Current status of the DAMIC experiment

Carla Bonifazi
for the DAMIC collaboration

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Current status

Several models predicting DM below $\sim 20 \text{ GeV/c}^2$

Constant need for different technologies to confirm/exclude incompatible scenarios
Charge Coupled Devices (CCDs)

**Goal:** lower the energy threshold in Si detectors
**Idea:** use CCDs as target and record the ionization produced in Si

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**Figure 1**
Cross-sectional diagram of the CCD described in this work.

**Figure 2**
(a) A CCD pixel plane may be used to reconstruct the 3D position of charged particles.

**Figure 2 (a)**
Portion of a DAMIC image showing 50 µm thick CCD's used in spectrographs.

**Figure 2 (c)**
WIMP detection in a CCD with pixel cluster defining a 3D position reconstruction.

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**Ionization efficiency in silicon**

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Charge Coupled Devices (CCDs)
4 BACKGROUND SOURCES AND REDUCTION TECHNIQUES

As the penetration range of radiation has an exponential dependence on the distance, most interactions take place close to the surface and background is effectively suppressed. Finally, detectors able to distinguish electronic recoils from nuclear recoils (see section 5.1) can reduce the background by exploiting the corresponding separation parameter.

4.2. Cosmogenic and radiogenic neutron radiation

Neutrons can interact with nuclei in the detector target via elastic scattering producing nuclear recoils. This is a dangerous background because the type of signal is identical to the one of the WIMPs. Note that there is also inelastic scattering where the nuclear recoil is typically accompanied by a gamma emission which can be used to tag these events. Cosmogenic neutrons are produced due to spallation reactions of muons on nuclei in the experimental setup or surrounding rock. These neutrons can have energies up to several GeV \cite{151} and are moderated by the detector surrounding materials resulting in MeV energies which can produce nuclear recoils in the energy regime relevant for dark matter searches. In addition, neutrons are emitted in ($\mu$,n) and spontaneous fission reactions from natural radioactivity (called radiogenic neutrons). These neutrons have lower energies of around a few MeV.

Dark matter experiments are typically placed at underground laboratories in order to minimise the number of produced muon-induced neutrons. The deeper the location of the experiment, the lower the muon flux. Figure 3 shows the muon flux as a function of depth for different laboratories hosting dark matter experiments. The effective depth is calculated using the parametrisation curve (thin line) from \cite{151}.
The DAMIC experiment

The DAMIC dark matter experiment

J.R.T. de Mello Neto

42 cm

21 cm

V

e

e

e

V
e

e

Pb

Polyethylene

2 km of rock

Cu box

with CCDs

Kapton

signal cable

Cu vacuum

vessel

a)

b)

c)

d)

Lead block

Kapton

signal cable

Cu box

with CCDs

Lead

Polyethylene

Figure 3.

a) A packaged DAMIC CCD. b) The copper box housing the CCDs. c) Components of the DAMIC setup, ready to be inserted in the vacuum vessel. d) The vessel inside the lead castle, during installation of the polyethylene shield.

ITO coating deposited on the backside after thinning the CCD to 500 µm. The third CCD was optimized for DAMIC by maximizing its mass (the CCD is un-thinned, 675 µm-thick) and minimizing radioactive contamination (the ITO layer containing b-radioactive 115 In is eliminated). The 500-µm CCDs are inserted in adjacent slots of the copper box, with copper plates above and below. The 675-µm CCD is in a lower slot of the box, separated from the other CCDs by ≈1 cm of copper.

The dark matter search will be performed with DAMIC100, a detector with 100 g of sensitive mass, consisting of 18 CCDs, each of 4k × 4k pixels and 675 µm thickness.

2.3 CCD image reduction and data samples

Clusters of energy deposits are found in the acquired images with the following procedure. First, the pedestal of each pixel is calculated as its median value over the set of images. The pedestals are then subtracted from every pixel value in all images. Hot pixels or defects are identified as recurrent patterns over many images, and eliminated (“masked”) from the analysis (>95% of the pixels were deemed good). Pixel clusters are selected as any group of adjacent pixels with signals greater than four times the RMS of the white noise in the image. The resulting clusters are considered candidates for particle interactions. Relevant variables (e.g. the total energy by summing over all pixel signals) are calculated for each cluster. For the studies presented in this paper, we required the cluster energy to be >1 keV, which guarantees a negligible probability of accidental clusters from readout noise. Selection criteria specific to the different analyses will be described in Sections 3–5–

Figure 4:

a) A packaged DAMIC CCD. b) The copper box housing the CCDs. c) Components of the DAMIC setup, ready to be inserted in the vacuum vessel. d) The vessel inside the lead castle, during installation of the polyethylene shield.

210 Pb content, strongly suppressing the background from bremsstrahlung produced by 210 Bi decays in the outer lead shield. A 42 cm-thick polyethylene shielding is used to moderate and absorb environmental neutrons.

4. Measurements of radioactive contamination

The ultimate sensitivity of the experiment is determined by the rate of the radioactive background that mimics the nuclear recoil signal from the WIMPS. The SNOLAB underground laboratory has low intrinsic background due to its 6000 m.w.e. overburden. Dedicated screening and selection of detector shielding materials, as well as radon-suppression methods, are extensively employed to decrease the background from radioactive decays in the surrounding environment.

The measurement of the intrinsic contamination of the detector is fundamental. For silicon-based experiments the cosmogenic isotope 32 Si, which could be present in the active target, is particularly relevant since its b-decay spectrum extends to the lowest energies and may become an irreducible background. The analysis methods used to establish the contamination levels exploit the unique spatial resolution of the CCDs.

The identification of a-induced clusters is the first step in establishing limits on uranium and thorium contamination [15]. Radiogenic a-s lose most of their energy by ionization, creating a dense column of electron-hole pairs that satisfy the plasma condition [16]. For interactions deep in the substrate, the charge carriers diffuse laterally and lead to round clusters of hundreds of
The DAMIC experiment

1 inch Spanish galleon lead

Cu box with CCDs
Charge Coupled Devices (CCDs)

- pixel size of 15 μm x 15 μm
- large mass compared to regular CCDs ~ 5.7 g/CCD (675 μm thick)
Readout of the CCDs

Each pixel readout introduces 7.2 eV (2e⁻) noise
Dark current negligible —> total noise depending on the number of readouts

CCD readout

Capacitance of the system is set by the SN: $C = 0.05 \text{pF}$
Performance

- Readout noise

![](image)

- Noise limited by readout and improved with correlated double sampling
- Equivalent to ~ 7 eV of ionization energy
- This is what makes DAMIC unique: 40 eV threshold is possible

- Dark current

![](exposure) ![](blank)

- Low dark current (0.001 e⁻/pix/day) @ 120 K
Calibration and energy resolution

- Energy calibration using a $^{55}\text{Fe}$ source noise
- Energy resolution down to 40 eV

5% linearity (LED source)
Depth reconstruction

- Recorded track: CCD top view

- CCD side view

- Diffusion can be measured as a function of the interaction depth. No need to rely on models.
Radioactive contamination

Unique spatial resolution: alpha sequences
Three alphas at the same location!
—> Powerful method to measure U/Th background in the bulk

- Limits on $^{238}$U and $^{232}$Th concentration
- Limits on cosmogenic $^{32}$Si (intrinsic background)

$^{32}$Si - $^{32}$P candidate from data:

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

$$E_2 = 328.0 \text{ keV}$$

$$^{32}\text{Si} = 80^{+110}_{-65} \text{ kg}^{-1} \text{ d}^{-1} \quad (95\% \text{ CL})$$
Nuclear recoil calibration

• Decreasing the energy threshold means we need to calibrate nuclear recoil ionization efficiency to low energies
• Challenging to get mono-energetic neutron beam Previously, Lindhard theory had been accepted
• Two calibrations using neutrons for calibrating silicon at low energies

$^{124}\text{Sb} \rightarrow \text{Te} + \gamma (1690 \text{ keV} + \ldots)$

$^9\text{Be} + \gamma \rightarrow n + ^8\text{Be} \rightarrow 2\alpha$

Phys. Rev. D, 94 (2016) 082007
Antonella

Journal of Instrumentation, 12 (2017)
Nuclear recoil calibration

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Event selection

Selection of bulk events

Energy spectrum

Standard Likelihood analysis employed
Spectrum consistent with background-only hypothesis
Competitive with a very low exposure taken during R&D phase
Background ~ 30 dru (now 5 dru)

1 dru = 1 event keV\(^{-1}\) kg\(^{-1}\) day\(^{-1}\)
Event selection

This work
0.6 kg d

CRESST II 2015 - 52 kg d

CDMSLite - 70 kg d

DAMA/Na

LUX - 14 ton d

CDMS-II Si - 140 kg d

Hidden-photon dark matter with DAMIC

- DAMIC can detect small ionization signals from DM-electron interactions.
- DAMIC has published the most stringent direct detection constraints on hidden-photon dark matter with masses 3 - 12 eV.
Summary

- 7 CCDs (16 Mpixel) installed and taking data currently
- 5 dru background and < 2e- noise achieved
Summary

- 7 CCDs (16 Mpixel) installed and taking data currently
- 5 dru background and <2e- noise achieved
- DAMIC100 CCDs calibration planned
- R&D for thicker, larger-area, low-noise detector
- Improve external and internal backgrounds (< 0.1 dru)
DAMIC 1kg

DM-nucleus SI coherent scattering

$\sigma_n$ [cm$^2$]

$m_{\chi}$ [GeV]

CRESST(2015)
52 kg-d

CDMSLite(2015)
70 kg-d

DAMIC1K(2020)
1 kg-y
0.1 dru, 2 e- thres.

LUX(2015)

CDMSII-Si (2013)

DAMIC(2016)
0.6 kg-d

DAMIC100(2017)
13 kg-d
DAMIC 1kg

DM-nucleus SI coherent scattering

\( \sigma_n \text{[cm}^2\text{]} \)

\[
\begin{array}{c|c|c|c|c}
\text{Experiment} & \text{det} & \text{year} & \text{mass} & \text{energy threshold} \\
\hline
\text{DAMIC100(2017)} & 13 & 2017 & \text{kg-d} & \\
\text{DAMIC(2016)} & 0.6 & 2016 & \text{kg-d} & \\
\text{CDMSII-Si (2013)} & & 2013 & \text{kg-d} & \\
\text{CRESST(2015)} & 52 & 2015 & \text{kg-d} & \\
\text{LUX(2015)} & 70 & 2015 & \text{kg-d} & \\
\text{CDMSLite(2015)} & 70 & 2015 & \text{kg-d} & \\
\text{DAMIC1K(2020)} & 1 & 2020 & \text{kg-y} & 0.1 \text{ dru, 2 e- thres.} \\
\end{array}
\]

Thank you !!
BACKUP
DAMIC scientific production

- Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment
  JINST 10 (2015) P080-14

- Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB

- First direct detection constraints on eV-scale hidden-photon dark matter with DAMIC at SNOLAB

- Measurement of the ionization produced by sub-keV silicon nuclear recoils in a CCD dark matter detector
  Phys. Rev. D, 94 (2016) 082007

- Antonella: A nuclear-recoil ionization-efficiency measurement in silicon at low energies
  Journal of Instrumentation, 12 (2017)
Towards a kg-size experiment

SENSEI project
Sub-Electron-Noise-SkipperCCD Experimental Instrument

Main difference: the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet

- Probe DM masses at 0.1 GeV through nuclear recoil
- Probe DM masses at MeV scale through electron recoil
- Probe axion/dark photon DM with masses down to 1 eV
- Coherent-nucleus interaction

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

A collaboration between Fermilab, LBNL, Stony Brook, Tel Aviv U., CERN, Stanford U.

From J. Tiffenberg’s talk, Berkeley 2016
Event selection

1) Fit a 2D gaussian around a 7x7 pixels window
2) Compute the Log-Likelihood (LL) of the best fit
3) Subtract from background LL —> \( \Delta LL \)

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\Delta LL = -\ln \left( \frac{\text{max}(L_G)}{L_n} \right)
\]

Number of ionized electrons \( N_e(E) \times \text{Gaus}(x, y | \mu_x, \mu_y, \sigma(Z)) \) — Lateral spread

Best estimator for mean of energy deposition