Superconducting Transition Edge Sensors for Particle Astrophysics and Cosmology

International Symposium on the Development of Detectors for Particle, Astro-Particle and Synchrotron Radiation Experiments

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Blas Cabrera - Stanford University & KIPAC

CDMS Detector Fabrication: Paul Brink, Astrid Tomada, Larry Novak, Matt Pyle
(collaborators: NIST, Boulder, Kent Irwin; UCD, Martin Huber)
Optical Detectors: Roger Romani, Jen Burney, TJ Bay, Joelle Barral
(collaborators: NIST, Boulder, Sae Woo Nam, Aaron Miller)
X-Ray Detectors: Steve Kahn, Steve Leman, Bill Craig
(collaborators: Lockheed, Palo Alto, Bob Stern, Steve Deiker, Dennis Martinez)
Overview of TES applications (*this talk)

- **CMB with polarization:** A. Lee (UCB) and A. Lange (Caltech)
- **Sub-mm astronomy:** SCUBA 2: more than 10,000 TES pixels
  - NIST delivering TES arrays
- **Near IR/optical/near UV ground & space:** Stanford/NIST
  - casualty of NASA downscaling R&D for future instruments
- **X-Ray astrophysics:** NIST/Goddard; Joel Ullom (next talk)
- **X-Ray macropixel:** Stanford/Lockheed/NIST
- **Dark matter searches:**
  - **CDMS collaboration:** TES sensors on Ge and Si crystals
  - **SuperCDMS future:** Walter Ogburn (#147/150 poster)
  - CRESST search uses SPT with SQUID readout
  - Large negative ion TCP: Jeff Martoff (#188 poster)
**TES Single Photon Detectors**

- **Demonstrated Sensitivity with TES**

- **Resolution target for Transition Edge Sensors**
  - **Fundamental limit for Tc = 70 mK**
  - With 100% ETF efficiency

- **Constellation-X Soft x-ray goal**
  - NIST Mo/Cu TESs
    - 2.37 eV FWHM @ 6 keV
  - Goddard Mo/Au TES
    - 3.7 eV FWHM @ 3.3 keV
  - NIST Mo/Cu TES
    - 2.0 eV FWHM @ 1.5 keV
  - Stanford W TES
    - 0.12 eV FWHM @ 1.5 eV

- **A factor of 2-3 improvement is likely with an additional factor of 4 to the fundamental limit**
Superconducting Transition Edge Sensors

- **Steep Resistive Superconducting Transition**
  
  ![Graph showing steep resistive transition](image)

  - $W_T \sim 70 \text{ mK}$
  - 10-90% <1 mK

- **Voltage bias is intrinsically stable**
  
  The Joule heating produced by bias
  
  $$P_J = \frac{V_B^2}{R} \Rightarrow P_J \downarrow \text{ when } R \uparrow$$

  is stable whereas for current bias
  
  $$P_J = I_B^2 R \Rightarrow P_J \uparrow \text{ when } R \uparrow$$

  which is intrinsically unstable

  $$\alpha = \frac{dR}{dT} \frac{R}{T}$$

  unitless measure of transition width
Characterize Performance of TES

We calculate transition width from power curve using

\[ P_J = \sum (T_c^5 - T_{ph}^5) \]

Sensor Current [µA]

Sensor Power [pW]

Sensor Resistance [ohms]

Sensor temperature [mK]
Three Types of Detectors

- Direct absorption of photon in TES (e.g., IR-optical-UV photons)

- Photon absorber in electrical contact with TES (e.g., x-ray detectors)

- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES (e.g., dark matter detectors)
TES Simulation

- Optical photon absorbed in TES (Tali Figueroa)
Science Objectives for Optical/UV TESs

• Time variable sources
  - White dwarf binaries, neutron stars, pulsars
  - Black hole binaries, and supernovae

• Distant galaxies
  - Direct redshift measurements for faint galaxies
  - Highest photon efficiency

• Imaging UV spectroscopy
  - R~300 for nearby sources
  - Search for ionized clouds as dark baryonic matter
Optical Photon Detectors

• Demonstration of W TES sensitivity

**Appl. Phys. Lett.** 73, 735 (1998)
B. Cabrera, R. Romani, A. J. Miller
E. Figueroa-Feliciano, S. W. Nam
Monochromator Calibrations

- IR thermal background
- 2nd order hits
McDonald Observatory 107” Demonstration

200 µm UV fiber optic
2.7 m aperture
3 m length cold loop
20 µm X 20 µm TES w/ Tc~70 mK

Dilution refrigerator 35 mK base

McDonald Observatory 107”
February 1-7, 2000
NIST & Stanford
• Crab pulsar
• PSR 0656
• Eskimo nebula
• Geminga
• ST-LMI white dwarf
• Hercules X1
• calibration stars

Crab pulsar
Crab Pulsar Data from McDonald 107"

\begin{figure}
\centering
\includegraphics[width=\textwidth]{crab_pulsar_data}
\caption{Crab Pulsar Data from McDonald 107"}
\end{figure}
Background Subtracted Energy vs Phase

Background Subtracted Crab Pulsar

Photon energy histogram

Phase timing histogram
ADR for Optical/UV Imaging Array

LN compartment

LHe compartment

3 Tesla magnet & magnetic shield

guide field CCD

f/15 from 10 meter telescope
Infrared Loading a Challenge

- Block ~2 µm and ~100 µm using sapphire, KG-3, KG-5, acrylic, and grid filters.

[Diagram showing infrared loading challenges with sapphire, acrylic, and grid filters at different temperatures: RT, 77K, and 4K.]
New 8 x 8 array

- Array of 24 $\mu$m square pixels on 36 $\mu$m centers
Improve PSF with Reflection Mask

Reflection mask covers rails and reflects photons that would have hit the rails back onto the active pixels.

![Graph showing spectrum for 2.33eV incident photons with a Gaussian fit and photon energy range from 1.6 to 2.6 eV.](image-url)
Large Area TES X-Ray Detectors

• Figure of merit is etendue given by: \( A\Omega = 0.012 \, d^2 \, \text{cm}^2\text{-sr} \), where the detector diameter \( d \) is in cm.

• Square detector 25 mm on an edge with 1 mm square pixels and with an energy resolution of 4 eV FWHM would enable:
  - Search for missing baryons in warm-hot interstellar medium (WHIM)
  - Surveys of clusters and groups of galaxies as a probe of the growth of structure

• A number of efforts to multiplex large numbers of single pixels - time domain and frequency domain schemes

• We are developing macropixel to cover large areas
Expanding universe - simulations and data
Huge Advances from Imaging TES

- XRS microcalorimeter diffuse background rocket flight versus state-of-the-art CCD over similar energy
- Astro E2 XRS dewar failure
Best Single Pixel X-Ray Resolution

- $R = \frac{E}{\Delta E} = 2,490$

Mo/Cu TES with Bi absorber
Center array pixel
$2.37 \pm 0.11$ eV FWHM
Macropixel Concept

- Demonstration with 300 $\mu$m thick Si wafer
- X-rays incident on backside converting to phonons
- Phonon absorbed by TES sensors on front side
Macropixel Sensitivity

- Response from $^{55}$Fe x-rays across macropixel
- Will improve using intrinsic Ge

![Graph showing energy distribution with peaks at 5900 and 6455 eV, with FWHM of 72 and 80 eV respectively, and events counts of 12120 and 1381]
Macropixel Concept

- Simultaneous energy and position resolution
- Inset is raw data and plot after position correction
Composition of the Cosmos

Dark Energy - expands 73%

WIMPs

Dark Matter - clumps 23%

Free H & He - cold 3%
Stars + gas 0.5%
Ghostly neutrinos 0.3%
Heavy elements - us 0.03%
CDMS Ge & Si ZIP Detectors

- Al/W Grid
- 37 - 5 mm Squares
- 60% Area Coverage
- Aluminum Collector Fins
- 8 Traps
- 888 x 1 µm tungsten TES in parallel
ZIP Phonon Position Sensitivity

Delay Plot

Am$^{241}$:
\[ \gamma \ 14, 18, 20, 26, 60 \text{ keV} \]

Cd$^{109}$ + Al foil:
\[ \gamma \ 22 \text{ keV} \]
The Signal and Backgrounds

**Signal (WIMPs)**

- Nucleus Recoils
  - $E_r$ 
  - $\nu/c \approx 7 \times 10^{-4}$
  - $E_r \approx 10$'s KeV phonons

**Background (gammas)**

- Electron Recoils
  - $E_r$ 
  - $\nu/c \approx 0.3$
  - Ionization

- Neutrons also interact with nuclei, but mean free path a few cms

- Surface electrons from beta decay can mimic nuclear recoils
ST1&2 Soudan -> SNOLab like Tower 1 SUF -> Soudan

- Tower 1 (4 Ge & 2 Si) at SUF then at Soudan

19 neutron events at SUF

0 events at Soudan
Improvements in Surface Event Rejection

- Significant improvements in our analysis of phonon timing information
  - Surface event rejection improved by x3; kept pace with exposure increase!
  - Cuts are set from calibration data (blind analysis)
- We still have more discrimination power available as needed
  - Can continue to keep backgrounds < 1 event as more data accumulates
  - This is the real strength of CDMS detectors!
Experimental Motivations

DAMA/NaI
Bernabei et al., astro-ph/0307403

EGRET
de Boer et al., astro-ph/0412620

DAMA 1996
Edelweiss 2003
Zeplin I
CDMS (Si)
CDMS (Ge) 2-Tower
CDMS (Ge) combined

astroph/0512120 claims ZEPLIN I limit x1000 worse!

For further details see PRL 96, 011302 (2006)
Spin Dependent WIMP limits

Spin-sensitivity from $^{73}\text{Ge}$ (J=9/2, 7.7%) and $^{29}\text{Si}$ (J=1/2, 4.7%)

For further details see PRD D73, 011102 (2006)
About to Operate Five Towers in Soudan
SUF (17 mwe), Soudan (2090 mwe), & SNOLab (6060 mwe)

- **At SUF**
  - 17 mwe
  - 0.5 n/d/kg

- **At Soudan**
  - 2090 mwe
  - 0.8 n/y/kg

- **At SNOLab**
  - 6060 mwe
  - 1 n/y/ton
SuperCDMS at SNOLab

 ★ SuperCDMS is approved to be sited at SNOLab

 ★ We have received strong interest from Canadian collaborators - Queens ...

New lab space
(under construction - ready in 2007)

Sudbury Neutron Obs.

Sudbury, Ont. CA
Baseline detector for SuperCDMS

CDMS-II ZIPs:
3” dia x 1 cm => 0.25 kg of Ge

Existing ZIPs

SuperCDMS ZIPs:
3” dia x 1” => 0.64 kg of Ge

ZIPs for SuperCDMS

Photolithography test with 1” Ti
Modifications for 1" processing

- sputtering (design complete parts in shop)
- spinner (ready)
- aligner (ready)
- dry etch (design complete)
- start first Ge 1" thick fabrication in Jan 06

1" Substrate
Exploring cryocooler system with little or no cryogen servicing.

Schematic of new 'SNObox'

- Cryogen-free dilution fridge
- Lid splits
- OVC
- IVC
- Outer polyethylene
- Electronics box
- Pulse tube cryocooler
- OVC-Pb-poly lid off as unit
Does the LHC supplant Direct Detection?

Accelerators are *mass-limited*  
⇒ spectral info, but often can’t see LSP or deduce its relic density

**CDMS** is *cross section-limited*  
⇒ TeV WIMPs detectable, direct connection to cosmology
Summary

• TES detectors are now a well established technology and are at the forefront of sensitivity for all energy scales including optical, x-ray and dark matter searches.

• IR-optical-UV detectors have 0.15 eV FWHM with counting rates up to 10 kHz for single pixels, for a 6 X 6 array. Exciting technology for ground based, long duration balloon instruments from near IR well into UV and satellite missions from 10 µm to 100 nm.

• Large area macropixel x-ray arrays open new science fronts to search for missing baryons as WHIM and study large scale structure with galaxy cluster surveys.

• Dark matter search (CDMS) leads field by factor of ten and is exploring very interesting region of supersymmetry. Another factor of ten with 5 Towers then SuperCDMS.