Searching for DM with the SuperCDMS HVeV Detector

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Dark Matter

1. Astronomical Observation
2. WIMPs
3. SuperCDMS

Detector R&D Development
DM Search
Beyond the Standard Model

M33 Galactic Rotation Curve

CMB Anisotropy

Gravitational Lensing

Insufficient mass in the universe!
Weakly Interacting Massive Particles

Four Forces:
Electromagnetic, Weak, Strong, Gravity

Super-Symmetry Theories:
Lightest supersymmetric particle (LSP)

Neutralino
Photino
Higgsino

Create a theory
Name your own DM particle

[Image of Electron Recoil]
[Image of Nuclear Recoil (Source Unknown)]
[Image of How Does Dark Matter Interact?]
SUSY Motivation

DM and SM in thermal equilibrium

\[ n_X = \frac{g}{2\pi^3} \int f(p, T) d^3 p \]

\[ n_X \propto T^3 \quad \text{for} \quad T \gg m_X \]

\[ n_X \approx g \left( \frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X / T} \quad \text{for} \quad T \ll m_X \]

DM annihilation rate into SM

\[ \Gamma(T) = n_X(T) \langle \sigma_A v \rangle \]

@ Freeze-out, \( T_f \)

\[ n_X(T_f) = \frac{1.66 g_*^{1/2} T_f^2}{m_{pl} \langle \sigma_A v \rangle} \]

\[ \frac{n_X}{s}(T_f) = \frac{4.15}{g_*^{1/2} T_f m_{pl} \langle \sigma_A v \rangle} \]

\[ \langle \sigma_A v \rangle = \frac{100}{g_*^{1/2} m_{pl} \rho_c \Omega_X h^2} \]

\[ \langle \sigma_A v \rangle = 2.8 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1} \cdot \frac{0.11}{\Omega_X h^2} \]
SuperCDMS primary goal is 300 MeV to 6 GeV mass range
SNOLAB SuperCDMS

Dilution Refrigerator

Shielding

SNOBOX

E-tank

Detector Tower

Seismic Platform
Quasiparticle-assisted Electrothermal-feedback Transition Edge Sensors (QETs)

High Voltage (HV):
- Phonon signal
- Large Bias Voltage
- Neganov-Trofimov-Luke Effect

interleaved Z-dependent Ionization and Phonon (iZIP):
- Phonon signal
- Charge signal
- Small Bias Voltage
Improved sensitivity to lower masses and cross-sections
Dark Matter

Detector R&D Developments
  1. High resolution phonon detectors
  2. Dilution refrigerator laser upgrade
  3. SuperCDMS HVeV response
  4. Detector Modeling

DM Search
High resolution detectors with tunable bandwidth
Neganov-Trofimov-Luke Effect

Phonon energy = $E_{\text{recoil}} + E_{\text{Luke}}$

Need to improve detector resolution!
SuperCDMS HVeV Detector R&D

Two channel QET with NTL amplification capabilities

Quasiparticle-trap-assisted Electro-thermal-feedback Transition-edge sensor (QET)

Pulsed monochromatic 650 nm (~1.9 eV) laser
Optimal Filtering Processing

Pulse Parameters

Zero photon events occur anywhere in this region

Max \( \text{OF}(t_i) = \text{amp} \)

\( t_i = \text{pulse timing} \)
HVeV Laser Response

First observation of $e^-h^+$ pairs in Si crystal with a phonon sensor

Integer $e^-h^+$ Pairs @ 160V Bias

Gain Linearity

First observation of $e^-h^+$ pairs in Si crystal with a phonon sensor

Appl. Phys. Lett. 112, 043501 (2018); https://doi.org/10.1063/1.5010699
Calibration laser shows new features between peaks!
Physical Model
Impact Ionization and Charge Trapping


\[
\begin{align*}
1e^-h^+ & \quad \text{Impact Ionization} & \quad \text{Bulk Leakage} \\
\text{Charge Trapping} & \quad \text{Surface Leakage} & \\
\end{align*}
\]

**Single e^-h^+ pair PDF:**

\[
(1) h(x) = A_1 \delta(x - 1) + A_- \Theta(x - 0) \Theta(1 - x) + A_+ \Theta(x - 1) \Theta(2 - x)
\]

**\(m\)th e^-h^+ pair PDF:**

\[
(m) h(x) = \int_{-\infty}^{\infty} (1) h(x') (m-1) h(x - x') dx'
\]

Where \(A_-\) is the charge trapping probability, \(A_+\) is the impact ionization probability, \(A_1 = (1 - A_- - A_+)\), and \(\Theta(x)\) is the Heaviside function.
Detector Leakage Background

The normalized background spectra (top), one residual at -140 V high intensity (middle) and fitted bulk & surface leakage probabilities (bottom) for all 8 configurations.

**Weighted Bulk Leakage:**

- $0.132 \pm 0.023\%$ @ $+140$ V
- $0.113 \pm 0.022\%$ @ $-140$ V

**Weighted Surface Leakage:**

- $0.087 \pm 0.001\%$ @ $+140$ V
- $0.101 \pm 0.007\%$ @ $-140$ V
Impact Ionization and Charge Trapping


\[ M(x) = \kappa P_0(\lambda) \cdot B(x) + \sum_{m=1}^{m_{\text{max}}} P_m(\lambda) \left( (m) h \ast G(\sigma) \right)(x) \]

(Top) Spectrum of laser-induced events (green) after cuts (~4 minutes), with analytical fit (black line) that includes charge leakage, impact ionization and charge trapping. (Bottom) Residuals normalized by the bin counting statistics. Bins with zero counts were artificially set to zero.
Weighted Charge Trapping Probability: 0.713 ± 0.093%
Mean free path: 56 cm

Weighted Impact Ionization Probability: 1.576 ± 0.110%
Mean free path: 25 cm
✓ Dark Matter

✓ Detector R&D Developments

➢ DM Search
  1. Run 1: Stanford University
  2. Run 2: Northwestern University
  3. Analysis and DM Exclusion
Stanford University Run 1


Si Crystal w/ Phonon sensor

G10 holder

Cu holder

HV bias line

Dilution refrigerator sample stage (30 mK)

Fiber Optic

~1 cm

KG-3 IR filters

NTL Amplification and monochromatic source
Northwestern University Run 2


Readout board SQUIDS (~1.3K)
GGG heat sinking (~300mK)
Detector Box (~50mK)

LED illumination from QET side

Outer channel
Inner channel

Nb Can location
DM search spectrum are similar in the two runs.
Electron Recoil DM Search

Improved heavy mediator ERDM limits to 0.5 MeV

\[
\frac{dR}{d(\ln(E_R))} = V_{\text{Det}} \frac{\rho_{\text{DM}}}{m_X} \frac{\rho_{\text{Si}}}{2m_{\text{Si}}} \overline{\sigma}_e \frac{m_e^2}{\mu_X^2} I_{\text{Crystal}}
\]

Electron Recoil DM Search

Improved heavy mediator ERDM limits to 0.5 MeV

\[
\frac{dR}{d(\ln(E_R))} = V_{Det} \frac{\rho_{DM}}{m_X} \frac{\rho_{Si}}{2m_{Si}} \bar{\sigma}_e \alpha \frac{m_e^2}{\mu_X^2} I_{\text{Crystal}}
\]

Dark Photon DM Search

\[ R = V_{Det} \frac{\rho_{DM}}{m_V} \varepsilon_{eff}^2 (m_V, \sigma) \sigma_1 (m_V) \]


Dark photon limit is consistent with other measurements
Conclusion

• Single e⁻h⁺ pair resolution with NTL gain

• Achieved comparable sensitivity to that reported by DAMIC for Dark Photons

• Improved constraints on inelastic ERDM for both heavy and light mediators down to 0.5 MeV

• Developed technique to measuring IICT

• Model is integrated into new DM search
Questions…

https://xkcd.com/2268/

We believe this resolves all remaining questions on this topic. No further research is needed.

References

1. 
2. 
3. 

JUST ONCE, I WANT TO SEE A RESEARCH PAPER WITH THE GUTS TO END THIS WAY.
Backup Slides
Questions…

https://loadingartist.com/comic/out-of-sight/

[Image: A comic strip showing a witch and frogs. The witch asks, "Wait, THREE frog eyes?" and the frogs reply, "WHERE AM I GONNA FIND A THREE-EYED FROG?" The frogs then say, "SHSHHSSHHHHH." ]
High Voltage (HV):
- Phonon signal
- Large Bias Voltage
- Neganov-Trofimov-Luke Effect

interleaved Z-dependent Ionization and Phonon (iZIP):
- Phonon signal
- Charge signal
- Small Bias Voltage

QET Design
✓ Dark Matter

✓ Detector R&D Developments

✓ DM Search

▸ Improved Detector Modeling
  1. Charge trapping and impact ionization model
  2. Data Quality
  3. Background analysis
  4. Charge trapping and impact ionization analysis
Energy (top) and counts (bottom) of events as a function of the pulse OF arrival time relative to laser TTL

Background can be selected based on timing
Run 2 Analysis

\[ M_{eff}(x) = \text{erf} \left( \frac{x - x_{eff}}{\sqrt{2\sigma_{eff}^2}} \right) \sum_{m=1}^{m_{max}} P_m(\lambda) \left( (m) h \odot G(\sigma) \right)(x) \]
Charge Trapping & Impact Ionization

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Charge Trapping Probability</th>
<th>Impact Ionization Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 V</td>
<td>16.9 ± 0.7%</td>
<td>0.2 ± 0.4%</td>
</tr>
<tr>
<td>100 V</td>
<td>13.7 ± 0.7%</td>
<td>0.1 ± 0.2%</td>
</tr>
</tbody>
</table>

Mean free path: 29 cm & 24 cm

Underfits in the 100 V spectra data are excluded from final weighted averages.
Conclusion

• Single $e^-h^+$ pair resolution with NTL gain
• Achieved comparable sensitivity to that reported by DAMIC for Dark Photons
• Improved constraints on inelastic ERDM for both heavy and light mediators down to 0.5 MeV
• Demonstrate time domain OF for semi-continuous mode acquisitions
• Developed technique to measuring IICT
• Observed no dependence on crystal polarity
• Observed dependence on crystal bias voltage
• Model is integrated into new DM search
NTL Amplification

Empty Electron States

(1) $e^- + eV\delta \rightarrow e^-$

(2) $e^- \rightarrow e^- + \hbar\omega_q$

Impurity States

Empty Hole States

(1) $h^+ + eV\delta \rightarrow h^+$

(2) $h^+ \rightarrow h^+ + \hbar\omega_q$
Charge Trapping

\[ (1) \text{e}^- + eV\delta \rightarrow \text{e}^- \quad (3) \text{e}^- \rightarrow \hbar \omega_q \]

\[ (1) \text{h}^+ + eV\delta \rightarrow \text{h}^+ \quad (3) \text{h}^+ \rightarrow \hbar \omega_q \]
Impact Ionization

\[ (1) \, e^- + eV\delta \rightarrow e^- \]
\[ (4a) \, e^- \rightarrow e^- + e^- \]
\[ (4b) \, e^- \rightarrow e^- + h^+ \]

\[ (1) \, h^+ + eV\delta \rightarrow h^+ \]
\[ (4a) \, h^+ \rightarrow h^+ + h^+ \]
\[ (4b) \, h^+ \rightarrow h^+ + e^- \]
Impact Ionization

(1) $\text{e}^- + eV\delta \rightarrow \text{e}^-$

(4a) $\text{e}^- \rightarrow \text{e}^- + \text{e}^-$

(4b) $\text{e}^- \rightarrow \text{e}^- + \text{h}^+$

(1) $\text{h}^+ + eV\delta \rightarrow \text{h}^+$

(4a) $\text{h}^+ \rightarrow \text{h}^+ + \text{h}^+$

(4b) $\text{h}^+ \rightarrow \text{h}^+ + \text{e}^-$

Theoretical Device Performance

Norm. PDF

$0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16$

$10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2}$
Semi-Continuous Acquisition

Tagged Laser Events

Time-shifting optimal filter (OF) amplitude as a function of time (blue curve).

Detector Stability

Detector responsivity over 27(18) hours of real-time acquisition with a +(-)140 V bias and four intensities for 8 configurations.

Eight configurations used in study and DR was nominally stable throughout.
Calibration was performed using the centroids of a Gaussian fit to the 1, 2, & 3 $n_{eh}$ peaks.

Energy (top) and counts (bottom) of events as a function of the OF estimated relative arrival time.

Background can be selected based on timing.
Data Selection Run 1

Calibration Laser Data

DM Search Data

Periods of high low-frequency background, high surface leakage, and poor system stability were removed as part of the live time cuts. Events with excessive noise in the pre-trigger, start times far from the trigger window or bad time domain chi-square were rejected as part of the reconstruction quality cuts.

Science exposure of 0.49 gram-days
Models and Cut Efficiency

Limit search region to expected DM signal regions

Optimal Interval

Optimal interval method is applied to sections of data within 2σ of quantized laser peaks.

\[ \langle n_{eh}(E_{\gamma}) \rangle = \begin{cases} 
0 & E_{\gamma} < E_{\text{gap}} \\
1 & E_{\text{gap}} < E_{\gamma} < \epsilon_{eh} \\
\frac{E_{\gamma}}{\epsilon_{eh}} & \epsilon_{eh} < E_{\gamma} 
\end{cases} \]

- \( E_{\text{gap}} \): Si indirect band gap (1.12 eV)
- \( \epsilon_{eh} \): Average energy per e^-h^+ pair (3.8 eV)

Laser spectrum is used to calculate the reconstruction quality cut efficiency

\[ n_{eh} \]

\[ E_{\gamma} \]

\[ \epsilon_{eh} \]
Example of modeling a Dark Photon no ILCT is considered
Detector Laser Response w/ Charge Trapping and Impact Ionization

\[ M'(x) = \sum_{m=1}^{m_{\text{max}}} P_m(\lambda) \left( ^m h \otimes G(\sigma) \right)(x) \]

Where \( P_m(\lambda) \) is the Poisson distribution, \( \lambda = 6 \) is the average number of photons per pulse, \( m \) is the number of photons, \( G(\sigma) \) is the Gaussian distribution, and \( \sigma = 0.1 \text{ e}^{-\text{h}^+} \) is the detector resolution.
Leakage Background

\[ R(x) = R_{Surf} \delta(x - c_1) + \frac{R_{Bulk}}{(c_1 - c_0)} \Theta(x - c_0) \Theta(c_1 - x) \]

\[ B(x) = \frac{NL_0}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-c_0)^2}{2\sigma^2}} \left( \frac{1}{2} \left( 1 + \text{erf} \left( \frac{x - c_0}{\sqrt{2\sigma^2}} \right) \right) \right)^{N-1} + \frac{L_{Surf}}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-c_1)^2}{2\sigma^2}} + \frac{L_{Bulk}}{(c_1 - c_0)} \left( \text{erf} \left( \frac{x - c_0}{\sqrt{2\sigma^2}} \right) - \text{erf} \left( \frac{x - c_1}{\sqrt{2\sigma^2}} \right) \right) \]

The acquisition is triggered on the laser TTL and analysis is carried out with a time-shifting OF
Impact ionization and charge trapping fit (black curves) for a single acquisition cycle at +140 V crystal bias with medium (red), and low (purple) intensity laser. The curves have been normalized by dividing by the total counts in the spectrum. (Bottom row) Residual counts normalized by the individual bin standard deviations. Bins with zero counts were artificially set to zero.
Multi-Photon Response

Biometrika, 19, 225–239 & 240–244 (1927); https://doi.org/10.1093/biomet/19.3-4.225, & https://doi.org/10.1093/biomet/19.3-4.240

\[ m^{\text{th}} \text{ e·h\textsuperscript{+} pair PDF with impact ionization and trapping}: \]

\[ m h(x) = \int_{-\infty}^{\infty} h(x')^{m-1} h(x-x') dx' \]

\[ = A_1^m \delta(x-m) + mA_1^{m-1} A_- \Theta(x-m+1) \Theta(m-x) + mA_1^{m-1} A_+ \Theta(x-m) \Theta(m+1-x) \]

\[ + \sum_{i=0} \sum_{j=0} \sum_{n=1} A_{mijn} (n + m - j - x)^{m-i-j} \Theta(n + m - j - x) \Theta(x - m + j) \]

Where

\[ A_{mijn} = \frac{A_1^i A_+^j A_-^{m-i-j} m! (-1)^{m-i-n} (m-i)!}{i! j! (m-i-j)! n! (m-i-n)! (m-i-1)!} \]
System Stability

Temperature Calibration

Reconstructed amplitude scales linearly with resistance from a RuOx thermometer used to measure the DR temperature.

Leakage Rates for DM Search

Detector neutralization performed at 70 hours due to increased levels of surface leakage. An increase in the bulk leakage rate was observed afterwards.

Temperature varied and bulk leakage rate was constant
Limitations on NTL Gain

- Bi-modal distribution caused by time shifting optimal filter
- Bulk leakage events have a flat distribution between 0-1 e⁻h⁺ pairs
- Surface leakage events have quantized energy
- Full break down at 180 V

Minimize surface leakage by using ±140 V
Relative Detector Calibration

QET A appears to have losses requiring a 13% correction to get surface events to land on lines of equal energy with the laser.