DAMIC at SNOLAB

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

Readout can be slow / non-destructive: very low noise (few e\textsuperscript{-}).

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

DAMIC CCD: 15x15 µm² pixels

Energy measured by pixel / keV
Device performance

**Linearity demonstrated for signals <10 e⁻.**

White readout noise <2 e⁻ RMS ~ 7 eV

**Characterization of Compton background at low energies**

- **Si K-shell**
- **Si L-shell**

*Source: arXiv:1706.06053*
Nuclear recoil response

a) Cross-section of setup

Vacuum chamber  

CCD  

3He counter  

Lead shielding  

Source  

Table  

b) $^{124}$Sb-$^9$Be source detail

24 keV neutrons from $^9$Be($\gamma$,n) reaction

Data - full BeO

Best-fit with Monte Carlo spectrum

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

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

- 16 Mpix CCD
- 5.8 g
- Copper module
- Kapton signal cable
- 6 cm
- Lead block
- VIB
- Poly-ethylene
- Lead
- Cu box with CCDs
- Cu vacuum vessel
WIMP search

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 search

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.

Si bulk

Hidden Photon

~1 week of data with 1 CCD.
Leakage current $4 \ e^{-} \ mm^{-2} \ d^{-1}$
$7 \times 10^{-22} \ A \ cm^{-2}$

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

- **210Pb** → **210Bi** → **210Po**
  - $\tau_{1/2} = 5 \text{ d}$
  - 64 keV → 1.2 MeV

- **32Si** → **32P** → **32S**
  - $\tau_{1/2} = 14 \text{ d}$
  - 0.22 MeV → 1.7 MeV

**57 days of data in 1 CCD:**

- **210Pb** < 37 kg$^{-1}$d$^{-1}$
  (95% C.L.)

- **32Si** = $80^{+110}_{-65}$ kg$^{-1}$d$^{-1}$
  (95% C.L.)

**32Si - 32P candidate**

- $E_1 = 114.5 \text{ keV}$
- $\Delta t = 35 \text{ days}$
- $E_2 = 328.0 \text{ keV}$
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.
  -³H mitigation: silicon transport in shielded container and removal by baking wafers (R&D).

Silicon wafer

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

$\Delta V$ (Signal)

Measure $\Delta V$ $N$ times.

4000 samples

Entries: 1635
$\chi^2$ / ndf: 19.6 / 25
Mean: -0.002 ± 0.0016
Sigma: 0.06 ± 0.001

Technology will allow 2 e⁻ (few eV) threshold.
DAMIC Program

DM-nucleus SI coherent scattering

DM-e Scattering via Ultra-light Hidden Photon

Also best limits for absorption of hidden photon dark matter.
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

$\sigma_e$ [cm$^2$] vs $m_\chi$ [MeV]

- DAMIC-1K - 1 kg y (2020)
- $F_{DM} = 1$
- LDMX
- Scalar fermion
- Earth scattering

$\chi \rightarrow g_D A' \rightarrow e e$

$A'$ is a hidden photon mediator.

Kinetically mixed hidden photon $A'$ couples to electrons, nuclei.

10$^{10}$

Mass scale of mediator $A'$ similar to (or lighter than) mass scale of $\mu_1$:

- same physics may generate both masses
- annihilation is sufficiently large in the early universe (overclosure)
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 $^{32}\text{Si}$).

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