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**
  - 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**

  \[ R \]
  \[ T \]

  unitless measure of transition width

  \[ \alpha = \frac{dR}{dT} \left/ \frac{R}{T} \right. \]

• **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

\[ W \text{ ETF-TES} \]

\[ W \text{ ETF-TES} \]
Characterize Performance of TES

We calculate transition width from power curve using

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

![Graph showing current change vs. time for a 531 nm photon]

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

IR thermal background

rail hits

2nd order
McDonald Observatory 107” Demonstration

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

- 200 µm UV fiber optic
- 2.7 m aperture
- 3 m length cold loop
- Grin & spherical lens
- 20 µm X 20 µm TES w/ Tc~70 mK
- Dilution refrigerator 35 mK base

Crab pulsar
Crab Pulsar Data from McDonald 107"

![Crab Pulsar Data Graph](image)
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
- f/15 from 10 meter telescope
- Guide field CCD
Infrared Loading a Challenge

- Block ~2 $\mu$m and ~100 $\mu$m using sapphire, KG-3, KG-5, acrylic, and grid filters

Diagram showing the absorption of light at different temperatures (RT, 77K, 4K) and wavelengths (1 to 1000 $\mu$m) with sapphire, grid, and acrylic filters.
New 8 x 8 array

- Array of 24 µm square pixels on 36 µm centers
Improve PSF with Reflection Mask

Reflection mask covers rails and reflects photons that would have hit the rails back onto the active pixels.
Large Area TES X-Ray Detectors

- Figure of merit is etendue given by: $A\Omega = 0.012 \, d^2 \, \text{cm}^2 \cdot \text{sr}$, 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 ± 0.11 eV FWHM
Macropixel Concept

- Demonstration with 300 µm 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 absorption and counts]
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%

WMAP best fit
CDMS Ge & Si ZIP Detectors

37 - 5 mm Squares

60% Area Coverage

Al/W Grid

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

\[ E_r \approx 10\text{'s KeV} \]

\[ v/c \approx 7 \times 10^{-4} \]

\[ E_r \approx 10\text{'s KeV} \quad \text{phonons} \]

**Background (gammas)**

Electron Recoils

\[ v/c \approx 0.3 \]

**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!
CDMS-II SI Results & Reach with five Towers

Experimental Motivations

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

EGRET de Boer et al., astro-ph/0412620
• Interpret EGRET gamma ray excess as DM annihilation

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

WIMP Mass [GeV/\text{c}^2]

Cross-section [cm^2] (normalized to the nucleon)

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

MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L’EXCELLENCE

SNIC - TES Particle Astro & Cosmo
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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)
- aligner (ready)
- spinner (ready)
- start first Ge 1” thick fabrication in Jan 06
- dry etch (design complete)
Exploring cryocooler system with little or no cryogen servicing
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

CDMS II 2005
CDMS II 2007
SuperCDMS 25kg
LCC1
LHC
LHC+ILC=1000
LHC+SupercDMS A

SuperCDMS 25 kg would see ~15 events

σ_x(χ+p) (pb)
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.