Superconducting detector arrays: from cosmology to nuclear non-proliferation

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Breakthroughs in superconducting and cryogenic technology are enabling practical large superconducting cameras and spectrometers:

- Superconducting transition-edge sensors
- Micromachining
- SQUIDs multiplexers
- Cryocoolers

Astronomical and particle physics applications have driven the development of superconducting detector arrays, but a broader variety of fields are being impacted:

- Cosmology
- X-ray and submm astronomy
- Quantum information
- Electron probe materials analysis
- Security
- Nuclear materials
- Particle physics
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Thermal detection

X-ray

E → Heat

C

Thermometer

G

Thermal Conductance

Heat Capacity

Photon → Heat

\[ \tau = \frac{C}{G} \]
Thermodynamic power noise: \[ \text{NEP}^2 = 4k_bT^2G \quad (W/\sqrt{Hz})^2 \]

Energy fluctuations:
\[ \Delta E_{\text{rms}}^2 = k_bT^2C \quad (J)^2 \]

Operate at low temperatures (T \sim 0.1K to 0.3K) where C, G and thermodynamic fluctuations are small.

Response time:
\[ \tau \propto C/G \quad (s) \]
X-ray energy resolution

Thermodynamic energy fluctuations

\[ \Delta E_{rms} = \sqrt{k_B TC} \]

- \( k_B \): Boltzmann’s constant
- \( T \): Temperature of operation
- \( C \): Heat capacity

- The energy resolution can be a bit better than the thermodynamic energy fluctuations.

- At 6 keV, conventional semiconductor detectors have energy resolution as good as about 120 eV

- TES x-ray calorimeters can have energy resolution ~ 2 eV – about 60 times better than SiLi.
Superconducting Transition-Edge Thermometer

Transition-Edge Thermometer (TES)

Temperature (mK)

Resistance (Ω)

Photon → Heat → Resistance

TES thermometer

membrane
A bilayer of a thin superconducting film and a thin normal metal acts as a single superconductor with a tunable $T_c$ - the “proximity effect”

One example system is Mo-Cu
- Robust and temperature stable
- Molybdenum $T_c \sim 0.92$ K
- Copper normal

- Sharp
- Reproducible $\sim 5$ mK
- Tunable
- Robust

Other systems: Ti / Al, Mo / Au, W, Ti, etc.
2001 – FIBRE 1

FIBRE 8-pixel bolometer array

2006 – SCUBA-2 subarrays

Three 1,280-pixel TES bolometer subarrays for SCUBA-2; with UK ATC; SMC
Temperature self-biasing:

Temperature self-biasing enables for large TES array applications.

As the film cools, \( R \rightarrow 0 \), and \( P_{\text{joule}} \) increases.

Stable equilibrium

\[
\frac{V^2}{R} = P_{\text{sink}}
\]

If you cool the heat sink to well below the transition temperature of a voltage-biased TES, the TES will self-heat into its transition (electrothermal feedback).

If \( V^2 \) is applied to the TES, then the power \( P_{\text{joule}} \) is given by

\[
P_{\text{joule}} = \frac{V^2}{R}
\]

and

\[
P_{\text{sink}} = \text{thermal conductance}
\]

These equations illustrate the self-biasing mechanism in TES systems.
SQUID power: \(~ nW\) per ‘on’ channel – operate at base temperature.

SQUID response:

- Input flux
- Output current (\(\mu A\))

Bias point

Output current:

- 90
- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

Input flux:

- -0.5
- 0
- 0.5
- 1
- 1.5
- 2
Multiplexing basis sets

Time division (TDM): different pixels at different times

Frequency division (FDM): different pixels at different frequencies

Same idea, different orthogonal basis set
Each colored block is 1 pixel

Row address currents:
- Row 1: on, off
- Row 2: on, off

Column outputs:
- Column 1: TES bias, SQ2 flux bias, SA flux bias, V<sub>er</sub>, P, T
- Column 2: SQ2

TDM operation:
- each TES coupled to its own SQ1
- TESs stay on all the time
- rows of SQ1s turned on and off sequentially
- SQUIDs are nonlinear amplifiers, so use digital FB
Each colored block is 1 pixel

Analog time-division multiplexing

Row address currents:

Column outputs:

Column 1

Column 2

V_{FB}

time

V_{FB}

time
Each colored block is 1 pixel.

Row address currents:

- **Row 1**
  - $I_{ad1}(t)$
  - $I_{ad1}$
  - $t$
  - on
  - off

- **Row 2**
  - $I_{ad2}(t)$
  - $I_{ad2}$
  - $t$
  - on
  - off

- **Column 1**
  - SQ1
  - TES
  - $V_{er}$
  - $V_{FB}$

- **Column 2**
  - SQ1
  - TES
  - $V_{er}$
  - $V_{FB}$

**20 mm**
UBC Room-temperature electronics

- **Electronics**
  - MCE from UBC – 8 columns per mux card, fully supported system, 10 person years of FPGA firmware development
  - NIST/UBC MUX used for SCUBA-2, ACT, SPIDER, BICEP-2, SPUD, CLOVER, ZEUS…

One crate controls 1,280 pixels
2-stage adiabatic demagnetization refrigerator (ADR)

- Cryocooler: no liquid cryogens
- Push button operation from room temperature to 50 mK
- Each magnet cycle gets you to ~ 45 mK and ~ 7 days < 100 mK
- NIST-designed cryostat and insert; now commercially available
Absorbers for the electromagnetic spectrum + beyond

- **submm/mm-wave**: resonant cavity absorbers
- **submm/mm-wave**: antennas (Berkeley)
- **Near IR & optical**: TES with antireflection coating (Nam / NIST / Stanford)
- **Soft x-ray**: thick Bi "mushroom" absorber
- **Dark matter**: thick Si or Ge crystals
- **Gamma-ray**: thick metal foil
Submm astronomy: SCUBA-1

Survey of the galactic center

Detection of a gas giant around Fomalhaut
• A collaboration of the UK, Canada, Raytheon, and NIST
• SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the James Clerk Maxwell Telescope real soon.
Submm astronomy: SCUBA-2

1,280-pixel TES bolometer

Deep-etched trench (10 μm)

1.135 mm

Indium bump bonds (80 per pixel)

Nitride membrane (0.5 μm)

Quarter-wave Si Brick

1,280-pixel SQUID Multiplexer

bump-bonded subarray (TES+MUX)

Tesla
THz/submm astronomy: SCUBA-2
Cosmology by the coordinated study of cosmic structure

- CMB
- Optical
- X-Ray
- Cosmic structure
- Cosmological Parameters
- ν Mass
- Dark energy Eqn. of state
Most of the normal, baryonic matter in clusters lies in the hot X-ray emitting gas ($10^6 - 10^8$ K)

Probe of total mass of galaxy cluster – constrains cosmological parameters

X-ray Microcalorimeter Spectrometer (XMS) for Constellation-X, GSFC, NIST, etc.
Hot electron gas imposes a unique spectral signature

Z-independent cluster surveys

NO SZ Contribution in Central Band

145 GHz decrement

220 GHz null

270 GHz increment

NO SZ Contribution in Central Band

Devlin, ACT collaboration

1.4° x 1.4°
The Atacama Cosmology Telescope - SZ

3,000 TES pixels (256 shown)

Collaboration:
Cardiff  Columbia  CUNY  Haverford  NASA/GSFC  NIST
Penn  Princeton  Rutgers  Univ. de Catolica  UMASS  Univ of Toronto
South Pole Telescope and APEX-SZ

APEX-SZ, 320 pixels

SPT, 960 pixels

Berkeley, Chicago, etc.

(NIST SQUIDs)
Future: TES CMB polarimeters for cosmology

- Signature of primordial gravitational waves

- CMB polarimetry microlensing: “cosmic shear”
  - Probe of expansion history of universe with different systematics

Polarization-sensitive TES provide excellent sensitivity
  - Need good systematic control

Balloons: SPIDER, EBEX

Ground-based: BICEP-2, SPUD, CIOVER, SPT, ACT, …
The universe is opaque to photons before 380,000 years: but not to gravitational waves and neutrinos

- Detection of the cosmic gravity wave (CGB) background would probe the inflationary era ($10^{-35}$ s?)
- Direct probe of inflation vs. cyclic / ekpyrotic models

The Surface of Last Scattering:

- 380,000 yr atoms form
- 400 million yrs Stars form

NIST
Two different types of anisotropies:

1. Decompose the temperature and gravitational wave distribution at the surface of last scattering into a superposition of plane waves.

2. The two types of waves will produce quadropole temperature anisotropies with different spin.

3. Integrate the light from all directions scattering off towards the observer.

4. The characteristic anisotropies of gravitational waves result in polarization with a curl-like symmetry (BB).

Credit: Wayne Hu, Chicago
CMB polarization so far (no gravity waves)

DASI: EE polarization of the CMB; small angular scale

WMAP: EE polarization of the CMB; large angular scale
TES polarimeter arrays

GSFC: metal platelet feedhorns

Berkeley: planar antennas

JPL/Caltech: beam-synthesized antennas

NIST: silicon micromachined corrugated feeds
About 96 % (>600 tons) of the all the Pu under International safeguards is in spent fuel. Is it all where it is supposed to be? Is any of it missing?

Current IAEA Methods

- $\gamma$ spectroscopy
- Gross neutron
- Calorimetry
- Computer models
- Operator's reactor history
- Limited destructive analysis
- Containment and surveillance

Spent fuel in North Korean cooling pond
Nuclear materials (various isotopes of U, Pu, etc.) emit characteristic $\gamma$ rays and X rays around 100 keV.

Industry-standard 100 keV spectrometer is HPGe:
- best $\Delta E \sim 500$ eV (can’t resolve some important lines)
- active collecting area ~ a few cm$^2$
- max count rate ~ 50 kHz

Arrays of TES microcalorimeters promise much better energy resolution, comparable collecting area and count rate.

Efforts at LANL / NIST and LLNL
TES Pu spectrum measured at LANL

Pu spectra (PIDIE-7) with both 52 eV μcal and HP Ge detector

μcal Counts / 15 eV bin

HPGe kCounts / 81.4 eV bin

Energy (keV)

PIDIE-7 (0.4 g Pu)

239\text{Pu}

\text{U K}\alpha_1

\text{Pu K}\alpha_2

\text{Np K}\alpha_1

238\text{Pu}

240\text{Pu}

241\text{Am}

Sn absorber

Mo/Cu TES

1 mm
Key measurements:

- Pu isotopes

\[ ^{239}\text{Pu} : ^{240}\text{Pu} \ \gamma \text{ray} \]  
\[ ^{239}\text{Pu} = \text{weapon} \]
TES Pu spectrum measured at LANL

Key measurements:

- Pu isotopes
  \(^{239}\text{Pu} : {^{240}\text{Pu}} \ \gamma \text{ray} \)  
  \(^{239}\text{Pu} = \text{weapon}\)  

- spent reactor fuel
  (different spectrum):
  \(\text{Pu} \ \text{Ka}_1 : \text{U} \ \text{Ka}_1\)
  x-ray fluorescence ratio
  (learn total Pu content without knowing reactor history)
TES Pu spectrum measured at LANL

Key measurements:

- Pu isotopes
  \[ ^{239}\text{Pu} : ^{240}\text{Pu} \ y \text{ray} \]
  \( ^{239}\text{Pu} = \text{weapon} \)

- spent reactor fuel
  (different spectrum):
  Pu \( \text{K} \alpha_1 : \text{U} \text{K} \alpha_1 \)
  x-ray fluorescence ratio
  (learn total Pu content without knowing reactor history)

Need TES arrays:
HPGe: \( t = 15 \text{ minutes} \)
uCal: \( t = 7 \text{ hours} \)
std. Mo/Cu TES process; add lithographed epoxy posts

spin-coat another Si wafer w/ glue

stamp-print glue onto epoxy posts

stamp-print glue onto epoxy posts

micro-machined “egg crate” containing Sn absorbers

glue on absorbers to complete array

grey = TES
cyan = epoxy post

dark blue = glue

yellow = Sn absorbers

6.25 mm

Batch fabrication of TES $\gamma$-ray arrays
NIST/LANL 1st generation γ-ray arrays

MUXed spectrum of $^{153}$Gd γ-ray source
13 coadded pixels

counts / 5 eV bin

energy (keV)

103.0 103.2 103.4

51 eV

Best pixel

counts / 4 eV bin

energy (keV)

103.10 103.20 103.30

27 eV
14-pixel $\gamma$-ray array system delivered to LANL
2nd-generation $\gamma$-ray arrays

Four 66-pixel array chips

Pixel from underneath

NIST/LANL

1.5 mm

absorber removed
Discrimination of $^{235}\text{U}$ from $^{226}\text{Ra}$

“The Kitty Litter Problem”
Alpha spectroscopy is a powerful tool for low level actinide measurements (μg – pg)

Approximately 3,000 samples analyzed per year at LANL for the IAEA and others

Poor resolution of conventional alpha spectroscopy (10-30 keV) is a problem:
- Can’t split $^{239}\text{Pu}/^{240}\text{Pu}$ → drives use of slow and expensive mass spec
- Elemental overlaps → slow and expensive wet chemistry to separate
Pu sources and mounting hardware

Completed sensors

Electroplated mixtures of Pu isotopes below 2 nCi (Boulder limit)

High resolution $\alpha$ spectroscopy
Alpha spectroscopy of $^{209}\text{Po}/^{210}\text{Po}$

- $^{210}\text{Po}$ spectrum
  - 2.46 keV resolution
  - in-source straggling (expected)

- $^{209}\text{Po}$ spectrum
  - satellite line - never before observed

World-record resolution: 2.46 keV at 5.3 MeV
First splitting of $^{239}\text{Pu}/^{240}\text{Pu} \alpha$ lines
# Applications of TES arrays

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Microwave SQUID multiplexer

rf-SQUIDs (flux variable inductors)
- unshunted + non-hysteretic
- dissipationless
- Junctions tune microwave resonances

Pixel variety #1

Chip with one feedline; 32 dissipationless SQUIDs

Measured resonance at 3 flux values
Initial prototypes work well
- 32 resonators on feedline
- $Q = 4,000 - 20,000$ at 5 GHz
- Resonator accuracy compatible with $> 1,000$ SQUIDs per HEMT
- Parasitic power loss (in dielectric) $\sim 5$ pW
- Stable operation
- Noise dominated by dielectric: $\Phi_n = 0.17 \mu \Phi_0 / \sqrt{Hz}$ at 100 kHz
- Input low-pass filters block microwaves from detector
- Now working coupling to TESs
Microwave MUX SQUIDs operate open loop (no feedback, but flux modulated)

- One common “flux ramp” wire for all SQUIDs
- 10 kHz sawtooth current on flux ramp wire with 10 $\Phi_0$ amplitude → SQUID response modulated at 100 kHz, above dielectric noise
- Detector signal recovered from phase of modulation

Should be possible to operate >1,000 SQUIDs with two coax cables (input & output), one HEMT, and one flux-ramp wire
## Applications of TES arrays

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Electron-probe materials analysis

128-pixel x-ray array

X-ray TES on an SEM

Energy (eV)

WM

γ

WM

ζ

1,2

Si K

β

WM

β

WM

α

1,2

WSi₂ on SiO₂

Si Kα₁₂

Microcalorimeter

EDS spectrometer

Counts

WM Mα₁₂

WM Mβ

S Kβ

WSi₂ on SiO₂

0 500 1000 1500 2000

1400 1600 1800 2000 2200

Energy (eV)
The high energy resolution of the microcalorimeter also provides a high peak-to-background ratio, allowing better thin film & trace element analysis.

TaSiN thin films on Si (SUNY-Albany)

- 3 keV beam energy
- ~500 s⁻¹ input rate
- 400 s live time
- ~0.6 nA beam current

Counts

Energy

Ta Mα
Si Kα₁,₂
Si Kα₃,₄
Ta Mβ

NIST μcal EDS

- 74 nm
- 32 nm
- 12 nm
- 7.5 nm
- 3.5 nm

Ref. Geer et. al.
• Contaminant particles in semiconductor processing lower yield
• Low beam energies to localize x-ray production in ~60 nm particle
• High energy resolution to resolve overlapping x-ray lines

High beam energy; x-rays from substrate
Resolving peak overlaps

The need for low-energy analysis of small particles means that many peaks are overlapping when measured with SiLi.

![Graphs showing peak overlaps in TiN and BaTiO₃](image-url)
The high energy resolution of the microcalorimeter also provides a high peak-to-background ratio, allowing better thin film & trace element analysis.

0.7 wt. % Cu measured in WSi₂ thin film

Collaboration with Vartuli and Stevie (Lucent)
• Chemical bonding state causes small (< 1 eV) shifts in x-ray line position
• Industrially important problem: Al particles on oxide substrates.

Particle samples provided by Alain Diebold (SEMATECH)
Chemical shift map

Al oxide  Al