Superconducting Detectors: 
the Past 30 Years and Future Prospects

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NIST and the University of Colorado, Boulder

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1\textsuperscript{st} International Workshop on Low Temperature Detectors

31\textsuperscript{th} anniversary: 1986, Ringberg Castle, Germany

Programm

• Update on Neutrinos, Dark Matter, and Cryogenic Detection.
  By L. Stodolsky

• New Results on the Basic Properties of Superheated Granules Detectors.
  By L. Gonzales-Mestres and D. Perret-Gallix

• Investigation of Superconducting Tin Granules for a Low-Energy Neutrino or Dark Matter Detector.
  By K. Pretzl

• SQUID Detection of Superheated Granules.
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• VLSI Superconducting Particle Detectors.
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• "Minicylinder" Design for Solar Neutrino Detection (A naive proposal).
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• Solar Neutrino Indium Detector Using Superheated Granules.
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• An Indium Solar Neutrino Experiment.
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• Cryogenic Detection of Particles, Development Effort in the United States.
  By B. Sadoulet

• Calorimetric Detectors at Low Temperatures.
  By F.v. Feilitzsch, F. Probst, and W. Seidel

• The Possible Impact of Thermal Detectors in Nuclear and Subnuclear Physics.
  By E. Fiorini

• Considerations on Front End Electronics for Bolometric Detectors with Resistive Readout.
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• Coherent Neutrino-Nucleus Elastic Scattering in Ultralow-Temperatures Calorimetric Detectors.
  By T.O. Niinikoski

• Data Acquisition and Analysis of Calorimetric Signals.
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• The Use of Rotons in Liquid Helium to Detect Neutrinos
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Invited presentation ED6-2-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.
Cryogenic Detectors in ~ 1987: Superconducting Granules

- Proposed in Bernas et al, Physics Letters, 1967
- Heavy interest (see LTD1 program) in detection of neutrinos and dark matter candidates
- Need detector with large interaction mass but very small energy threshold
- Spheres of type I superconductor in a B field < Hc. Temperature rise from interaction causes field to penetrate sphere change in B field detected with pick-up coil

And if that works ... scale up with more granules

From D. Twerenbold, Rep Prog Phys, 1996, p381
Cryogenic Detectors in ~ 1987: Superconducting Tunnel Junctions

Long history subsequent to Giaever’s 1960 and 1961 tunnel junction papers:

- Wood and White, APL, 1969, “Pulses induced in tunneling currents between superconductors by alpha-particle bombardment”
- 1970s: Numerous papers on detection of phonons and excess quasiparticles with STJs
- Kurakado, NIM, 1981 & 1982, “Possibility of high resolution detectors using superconducting tunnel junctions”
- Excess QPs created on one side of junction produce detectable current through biased junction

Around 1987, measure energy of single 6 keV x-rays with ~50 eV resolution (Rothmund and Zehnder, 1988)
Cryogenic Detectors in ~ 1987: Thermistors

- Andrews, 1942 and 1949, detection of infrared light and alpha particles with current biased superconductors
- Boyle and Rodgers, 1959, carbon resistor bolometer at 4K
- Modern formulation: Moseley, Mather, and McCammon, J Appl Phys, 1984, “Thermal detectors as x-ray spectrometers”
- Fiorini and Niinikoski, NIM, 1984, “Low-temperature calorimetry for rare decays”

Various thermometers: superconductors, implanted silicon, carbon, neutron transmutation doped germanium

From Boyle and Rodgers, J Opt Sci Am, 1959, v49, p67  
From Moseley et al, J Appl Phys, 1984, v56, p1257
Early Detectors Illustrate Motivating Principles

- Use superconductors and low temperatures because of low specific heat (granules)

\[ C_{ph} \sim T^3 \quad \text{and} \quad C_{el} \sim e^{-T/T_c} \]
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  \[ \Delta_{Si} \sim 1 \text{ eV} \quad \Delta_{Nb} \sim 1 \text{ meV} \quad \text{if you count excitations,} \quad N = \frac{E_\gamma}{\Delta} \quad \text{and energy resolution} \quad \propto \sqrt[2]{\frac{N}{N}} \quad E_\gamma = \sqrt{E_\gamma \Delta} \]
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- Use thermometers with strong temperature dependence (thermistors and especially superconductors)
  \[ (T/R) \ (dR/dT) = 100 - 1,000 \]
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- Use low temperatures because of the suppression of thermal and electrical noise (all)

\[ P_N = (4kT^2 G)^{1/2} \text{ W/Hz}^{1/2} \quad \text{and} \quad V_N = (4kTR)^{1/2} \text{ V/Hz}^{1/2} \]
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- Find ways to read out many discrete elements with fewer amplifier channels (granules)
Big Ideas

1. Microfabrication
2. SQUID Readout
3. TESs
4. Multiplexed Readout
5. Dry Cryogenics
6. MKIDs
7. Microwave Readout
Microfabrication

- mostly optical lithography, physical vapor deposition, wet & dry etches, and silicon micromachining
- conventional techniques and tools that lag the semiconductor industry by 20 years are still incredibly powerful

Tilted view of array of sensors with electroplated gold absorbers suspended above sensors and wiring

Underneath one absorber: 0.8 um trace and space

images from S. Bandler, NASA GSFC

Transition Edge Sensors (TESs)

- Thin metal film electrically biased in superconducting-to-normal transition
- Early work used current-biased films and voltage readout (beginning with Andrews in 1940s)
- Current bias has severe problems: thermal run-away and extreme sensitivity to inhomogeneity
- Highly successful in many application areas. TESs critical to growth of cryogenic detector field (although no longer alone)
- Many implementations: elemental films, bilayers, and alloys
- For many years, TES physics poorly understood, but lots of recent progress: weak-links and phase slip lines

![Graph of resistance vs. temperature](image1)

![Graph of R_n vs. T](image2)

![Graph of pulse height vs. photon energy](image3)

*Sadleir et al., PRL, 2010*

*Ullom & Bennett, SuST, 2015*
SQUIDs

- low noise current-to-voltage amplifiers with low input impedance; required for TESs

- There are some who complain about SQUIDs but we are lucky to be able to use them:
  - can locate near sensors
  - low noise
  - low power dissipation
  - low input impedance, high bandwidth operation
  - made by microfabrication -> large quantities, many variants
Multiplexed SQUID Readout

- Most applications require sensor arrays. Having 1 amplifier at 300K for each sensor is challenging. Largest (?) example: Sharc II with 384 implanted Si thermistors
- SQUID circuits have enabled 10-100 sensors per 300K amplifier: multiplexed readout
  - microfabricated amplifiers can “easily” be made in more complex configurations
  - need an orthogonal basis set for each sensor’s signal
  - time-division, frequency-division, and code-division (TDM, FDM, and CDM) readout: fairly similar performance, ≤ 10 MHz bandwidth per channel
Dry Cryogenics

- MilliKelvin systems precooled by pulse tubes are now common in many fields but particularly impactful for sensors which often must be brought to the photon source
- Many commercial vendors of dilution refrigerators and adiabatic demagnetization refrigerators

ADR that mounts on electron microscope

$\leq 1\ m$

DR in Atacama desert
Microwave Kinetic Inductance Detectors

- Cooper pair breaking changes surface impedance of superconducting film: athermal sensors
- Film embedded in μwave resonator and probed by a μwave signal
- Both quarter-wave (Day et al, Nature, 2003) and lumped element (Doyle et al, JLTP, 2008) resonators possible
- Vigorous activity from many groups because of potential for large arrays
- Recent thermal variant exploits L(T/Tc) “TKID”. Addresses internal position dependence.
  Actually an old idea: D. McDonald, APL, 1987

Operating Principle

\[
\begin{align*}
\lambda/4 \text{ KID} & \\
\text{Lumped Element KiD} & \\
\text{Large Arrays} & \\
\end{align*}
\]

From A. Micelli, Argonne Natl Lab

5400 FIR MKIDs at center, from SRON

Microwave Readout

- MKID readout is extremely attractive: many resonators on shared feedline with one input and one output. 1 shared amplifier at output port.

- 50 Ohm impedances and commercial HEMT amplifiers provide many GHz of readout bandwidth. Multiplexing factors of $10^3$ possible.

![Circuit $S_{21}$ showing few hundred resonators](image)

From C. McKenney, NIST
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Resonator 1 $f_1 + \Delta f$
Resonator 2 $f_2$
Resonator 3 $f_3$

stimulus changes resonator frequency to $f_1 + \Delta f$. This changes amount of power at $v_1$ that reaches amplifier

- Circuit can be adapted for TES readout by addition of RF-SQUID: J.A.B. Mates, PhD thesis, 2011
Evolution of Technologies

- Granules gone

Critical Field of Single Granule vs. Angle

Data shows grave obstacle to getting good performance from ensemble of granules.

Frank et al, NIM A, 1990
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**Magnetic MicroCalorimeters (MMCs)**

- Deposited energy changes paramagnetic or diamagnetic response
- SQUID sensor sees this as change in flux
- Excellent E/ΔE results from Heidelberg, KRISS, and NASA GSFC

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- SNSPDs emerge and flourish

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Superconducting Nanowire Single Photon Detectors (SNSPDs)
- Gol'tsman et al, APL, 2001
- Superconducting wire (few nm thick, ~100 nm wide) under current bias
- Absorption of single optical photon produces resistance and voltage
- Fast response, low jitter
  - F. Marsili et al, Nature Photonics, 2013
Explosion of Applications

x-rays
- astrophysics
- beamline science
- tabletop time-resolved science
- microbeam analysis
- fundamental parameters

γ-rays
- nuclear materials analysis

mm waves
- cosmic microwave background

sub-mm waves
- astrophysics
- concealed weapons detection

astroparticle physics
- WIMP searches
- hidden photon searches

neutrino physics
- 0νββ
- neutrino mass

mass spectrometry
- biomolecules
- neutral fragments

optical and near-IR
- astronomy
- quantum information
- laser-based communication
- LIDAR

alpha particles and neutrons
- nuclear materials analysis

decay energy spectroscopy
- nuclear materials analysis
- nuclear data
Cosmic Microwave Background Science

- Measurements of the Cosmic Microwave Background (CMB) shape our understanding of the Universe
- Cryogenic, and especially superconducting sensors, are now used in almost every CMB experiment
- In recent past, measurements of temperature anisotropy. Planck (NTD Ge) results definitive.
- Now, searches for B-mode polarization: signature of inflationary epoch

- Same works also constrains sum of neutrino masses, age of universe, Hubble parameter, baryon density, dark matter and dark energy densities

Temperature Anisotropy

Temperature and Polarization Signals vs Angular Scale

B-mode search requires finding nK signals on top of K background

Technology

- Sensitivity of individual sensors limited by photon noise from sky map faster by having more sensors and multichroic sensors
- Instruments typically have several thousand multiplexed TESs
X-ray Science

- Why superconducting sensors? Unique combination of resolving power and collecting efficiency
  - Resolving power gives access to chemical and spin effects, reduces backgrounds and overlapping lines
  - Collecting efficiency (100-1,000x better than xtals or gratings) good for dilute and radiation sensitive materials, also good for weak laboratory sources
- Case for superconducting sensors in laboratory x-ray science was always strong. Recent work shows sup. sensors also have role at large facilities. Several spectrometers at synchrotrons, one under development for LCLSII XFEL.
- Case for use in ultrafast time-resolved x-ray science particularly strong
- Most x-ray techniques now demonstrated: XRF, XES, XAS, RIXS, elastic scattering, PIXE, ...

NIST TES spectrometer

AIST STJ data on N-implanted SiC: Ohkubo et al, IEEE TAS, 2014

Spin cross-over measured at APS (above) and NIST tabletop. Tabletop result has 10x better time resolution and uses ~10⁴x fewer photons: Miaja-Avila et al, PRX, 2016
Single Optical and NIR Photon Detection

- Done with TESs, SNSPDs, and MKIDs, each with different strengths
- Wide range of applications:

**Quantum Information**
Loophole-free tests of Bell’s inequalities → exclude theories of local realism
- Giustina et al, PRL, 2015
- Shalm et al, PRL, 2015

**Quantum Key Distribution**
Provably secure communications.

**Laser-Based Communication**
Lunar Laser Communication Demonstration (LLCD), 2013-2014

SNSPDs in ground station receive information via laser light from satellite in lunar orbit (JPL, MIT LL)

**Microscopy**
K. Hattori presentation this past Weds.

**Astronomy**
Exoplanet searches, maybe redshift surveys
Future Trends

**Bigger and more ambitious systems? Absolutely**
- DOE planning CMB Stage 4 (CMB S4): O(10^5) sensors
- X-ray spectrometer for LCLSII: 10^4 sensors each counting at several kHz
- Litebird (CMB) and Athena (x-ray) satellites

**Ubiquity? Meaning some widespread application of cryogenic sensors? Maybe**
- Cost of mK cryogenics is a significant obstacle: >$200K. Maybe a Kelvin-range instrument will be first. SNSPDs for a communication application?
- Commercial XRF continues to look promising

**Colder? Yes**
- Magnetic calorimeters already at 10-20 mK
- Desire for soft x-ray TESs with resolution of 0.5 eV at 500 eV: will see TESs move from ~100 mK to ~40-50 mK

**Microwavier? Absolutely**
- Microwave readout architectures (MKIDs and uwave SQUIDs) compelling. Expect them to dominate.
- HEMT amplifiers used in uwave readout have input noise T of few K: mismatch to mK sensors. Expect to see quantum amplifiers play a growing role.
Thank you!

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