DAMIC at SNOLAB

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for the DAMIC Collaboration
Outline

• Charge coupled devices (CCDs) as detectors for low-energy particles.
• Characterization of the DAMIC devices.
• DAMIC installation at SNOLAB.
• **Low-mass** dark matter search results.
• Background suppression techniques.
• Future of the DAMIC program.
Charge coupled device

Device is “exposed,” collecting charge until user commands readout.

Readout can be slow / non-destructive: very low noise (few e⁻).

Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.
Particle tracks

50 pixels

X-ray? 
\text{n, WIMP?}

Diffusion limited

Front

\(\alpha\)

\(\mu\)

Back

\text{DAMIC CCD: 15x15 \(\mu m^2\) pixels}

Energy measured by pixel / keV

6 keV front

6 keV back

Energy measured by pixel / keV
Device performance

Linearity demonstrated for signals <10 e-.

White readout noise <2 e- RMS ~ 7 eVee

Characterization of Compton background at low energies

2. Experimental Setup
2.1. Detector
The DAMIC detector at UChicago, seen in Figure 7a, is a scaled down version of the primary SNOLAB setup. It contains only a single CCD with an area of approx. 18cm^2.

It is housed in a 301 stainless steel frame and is operated at a vacuum pressure of roughly 1x10^{-6} mbar and temperature of 125K. The front flange where the source is kapton taped onto is 2.3mm thick. The CCD itself is supported on a copper frame, Figure 7b, with read out cables attached to an external electronic box (“Leach”) that feeds into a data collection software (“Owl”) on an external PC. Raw image values are in ADC (Analogue-to-Digital Converter) count from the Leach output.

While there are many parameters that can tune the functionality of the detector, we briefly discuss two of interest: Substrate Bias Voltage (V_{sub}).

V_{sub} controls the electric field across the CCD that drives charge to the collection face for readout. High V_{sub} limits charge diffusion but at a cost of slightly increased noise. Data was taken at two V_{sub} levels - 45V and 127V.

Binning is the act of combining charge in neighboring pixels and reading it out. For instance 4x4 binning means that a square of 16 pixels is combined into a single new pixel. Because pixel noise accumulates in quadrature and read noise is a constant, we obtain an increase in energy resolution by trading spatial resolution - as can be seen in Figure 8 from [12]. Data was taken at two binning levels - 1x1 (no binning) and 4x4 (16 pixel squares).

Figure 7: a) UChicago DAMIC test detector with $^{57}$Co source shown b) CCD element with copper frame and cable
Nuclear recoil response

Single-recoil spectrum very similar to signal from 3 GeV WIMP. End-point = $3.2 \text{ keV}_r$

Calibration down to 60 eV$_{ee}$.
SNOLAB Installation

16 Mpix CCD 5.8 g

6 cm

Copper module Kapton signal cable

Lead block Kapton signal cable

Cu box with CCDs

Cu vacuum vessel

Polyethylene

Lead

J. Zhou
Elastic scattering of WIMPs with silicon nuclei.

2D Gaussian distribution of free charge on pixel array.

Recoil spectrum in Si target

Measure $E$ and $\sigma_{xy}$ for every event.

WIMP-nucleon cross section: $10^{-40}$ cm$^2$

WIMP mass:
- 10 GeV/c$^2$
- 100 GeV/c$^2$

All data candidates
0.6 kg days of data with test devices at SNOLAB.
~30 dru total background.

Spectrum consistent with Compton scattered electrons in fiducial region:
No WIMP signal.
Hidden photon search

Absorption of hidden-photon dark matter.

~1 week of data with 1 CCD.
Leakage current $4 \, \text{e}^{-} \, \text{mm}^{-2} \, \text{d}^{-1}$.

Pixel distribution consistent with white noise + uniform leakage current.
**ββ coincidences**

<table>
<thead>
<tr>
<th>Decay Chain</th>
<th>Energy 1</th>
<th>Energy 2</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$ → $^{210}\text{Bi}$ → $^{210}\text{Po}$</td>
<td>64 keV</td>
<td>1.2 MeV</td>
<td>$T_{1/2} = 5 \text{ d}$</td>
</tr>
<tr>
<td>$^{32}\text{Si}$ → $^{32}\text{P}$ → $^{32}\text{S}$</td>
<td>0.22 MeV</td>
<td>1.7 MeV</td>
<td>$T_{1/2} = 14 \text{ d}$</td>
</tr>
</tbody>
</table>

57 days of data in 1 CCD:

$^{210}\text{Pb} < 37 \text{ kg}^{-1}\text{d}^{-1}$

(95% C.L.)

$^{32}\text{Si} = 80^{+110}_{-65} \text{ kg}^{-1}\text{d}^{-1}$

(95% C.L.)

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$^{32}\text{Si} - ^{32}\text{P}$ candidate

- $E_1 = 114.5 \text{ keV}$
- $\Delta t = 35 \text{ days}$
- $E_2 = 328.0 \text{ keV}$

JINST 10 P08014
**DAMIC100**

- Seven CCDs (~40 g) running at SNOLAB since Jan 2017.
- Already have ~6 kg-day of data with 5-15 dru *total* background rate. Analysis ongoing.

**DAMIC-1K**

- A 1 kg detector built with *existing* technology.
- Sub-e⁻ resolution, 2 e⁻ threshold.
- Background improvement to 0.1 dru:
  - Improved design for background suppression.
  - Strict handling and packaging procedures.
  - Baking of wafers during/after fabrication to remove $^3$H.

Silicon wafer

6k x 6k pixels, 1 mm thick
≈ 20 g / CCD
≈ 50 CCDs / 1 Kg
SENSEI

LDRD at Fermilab (PI Tiffenberg): Skipper CCDs (LBNL design) successfully tested with sub e\(^-\) noise. X-ray spectroscopy demonstrated.

Non destructive “skipper” readout:
Perform \( N \) uncorrelated measurements of the same pixel. Noise decreases by \( \sim 1/\sqrt{N} \).

Reference

\[ \Delta V \]

Measure \( \Delta V \) \( N \) times.

\( \chi^2 / \text{ndf} = 19.6 / 25 \)

\[ \text{Mean} = -0.002 \pm 0.0016 \]

\[ \text{Sigma} = 0.06 \pm 0.001 \]

Technology will allow 2 e\(^-\) (few eV) threshold.

\[ \text{arXiv:1706.00028} \]
DM-nucleus SI coherent scattering

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ana. mass [kg]</th>
<th>sensitivity <a href="GeV">cm$^2$</a></th>
<th>energy threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMIC Program</td>
<td>1</td>
<td>$10^{-35}$</td>
<td>5 dru, 2 e$^-$ thres.</td>
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<tr>
<td>CDMSII-Si (2013)</td>
<td>1.34</td>
<td>$10^{-38}$</td>
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<tr>
<td>LUX (2015)</td>
<td>70</td>
<td>$10^{-40}$</td>
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<tr>
<td>DAMIC100 (2017)</td>
<td>13</td>
<td>$10^{-40}$</td>
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<tr>
<td>DAMIC1K (2020)</td>
<td>52</td>
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<tr>
<td>CRESST (2015)</td>
<td>70</td>
<td>$10^{-35}$</td>
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<tr>
<td>CDMSLite (2015)</td>
<td>70</td>
<td>$10^{-35}$</td>
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</table>

Also best limits for absorption of hidden photon dark matter.
DAMIC Program

Direct search:

Ionization produced by dark matter - electron / nucleus scattering.

Accelerators:

Look for electron’s missing momentum (LDMX) or χ interacting directly (BDX).

DM-e Scattering via heavy Hidden Photon

$m_{A'} > 2M_\chi$

Earth scattering

XENON10

XENON100

Direct search:

Ionization produced by dark matter - electron / nucleus scattering.

Accelerators:

Look for electron’s missing momentum (LDMX) or χ interacting directly (BDX).
Conclusion

- CCDs are low-radioactivity, low-noise particle detectors whose response to ionizing radiation has been thoroughly characterized.

- DAMIC has placed competitive dark matter search results (WIMPs + hidden photons) with early R&D data.

- Established discrimination techniques to measure and suppress backgrounds (esp. dominant $^{32}$Si).

- Ongoing R&D efforts for a DAMIC-1K: 50 skipper CCDs for a 1 kg detector with 2 e$^{-}$ threshold to search for low-mass dark matter by DM-nucleon and DM-electron scattering.
Thank you!