Cryogenic TES based Micro-calorimeters and use in space science

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Superconductivity

- Superconductivity was discovered by Heike Kamerlingh Onnes at Leiden University in 1911 -> Nobel Prize 1913
- Superconductive state was found to be characterized by infinite electrical conductivity and (near) perfect diamagnetism, and is emerged only in temperatures close to absolute zero
- The explaining theory for superconductivity (for conventional superconductors) was developed by Bardeen, Cooper and Schrieffer and was published in 1957 (BCS theory - Nobel Prize 1972)
- In 1986 Muller and Bednorz found high temperature superconductors – a new class of superconductors not explained by the BCS theory
Superconductivity

Predictions (left) and findings (right) of resistances near absolute zero. The transition from normal to superconductive state is sharp and occurs in so called critical temperature $T_c$ specific to different materials.
BCS theory

- Electrons form Cooper Pairs (CP) in cold temperatures through electron-phonon interaction.
  - Cooper pairing is a quantum effect, and CP’s behave effectively as bosons since CP’s spin = $\frac{1}{2} + \frac{1}{2} = 1$.

- Josephson effect: tunneling of cooper pairs through insulating barriers (used in SQUIDS’s)

- Meissner effect: Superconductor expels magnetic field from its interior by introducing supercurrent which induces an opposite magnetic field
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$$\alpha \equiv \frac{d \log R}{d \log T} \rightarrow \alpha = \frac{T_0}{R_0} \frac{dR}{dT}$$

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\alpha \equiv \frac{d \log R}{d \log T} \quad \Rightarrow \quad \alpha = \frac{T_0}{R_0} \frac{dR}{dT}
\]

- Superconductor transition-edge has a large positive \( dR/dT \), unlike e.g. normal semiconductors.

\( T_c \) of Mo/Cu bilayer at \( \sim 96\text{mK} \)
TES measurement principle (simplified single photon case)

1) TES pixel with heat capacity $C$ is heated to $T_c$ by balancing Joule heating, $(P_j = V^2/R)$, in TES circuitry to that of cooling by thermal conductance to thermal sink (through thermal link with conductance $G$). The equilibrium is reached by appropriate voltage biasing of the TES circuitry.

2) When photon of energy $E_X$ is absorbed in TES pixel, the temperature quickly rises a corresponding amount, $\Delta T = E_X/C$. This causes TES circuitry resistance to increase accordingly; with use of Eq.1 and by assuming linear relation between $T$ and $R$ within the transition edge, the increase equals $\Delta R = \alpha \Delta T/T_0$. Thermal signal of the TES is now transformed into electrical signal in TES circuitry.

3) The increase in resistance reduces current in voltage biased TES circuitry, hence reducing $P_j$. Accordingly the temperature restores into the initial equilibrium state by conducting thermal energy away through the thermal link of TES. The timescale to reach the equilibrium depends on both the TES circuitry and the value of $G$.

TES work thus through negative electrothermal feedback
TES measurement principle

\[ \tau \propto \frac{C}{G} \]

\[ \Delta I_{\text{max}}^{10\text{keV}} e^{-1} \]

\[ \Delta I_{\text{max}}^{10\text{keV}} \]

\[ I_{[\mu A]} \]

\[ t [\text{us}] \]
TES measuring principle

Thermal schematics of a TES pixel (left) and Thevenin-Equivalent of voltage biased TES circuitry (right).
SQUID readout

- Superconductive QUantum Interference Devices SQUID’s are superconductive components that comprise of superconductive loop with two weak links, *i.e.* Josephson junctions.
- Penetrating magnetic flux induces current in SQUID loop, which determinates the Josephson current over the weak links.
- Non biased SQUID can be used measuring magnetic flux absolute magnitude.
- Biased SQUIDs can be used in measuring the changes in magnetic field in units of magnetic field quanta $\Phi_0 = \hbar/2e$.
- SQUID’s are therefore ideal components to read the changing current of TES circuitry.
**SQUID readout**

- After magnetic signal of TES circuitry is transformed into current signal through readout SQUID signal it must be amplified:

\[
\langle \Delta U^2 \rangle = k_B T^2 C \quad , \quad C \propto T^\gamma , \gamma = 1...3
\]

\[\Rightarrow \quad \langle \Delta U^2 \rangle \propto T^{3...5} \quad !!!\]

- SQUID 's can also be used to build amplifiers that work in cryogenic temperatures
  
  -> enables to magnify signal sufficiently that good signal-to-noise ratio can be obtained for room temperature electronics
Cryogenic micro-calorimeter detector schematics
TES – based microcalorimeter with SQUID readout

Information of energy is yielded by curve fitting measured pulses with average pulse shape – noise manifests itself as degrading energy resolution

Different noise sources:
- Phonon noise from thermal link to bath
- Johnson noise of TES resistance
- Thermal noise of internal thermal conduction
Micro-calorimeter performance

TES based detector’s (theoretical) energy resolution is dominated by the fluctuations in its thermal energy content:

\[ \delta E = \sqrt{k_B T^2 C} \]

Fig. 12. Measurement of the spectrum of BaTiO₃ excited with low beam energy (3 keV): (a) conventional Si-EDS, O-K is the only prominent peak, and it interferes with Ti-LI and Ti-Lo. (b) microcalorimeter EDS, Ti-LI and Ti-Lo are well separated from O-K, and details of the complex Ba-M family peaks are clearly resolved.
TES based Calorimeters and bolometers

- Calorimeters measuring individual photon pulses
  - excellent resolution with possibility to build imaging devices

- Microbolometers measuring photon flux
  - capability to measure fluxes with great accuracy (e.g. in IR band Noise Equivalent Power of order of $10^{-19}$ W/√Hz has been reached)
Imaging micro-calorimeter arrays

Problem: Cryostat’s cooling power set limitations to wiring between warm electronics and experiment end, which in turn limits the total number of pixels in micro-calorimeter device

Solution: SQUID readout system that both amplifies and multiplexes signals at cold end. The demultiplexers can be situated at room temperature.

Figure 22: $^{55}$Fe X-ray spectra measured simultaneously with an array of four TES x-ray calorimeters time-division multiplexed into one output channel. The spectra are offset vertically by 200 counts per eV. The data points are shown with statistical error bars, and the line is a fit to the Lorentzian natural linewidths of the Mn-K$\alpha$ complex [135] convolved with a Gaussian detector response.
Signal multiplexing

- Schemes: time domain, Frequency domain, Code domain
- Multiplexed systems are still under development
- UH participates in development work of multipixel microcalorimeter system which uses code domain multiplexing
Future missions

On build: Astro H (JAXA), launch 2014

Proposed:
IXO -> ATHENA (ESA), launch at 2020’s
SPICA (JAXA), launch 2018
# ATHENA micro-calorimeter scientific requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
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<th>Outer array</th>
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<td>Energy range</td>
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<td>0.3 – 12 keV</td>
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<td>($\Delta E &lt; 2.5$ eV)</td>
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<td>Full array</td>
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<td>@ 7 keV</td>
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<td>$&gt; 80%$</td>
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<td>Total count rate all events</td>
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<td>10000 counts/sec/array</td>
<td>(assumes defocusing optics applied) 1 eV / h (pk-pk)</td>
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<td>Continuous observing time</td>
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<td>$&gt; 31$ hour</td>
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space science

Collecting area vs. time

Exponential growth in collecting area
Factor 10 increase every 27.5 years

Athena: 5-10"

XMM: 15"

Einstein IPC: 60"

launch date


R. Willingale
Astro-H microcalorimeter vs. Athena XMS

D. Lumb
Figure 2.10. Left: IXO high-resolution X-ray spectra (blue) show the metal-enriched hot gas outflowing from starburst galaxy Messier 82, a part of the feedback process unresolvable with current X-ray CCD data (magenta). The insert shows that the He-like emission line triplet of NeIX can be resolved, and that not only velocities can be measured, but the plasma temperature and ionisation state can be diagnosed. Right: Superwinds in Messier 82, exhibiting a starburst-driven superwind. Diffuse thermal X-ray emission as seen by Chandra is shown in blue. Hydrocarbon emission at 8μm from SPITZER is shown in red. Optical starlight (cyan) and Hα+[NII] (yellow) are from HST-ACS observations.