors

\[ R(T) = R_0 e^{\sqrt{T_0/T}} \]

Variable Range Hopping

Transition Edge Sensors are superconducting films (W, Ir, Au/Ir, etc.)

W: \( T_C \sim 15 \text{ mK} \)

Ir: \( T_C \sim 110 \text{ mK} \)
MicroLTD

Metallic Magnetic Calorimeters (MMC)
Absorber: 250 μm × 250 μm Gold, 5μm thick (6 μg)
Au:Er paramagnetic sensor

\[ M \text{ vs. } T \]

\[ \Delta E_{FWHM} = 1.58 \text{ eV} \]
**MacrolTD**

**TeO₂ bolometer**
Absorber: 5 cm × 5 cm × 5 cm thick (0.75 kg)
NTD-Ge sensor

![TeO₂ bolometer image]

\[ \Delta E_{FWMH} = 4.8 \text{ keV} \]

![Graph showing energy peaks]

- 2615 keV (²⁰⁸Tl)
- 208Tl single escape
- 2104 keV (²⁰⁸Tl)
- 1588 keV (²²⁸Ac) + 1595 keV (²⁰⁸Tl)
- 1591 keV (²²⁸Ac) + 1595 keV (²⁰⁸Tl)
- 583 keV (²⁰⁸Tl)
- 511 keV (e⁺e⁻)
- 911 keV (²²⁸Ac)
- 965 keV + 969 keV (²²⁸Ac)
- 4.8 keV

*JENAS meeting - 15 October 2019*
CUORE TeO$_2$ bolometers history

<table>
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<tr>
<th>Detector mass [kg]</th>
<th>Time from start [years]</th>
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<td>6 g</td>
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<tr>
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<td>Cuoricino</td>
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<td>CUORE</td>
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Refrigeration at mK temperature

Dilution refrigerators are the workhorse at mK temperature

Based on quantum properties of $^3\text{He}-^4\text{He}$ mixtures

Continuous flow refrigerators

Cooling power ~ $\mu W$ @ 10 mK

Phase diagram of liquid $^3\text{He}-^4\text{He}$ mixtures

$T_F$ (0.675, 0.867 K)
COBE (1989-1993) measured CMB showing that has a nearly perfect black-body spectrum
• FIRAS instruments (4 diamond absorbers on Si thermistors @ 1.6 K

PLANCK (2009-2013) provided the most precise measurements of several key cosmological parameters
• HFI instruments covering 6 frequencies from 100 to 857 GHz (56 spiderweb NTD-Ge @ 100 mK)
CMB

The focal plane of the STP is composed by 960 Al/Ti spiderweb TES operated at ~ 500 mK
X-ray astrophysics

ASTRO-H (Hitomi) mission (2016)
SXS instrument: 6x6 HgTe absorbers with Si thermistors
7 eV FWHM in the energy range 0.3-12 keV

ATHENA mission (2028)
SXS instrument: 3840 Si absorbers with MoAu TES
<2.5 eV FWHM in the energy range 0.2-12 keV
LTDs for neutrino mass

\[ ^{163}Ho + e^- \rightarrow ^{163}Dy^* + \nu_e \]


- Holmium experiments: calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- Rate at the end point depends on (Q–EM1): the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on \( m_\nu \))
- \( t_{1/2} \sim 4570 \) years: few nuclei are needed (\( 2 \times 10^{11} ^{163}Ho \) nuclei = 1 Bq)
ECHo

Detectors: Au:Er Metallic Magnetic Calorimeter (MMC) with implanted $^{163}$Ho
Activity: $6.5 \times 10^{13}$ nuclei per detector $\rightarrow$ 300 dec/s
Performances: $\Delta E \approx 1$ eV, $\tau_R \approx 1$ µs

Prove scalability with medium large experiment ECHo-1k (2015-2018)
- total activity 1 kBq, high purity $^{163}$Ho source (produced at reactor)
- $\Delta E_{\text{FWHM}} < 5$ eV, $\tau_R < 1$ µs
- multiplexed arrays $\rightarrow$ microwave SQUID multiplexing
- 1 year measuring time $10^{10}$ counts $\rightarrow$ neutrino mass sensitivity $m < 10$ eV
- Data taking will starting early 2018

Future: ECHo-10M sub-eV sensitivity
HOLMES

Detectors: Transition Edge Sensor with $^{163}$Ho implanted in Au absorbers
Activity: $6.5 \times 10^{13}$ nuclei per detector $\rightarrow$ 300 dec/s
Performances: $\Delta E_{\text{FWHM}} \approx 1$ eV, $\tau_R \approx 1$ µs

MonteCarlo with 1000 detectors x 3 years

- Proof potential and scalability of the approach
- Precise calorimetric determination of $Q$
- Systematic errors assessment

GOAL
Neutrino mass determination with a sensitivity as low as $\sim 1$ eV

- 64 channels mid-term prototype, ($t_M = 1$ month, $m_\nu < 10$ eV)
- Full scale: 1000 channels, $3 \times 10^{13}$ events collected in 3 years
- $6.5 \times 10^{16} \ ^{163}\text{Ho}$ nuclei ($\approx 18$ mg)

HOLMES (ERC-Adv. Grant 340321)
5 years project started on Feb. 1st 2014

LTDs for Dark Matter (WIMPs)

At large dark matter masses sensitivity is dominated by exposure:
- large mass noble liquid detectors prevail

At light dark matter masses sensitivity is dominated by energy threshold:
- cryogenic detectors are superior
LTDs for Dark Matter (WIMPs)

Electron/Nuclear recoil discrimination
Double readout
  phonons-ionization (Edelweiss, CDMS)
  phonons-scintillation (CRESST)
Low energy threshold (<100 eV)

Scintillating bolometer
24 g CaWO\textsubscript{4} crystals
Best energy threshold: 30 eV

Ionization+athermal phonons
600 g Ge crystals

Ionization + heat
850 g Ge crystals
LTDs for CNNS

Coherent neutrino-nucleus elastic scattering

CNNS vs inverse beta decay:
- Larger cross section
- Smaller measurable energy (few tens of eV)

Measured in 2017 in the COHERENT experiment
LTDs for CNNS

LTDs are suitable for this challenge

NUCLEUS, MINER and RICOCHET aim to detect neutrinos from nuclear reactors measuring cross section at 10% precision

Non-proliferation application
LTDs for $0\nu\beta\beta$ searches

LTDs are ideal for $0\nu\beta\beta$
- Detectors with embedded $0\nu\beta\beta$ isotope candidate (TeO$_2$, Li$_2$MoO$_4$, ZnSe, etc.)
- Excellent energy resolution
- Background reduction through particle identification

CUORE: Ge-NTD on 750g TeO$_2$ absorbers
  - only phonons

CUPID: Ge-NTD on 300g Li$_2$MoO$_4$ absorbers
  - phonons & scintillation
CUPID-Mo

- 20 Li$_2^{100}$MoO$_4$ scintillating crystals instrumented with light detectors in the Edelweiss cryogenic setup at the Modane underground lab
- Cylindrical crystals: $\varnothing$ 43.8 $\times$ 45 mm
- 2.34 kg of $^{100}$Mo
- Light detectors: $\varnothing$ 44.5 mm $\times$ 170 $\mu$m Ge wafer with SiO coating on both sides, instrumented with NTDs
CUPID-Mo

Demonstrated
• Energy resolution ~ 5-6 keV FWHM
• Light Yield: 0.5-1 keV/MeV for $\beta/\gamma$
• Discrimination at 9 $\sigma$ level

To be improved
• Pileup events induced by short $2\nu\beta\beta$ decay half-life
  ➡ Time resolution $\leq$ 1 ms required
Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO$_2$ crystals (19 towers of 52 crystals $5 \times 5 \times 5$ cm$^3$, 0.75 kg each)
- Mass of TeO$_2$: 742 kg (~206 kg of $^{130}$Te)
- Operating temperature: ~10 mK
- Mass to be cooled down: ~15 tonnes (Pb, Cu and TeO$_2$)
- Background aim: $10^{-2}$ c/keV/kg/year
- Target energy resolution: 5 keV FWHM @ 2615 keV
- Projected sensitivity in 5 years (90% C.L.): $T_{1/2} > 9 \times 10^{25}$ yr
CUORE cryostat

- Cryogen-free
  5 Pulse tubes, JT expansion instead of 1K Pot
- Base temperature <10 mK
  high cooling power custom Dilution Unit
- Straight cryostat (more mass to cool down, simpler design)
  dimensions: external $\varnothing$ 1.7 m $\times$ h 3.1 m, experimental volume $\varnothing$ 0.9 m $\times$ h 1.37 m
- Large cold lead shielding close to detector
- Heavy load support
  detector $\sim$ 1 tonne
  lead radioactivity shielding $\sim$ 10 tonnes
- Redundancy (to improve reliability)
- Strict material selection
  mainly pure copper
  other selected materials only in small amounts (SS, TiAlSn, Kevlar…)
  limited amount of Multi Layer Insulation (MLI)
- Low mechanical vibration input on detector
  independent detector suspension
- The design was an iterative process in which every choice had to be validated from the thermal and radioactivity budget point of view
Dilution unit

Custom Dilution Unit:
- cooling power: 5 μW @ 12 mK; >1.5 mW @ 120 mK
- base temperature: < 6 mK
- condensation flow: > 10 mmoles/s
- easily removable from the CUORE cryostat in order to be tested in a separate test cryostat
- 2 independent condensing lines with spring loaded variable flow impedances

Actual performances in the test cryostat were better than specs
- cryogen-free DU with the largest power ever built!
PT noise cancellation

Pulse Tubes are substituting liquid helium for a number of reasons

- Main drawback are the induced vibrations: active noise cancellation
- Relevant technological development in CUORE
- Interesting for all the PT based project (e.g. Einstein Telescope)
Conclusions

Cryogenic detectors have a solid present and brilliant future

Are crucial instruments for all the future astrophysics missions

Will play a dominant role in search for low-mass WIMPs

Will have a prominent role in the $0\nu\beta\beta$ search in the next decade

Many other science and technology fields will benefit from their characteristics