Cryogenic detectors and sensors for High Energy Physics
Low Temperature detectors

Neutrino Physics
- SuperCDMS (google images)
- CRESST (google images)
- EDELWEISS (google images)
- Neutrinoless Double Beta experiments
- AMORE (google images)
- CUORE (google images) / CUPID
- Experiment for direct neutrino mass search

Cosmology

Dark Matter searches

+ Nuclear and Atomic Physics
+ Material sciences, security
+ Quantum computing and technologies
+ .......

No one size fits all!

tiny to massive depending on the application

Out of scope to describe all LTDs and applications
Low Temperature detectors

India-based Neutrino Observatory (INO)

+ Nuclear and Atomic Physics
+ Material sciences, security
+ Quantum computing and technologies
+ ……

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Out of scope to describe all LTDs and applications
Low Temperature detectors (LTD)

- "Direct detection"
- Measure total energy deposited or power in the absorber or sensor
- Size of the detector/sensor dependent on the application

Particle / electromagnetic radiation

Detector / Sensor

Particle / electromagnetic radiation

Energy will be transformed to

Light

Charge

Heat

Particle / electromagnetic radiation

X-ray detectors
astronomy and materials

Gamma ray detectors
for nuclear science and material analysis

Optical photon sensors

Detectors for cosmology /astronomy

Energy (eV)

Frequency (Hz)

Wavelength (m)

10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6

10^{-3} 10^{-2} 10^{-1} 1 10 100 1000 10^3 10^4 10^5 10^6

10^{12} 10^{11} 10^{10} 10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1
Low Temperature detectors (LTD)

Scintillator detectors
- Poor resolution
  ~ few photons per keV
- Extremely fast (can get ~ ps)

Light (scintillation)

Semiconductor detectors
- Good resolution
  ~ few 100 electrons per keV
- Fast (can get ~ ns)

Charge (ionization)

Low-temperature detectors
- Excellent resolution
  ~ few 1000 phonons per keV
- Slow (can get ~ μs)

Heat (phonons)

It is hard to find a material where you can measure all three channels together
Thermodynamic limit for energy resolution can be made small by operating the detectors at a very low temperature.

Requires ultra-low temperature facility with ultra-stable operating conditions.

Life is slightly harder as low temperature experimentalist

\[ \langle \Delta E_{FWHM} \rangle^2 = \langle \Delta E_{TFN} \rangle^2 + \langle \Delta E_{electronics} \rangle^2 + \langle \Delta E_{vibration} \rangle^2 + \ldots \]

Absorber can be any material as long as heat capacity is very low (superconductors and dielectric crystals)
Low temperature sensors

- Transition Edge Sensors
- Superconducting metal films
- Narrow operating temperature
- SQUID readout
- Time response $\sim \mu$s
- Resistance of $\sim \Omega$

- Semiconductors thermistors
- Neutron transmutation doped germanium (NTD-Ge) sensors
- Wide operating temperature
- Time response $\sim$ ms
- Voltage amplifiers
- Resistance of $\sim k\Omega - M\Omega$

- Metallic Magnetic Calorimeters
- Paramagnetic sensor material
- Wide operating temperature
- Time response $\sim 100$ ns
- SQUID readout
LTD Amplifiers

- Resolution and performance not only determined by the sensor but also the amplifier in the chain
- Ideally, amplifier should be as close to the sensor as possible.
- Harder for cryogenic experiments, especially low background experiments.

+ SQUIDS
+ Workhorse of LTD (TES, MKIDS, MMC’s)

+ HEMT
+ Much higher bandwidth than SQUIDS

+ CMOS at cryogenic temperatures
+ Has attracted interest in quantum computing for their use as precision controllers and low noise amplifiers.

R.G. Huang et al 2020 JINST 15 P06026
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Power Consumption at lower stages an issue as the number of channels increase to thousands or more

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  + Higher bandwidths than SQUIDs

+ Work on Cryogenic CMOS
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Cryogenic Infrastructure for Rare Events

- Deep underground facility to minimize cosmic ray background.
- Extremely low radioactivity around the detectors
  - Internal and external shielding (gamma, neutrons, … )
- Ultra-low vibrations and minimal electromagnetic interference
- High cooling power.
- Long running time with large target mass

Neutrinoless double beta decay

Dark Matter Searches
Neutrinoless Double Beta Decay

- Possible only if neutrinos have mass
- Lepton number not conserved
- Occurs if neutrinos have mass and are their own antiparticle

Sensitivity of the search

\[ T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma} \frac{N_A}{A} f(\Delta E) \left( \sqrt{\frac{M t}{B \Delta E}} \right) \]

- \( i \) = isotopic abundance
- \( \varepsilon \) = Efficiency of detector
- \( f(\Delta E) \) = fraction of signal events in \( \Delta E \)
- \( n_\sigma \) = Number of standard deviations
LTD for Neutrinoless Double Beta Decay

- AMORE
- CUPID (next-gen experiment)

Initiative at INO

Pro: Easy to scale up

Con: Not Background Free
CUORE (tonne-scale LTD)

- Search for $0\nu\beta\beta$ in $^{130}$Te at LNGS, Italy (depth ~ 3600 m.w.e)
- Operated at ~ 10 mK
- Demonstrated energy resolution 7.0 ± 0.4 keV
- Over 1000 kg-yr of data so far.
Detector Shielding

Total mass cooled ~ 14 tons
Mass cooled below 4K ~ 13 tons

6 cm Roman Pb Shield
(5 tons@4K)

30 cm of Pb Top Shield
(2.5 tons@50 mK)
Cryogenics for CUORE

- Custom built DU by Leiden Cryogenics
- Cooling power:
  - > 4 μW @ 10 mK;
  - >1.5 mW @ 120 mK
- Cryogen-free DU with the largest cooling power ever built!

- 5 Cryomech PT415 with remote motor option
- 1.2 W @ 4.2K and 32 W @ 40K
Detector Principle

- 750 g (5x5x5 cm$^3$) crystal
- $\Delta T \sim 100 \, \mu K$ for 1 MeV energy deposit
- NTD-Ge thermistor read out
  - $R(T) \sim R_0 \exp \left[ \left( \frac{T_0}{T} \right)^{1/2} \right]$ (large sensitivity at low T)
- Energy response calibrated using known gamma sources

- Note:
  - Bandwidth $\sim$ tens of Hz
  - Signal $\rightarrow$ thermal channel only
  - No active background rejection
CUORE and CUPID

- Bayesian limit @ 90% C.I. (flat prior for $\Gamma_{\beta\beta}>0$): $3.2 \times 10^{25}$ yr
- $\langle m_{\beta\beta} \rangle < (75 - 350)$ meV depending on the chosen NME.
CUORE to CUPID

- Dominant background is degraded alphas from surface contamination
- Leverage energy loss mechanism in the crystal to tag particle type

Use auxiliary low temperature calorimeter to detect light:
- High radiopurity
- Low heat capacity
- High photon collection efficiency
- Very low threshold (~ 100 eV)
- Excellent timing resolution to discriminate the $2\nu\beta\beta$ pile up events from $0\nu\beta\beta$ events
CUPID-Mo demonstrator

- Set the best limit for 100Mo decay.
- Germanium wafer with NTD as light detector.
- Resolution of 0.11% (1σ) at Q_{ββ}
- Enrichment > 95%
- Demonstrated active background rejection.

CUPID:
- ~ 1500 crystals with ~ 250 kg of $^{100}$Mo
- ~ 1600 photon detectors needed

Li$_2$MoO$_4$ detectors recognized as baseline for CUPID
Transition-Edge Sensor based Light Detectors

Device specification:
- 2” Silicon wafer as optical photon absorber
- Ir/Pt (100 nm/60nm) bilayer with Nb traces as electrical leads.
- Faster response than NTD based detectors.
- Potential of multiplexing an attractive feature

- Transition temperature of \( \sim 37 \text{ mK} \)
- Sensor dimension 300 \( \mu \text{m} \times 300 \mu \text{m} \)
- Au link from sensor to wafer improves SNR
Neutrinoless double beta decay initiative in India

Low temperature lab at TIFR

Cryogenic amplifier operating at 120 K

• Proposal to use superconducting Sn crystal
• Fabrication of NTD-Ge sensor at BARC/TIFR
Dark Matter Searches

+ Stable, neutral, non-relativistic
+ Non-baryonic
+ Gravitational and (maybe) weak force.
Direct Dark Matter Searches

WIMP

Nucleus

v \sim 230 \text{ km/s}

v \sim 0 \text{ km/s}

elastic collision

\begin{equation}
\frac{dR}{dE_R} = \frac{\rho_0}{m_X m_N} \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{d\sigma_{XN}}{dE_R}(v, E_R) v f(v) dv
\end{equation}

Nucleus

E \sim \text{few keV}
Different target material will be needed to nail down nuclear physics of any detected signal.

Unlike, neutrinoless double beta decay there is no peak hunting here and energies are much lower.
Cryogenic Detectors for WIMPS

SuperCDMS

Super Cryogenic Dark Matter Detector
(Initial payload of 30 kg followed by 200 kgs)
Germanium detectors with transition edge sensors

Edelweiss

Germanium crystals with NTD-Ge sensors

CRESST

CaWO₄ crystals with transition edge sensors

COSINUS

NaI crystals with transition edge sensors
Cryogenic Detectors for WIMPS

Cryogenic detectors pushing limits for lower WIMP mass

XXIV DAE-BRNS high energy physics symposium

Vivek Singh (University of California, Berkeley)
Dark Matter experiment in India

- Proposal to use scintillating crystals (CsI)
- Simulation studies carried out to understand background at Jaduguda Underground Science Lab (JUSL)

Projected sensitivity of CsI detector at JUSL

Cryogenic Detectors for sub-GeV WIMPS

Baseline Energy resolution $\sim 4$ eV
Timing resolution $\sim 2.3 \mu$s

Quasiparticle-trap-assisted Electrothermal feedback
Transition-edge sensors

+ Operated overground and already pushing limits
CEvNS: Coherent elastic neutrino-nucleus scattering

A neutrino recoils against the whole nucleus for small momentum transfer. The neutrino “sees” the whole nucleus and no single proton or neutron is interacted with.

\[ \sigma \approx \frac{G_F^2 N^2}{4\pi} E_{\nu}^2 \]

+ Experiments for detecting neutrinos from nuclear reactors
  + MINER
  + Richochet (Zn crystal + TES sensor)

+ Ge-based cryo detector inspired by SuperCDMS
+ Baseline resolution of 1 electron-hole pair
Supernova neutrino detection

CEvNS ideal channel for SN detection

+ Pb has the highest cross-section
+ Pb-based cryo detector

RES-NOVA newly proposed experiment at LNGS
+ Will have ~ 1 keV threshold
+ 5 Sigma sensitivity to SN bursts unto Andromeda galaxy
+ Phys. Rev. D 102, 063001 (2020)

Use high purity archaeological Pb (Roman lead)

- Pb has the highest cross-section
- Pb-based cryo detector
Conclusions

+ No where close to harnessing the limits of cryogenic detectors
+ Detectors will be scaled up
  + Multiplexing, cryogenic readout active areas of research
+ Resolution will be pushed to quantum limits.
+ Wide application in almost all areas of Physics
+ Lot of synergy with technologies being developed for Quantum Information Science
  + Quantum computing approaches will benefit particle physics experiments too.

Cryogenic detectors are a mature technology but they are just warming up (pun intended).