CDMS Soudan iZIPs in voltage-assisted calorimetric ionization mode
interleaved
Z-sensitive
Ionization and
Phonon-mediated detectors

2.5 cm thick
3”diameter
620 g Germanium
SuperCDMS at Soudan

interleaved Z-sensitive Ionization and Phonon-mediated detectors

CDMSlite: one iZIP in HV mode

Run 1 Aug – Sept 2012
Run 2a Feb – July 2014
Run 2b Sept – Nov 2014
Run 3 Feb – May 2015

2.5 cm thick 3” diameter 620 g Germanium
SuperCDMS iZIP technology

Target = Si or Ge

Phonon signal measures energy deposition

Ionization quenched for nuclear recoils

Excellent (>10^5) rejection of electron recoil background

Ionization vs. Phonon Signals

Calibration Sources

133Ba and 252Cf

Phonon [keV]

Ionization [keV]
Phonon signal measures energy deposition

Ionization quenched for nuclear recoils

Excellent (>10^5) rejection of electron recoil background

Yield = Y(E_r) = \frac{\text{Ionization Energy}}{\text{Recoil Energy}}

Target = Si or Ge
For sensitivity to the lowest mass WIMPs, we need to lower our threshold.

This can be done by running at much higher voltages, but without ER/NR discrimination.

SuperCDMS iZIP ➔ lite

Phonon and ionization signals read out from both sides

Read out phonon sensors on grounded side
Trade-offs

As e-h pairs move through crystal they create Luke Phonons

Total Phonon Energy = E(Recoil) + E(Luke)

\[ E_{\text{tot}} = E_r + E_L = E_r + N_{e-h} eV_b = E_r \left(1 + Y(E_r) \frac{eV_b}{\varepsilon_{\gamma}}\right) \]

\[ \varepsilon_{\gamma} \sim 3 \text{ eV}: \text{ Avg E needed by ER to create an e-h pair} \]

Electron Recoils: \( Y \equiv 1 \)
Nuclear Recoils: \( Y(E_r) \approx 1/3 \)

CDMSlite \( V_b >> \varepsilon_{\gamma} \)

\[ E_{\text{tot}} = E_r \left(1 + g(V_b)\right) \]
Luke phonons dominate

ER:NR Discrimination Mode \( V_b = 4 \text{ V} \)

\[ Y(E_r) = \frac{E_Q}{E_r} = \frac{E_Q}{E_{\text{tot}} - N_{e-h} eV_b} \]

Keep \( E_L \) small, measure \( E_Q \) (\(^{133}\text{Ba}\)) and the Yield Band centroid (\(^{252}\text{CF}\)) to find the NR scale
Trade-offs

As e-h pairs move through crystal they create Luke Phonons

Total Phonon Energy = Recoil + Luke

\[ E_{\text{tot}} = E_r + E_L = E_r + N_{e-h} eV_b = E_r \left( 1 + Y(E_r) \frac{eV_b}{\varepsilon_\gamma} \right) \]

CDMSlite \( V_b >> \varepsilon_\gamma \)

\[ E_{\text{tot}} = E_r (1 + g_L(V_b)) \]

Luke phonons dominate

Amplification = 24 at \( V_b = 70 \text{ V} \)

But only \( x \times 12 \) for one-sided readout
Run 1: First look at our low energy spectral features

$^{252}\text{Cf}$ neutron source gives activation lines with 11.4 d half life
CDMSlite Run 1

Proof of Principle (2013)  

- 69 V bias on one detector.
- 6.5 kg·d, \(\sim 170 \text{ eV}_{ee}\) ionization threshold
CDMSlite Run 1

Proof of Principle (2013)


- 69 V bias on one detector.
- 6.5 kg-d, \( \sim 170 \, \text{eV}_{\text{ee}} \) ionization threshold corresponding to \( \sim 841 \, \text{eV}_{\text{nr}} \)

\[
\begin{align*}
\text{Counts/keVnr/kg/day} & \\
\text{Energy [keVnr], bin width of 90 eVnr} & \\
\end{align*}
\]

Convert to nuclear recoil equivalent energy using Lindhard model

\[
Y(E_{nr}) = \frac{k \, g(\varepsilon)}{1+k \, g(\varepsilon)}
\]

- For Ge, \( k = 0.157 \)
Operational Improvements

10 times more exposure!
Detector pre-biasing (10 min @ 80 V)
Install vibration sensors on cryocooler
Mitigate transient detector leakage current
Seal and “de-humidify” HV distribution board

Analysis Improvements

Better energy calibration
Correct for base temperature variation
Better low freq. noise rejection
  ➔ lower threshold
New radial fiducial volume cut
Low Frequency Noise monitoring

- Sensors installed on cryocooler signals filtered, digitized, and time-stamped
- Sensor data and derived triggers recorded in the experimental data stream (evt by evt)
- Discovered clear LF noise correlation with the 830 ms cryocooler cycle and a secondary mid-cycle thump
For each pulse, fit to a LF pulse template.

Compare to a good pulse template fit by forming $\Delta \chi^2$

Create a correlated noise score based on the sensor data
  Define time blocks with similar cryocooler noise

Tailor the pulse shape cuts to each period
Pulse Shape Cut Efficiencies

- Measure efficiency via simulation:
  - Scale template pulse to low energy
  - Add real noise
    
    *comes from randoms within and at end of run*
    
    *provides appropriate run-by-run noise environment*
  - Determine fraction that passes cuts

![Diagram](image)

Pulse Shape Cut Efficiency

- Energy [keVee]
- Run 2a
- Run 2b

![Graph](image)
Low Frequency Noise monitoring – Run 2b

- Warm up and repair cryocooler, Ice box remains closed
- Vibration significantly reduced, lower hardware threshold.

**Hardware threshold determination:** Use multiple scattering evts from Cf calib
Find probability that CDMSlite detector triggered, given another detector did.
Fit to err function using Markov chain MC.

**Run 2a** (59.32 kg-d)
50% efficiency at $75 \pm 5 \text{ eV}_{ee}$

**Run 2b** (10.78 kg-d)
50% efficiency at $56 \pm 6 \text{ eV}_{ee}$
Use high-statistics K-shell to calibrate energy scale

$^{252}$Cf neutron source
n-capture $\rightarrow$ $^{71}$Ge
e-capture decay: K-shell 10.37 keV
L-shell 1.30 keV
M-shell 0.16 keV
Energy Scale Calibration

- Clean and seal HV distribution board, operate under N₂
- Correct for changing parasitic resistance with new current readout
- Correct for change in base temperature
- Discrete period shifts, position dependence.

\[ E_{\text{tot}}[\text{keV}_t] = E_r[\text{keV}_{ee}](1 + g_L(V_b)) \]
Two-Template Phonon Pulse Fitting

Initial absorption of phonons is localized. Thus the fast component encodes for position. The fast template is formed from the residuals of the standard averaged template.
Poor E-field uniformity near the outer radius

grounded sidewall and one-sided readout

e-h pairs created at large radii traverse $V < V_b \Rightarrow$ reduced Luke Amplification

K-shell peak from Detector MC
Fiducial cut on the radial partition
$R = \text{Outer channel} < 0.2$
$\text{All channels}$
Fiducial Cut using 2-template fit

Use two-template fit to derive an empirical radial parameter from comparison of inner and outer channels.

Localized bkg near connector
Efficiency of fiducial cut

\[ \varepsilon = \frac{P_i}{R + P_i + P_o} = \frac{P}{R + P} \cdot \frac{P_i}{P} = \varepsilon_E \varepsilon_P \]

- 86% have full energy
- 55-60% peak evts pass radial cut

Measure efficiency at lower energy with energy-scaled pulse simulation
L-Shell pulse templates + noise

It’s Complicated!

Needed to disentangle L and K shells from each other and from the Compton bkgd!

Fits to the exp. decay of lines after each Cf calibration, and relative strengths of K vs L determine shell strength in each bin
Efficiency of fiducial cut

\[
\varepsilon = \frac{P_i}{R + P_i + P_o} = \frac{P}{R + P} \cdot \frac{P_i}{P} = \varepsilon_E \varepsilon_P
\]

86% have full energy
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Measure efficiency at lower energy with energy-scaled pulse simulation
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Total Efficiency

Run 2a
Run 2b
Run 2 Energy Spectrum

- Reached an energy threshold of 56 eV$_{ee}$ for electron recoils
- Bkgd $\sim 1$ ct/(keV-kg-d) between K and L
- All three activation peaks can be seen
  
  M: 0.16 keV
  L: 1.30 keV
  K: 10.37 keV
Setting the Limit

Use Optimum Interval with no background subtraction

Convert to nuclear recoil equivalent energy using Lindhard Model

\[ Y(E_{nr}) = \frac{kg(\varepsilon)}{1 + kg(\varepsilon)} \]

Redo 1000 times with input parameters drawn from the full uncertainty distributions. The median is the final result. Uncertainty is given by distribution.

Nuclear recoil model is also treated same way. k scanned from 0.1 → 0.2
Run 2: Median (90% C.L.) and 95% interval from 1000 samples

33 x improvement due to
Lower thresholds
Lower bkgd (fiducial cut)

Effect of M-Shell

Published Wednesday: R. Agnese et al. (SuperCDMS Collaboration) Phys. Rev. Lett. 116, 071301
CDMSlite Run 3

The Run

• Different detector: 75 Volts across T2Z1
• Potentially lowest threshold yet
  • Lower hardware threshold
  • Lower LF noise
• But not larger exposure. (40 kg-d)

Tasks

• Develop low-energy background modeling
  • GEANT4 physics processes (e.g. Comptons, Monash Model, tritium)
  • Detector MC (E-field, radial cuts, phonon physics)
• Understand Luke Gain scaling. Study bias scans, fold in test facility data
• Improve the 2-template fit and radial parameter
• Apply “salting” technique for unbiased analysis (Practice with the Run 2 data)
• Prepare analysis techniques for SNOLAB
SNOLAB HV Detectors (see Sunil’s talk)

- Improvements for SuperCDMS SNOLAB include:
  - larger detectors
  - improved phonon sensors
  - double sided readout
  - increased HV and improved resolution
  - thresholds in the eV\_ee range
Mystery Spot

- A localized background which appeared in Run 2b at low energy
- Possibly connected to electrical anomalies near the DIBs
  similar effects observed in the past
- Mostly removed by fiducial volume cut
- Currently doing forensics on detector
$\Delta \chi^2 = \chi^2(\text{OF}) - \chi^2(\text{LF})$