WIMPs taking selfies: the DAMIC experiment at SNOLAB

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KICP Colloquium, April 27th, 2016
1) Astrophysical evidence for DM: Galaxy rotation curve, lensing, CMB

2) Natural candidate: a Weakly Interacting Massive Particle, yet unknown, in equilibrium in the early universe \((\chi \chi \leftrightarrow q \bar{q}, \ell \bar{\ell}, \ldots)\) which “freezes out” according to its cross section (WIMP miracle)
3) Milky Way motion

WIMP Wind

$\nu_0 \sim 220 \text{km/s}$

Cygnus

Sun

galactic plane

June

$60^\circ$

December

4) WIMP kinetic energy in the Earth (detector) frame

$$\frac{1}{2} m_\chi v_0^2 \approx 30 \text{ keV}$$

($m_\chi = 100 \text{ GeV }$)

Low energy interaction with matter

5) Coherent elastic scattering

WIMP

$E_\chi$, $m_\chi$, $v_0$

$\lambda_\chi \approx 10 \text{ F}$

nucleus

$m_N$

Detection of nucleus recoil

$E_R$, $v_R$

6) WIMP escapes detector (weakly interacting)

$E_\chi'$

$n = 10^{-44} \text{ cm}^2$

$m = 10 \text{ GeV}$
Experimental challenges

- Massive target-detector
- Ultra-pure target (radioactive contaminants)
- Low energy threshold (tens of keV vs MeV in neutrino physics)
- Low background (deep underground; material screening and selection)
7) Nuclear recoil ionization efficiency (quenching factor)

Take a nucleus and an electron of the same energy ($E_R = E_e$).

In general, $E_{det}^R < E_{det}^e$ (the nucleus dissipates its energy through mechanisms other than ionization) “Lindhard theory”

For a given detector (“electron”) energy threshold, the nuclear recoil energy threshold depends on the QF. Essential to measure.
WIMP exclusion plot

Detector energy threshold, resolution and QF

\[ E_R \approx E_\chi \cdot r \]
\[ E_\chi = 0.5 \ m_\chi \ v^2 \]
\[ r = \frac{4m_\chi m_N}{(m_\chi + m_N)^2} \]

\[ m_\chi \approx m_N \]

\[ n \sim \frac{\rho}{m_\chi} \]

\[ E_R \approx 0.5 \ m_N \ v^2 \]
Dark Matter in CCDs


J. Estrada, Fermilab

Designed to explore the low-mass WIMP region with very low threshold.
Exploring low-mass Dark Matter

- Dark photon models
- DAMIC100
- XENON10
- ADM models
- SUSY models
- Solar neutrinos
- DSNB + Atmospheric neutrinos
- Will not make it to lab
- Nuclear recoils

Graph showing WIMP 90% exclusion limits.
Charge-Coupled-Devices

Dark Energy Survey Camera

250 μm thick CCDs with enhanced IR sensitivity developed at LBNL
COSMIC RAYS AND OTHER NONSENSE IN ASTRONOMICAL CCD IMAGERS

DON GROOM
Lawrence Berkeley National Laboratory

(Accepted 23 July 2003)

Abstract. Cosmic-ray muons make recognizable straight tracks in the new-generation CCD’s with thick sensitive regions. Wandering tracks (‘worms’), which we identify with multiply-scattered low-energy electrons, are readily recognized as different from the muon tracks. These appear to be mostly recoils from Compton-scattered gamma rays, although worms are also produced directly by beta emitters in debar windows and field lenses. The gamma rays are mostly byproducts of $^{40}$K decay and the U and Th decay chains. Trace amounts of these elements are nearly always present in concrete and other materials. The direct betas can be eliminated and the Compton recoils can be reduced significantly by the judicious choice of materials and shielding. The cosmic-ray muon rate is irreducible. Our conclusions are supported by tests at the Lawrence Berkeley National Laboratory low-level counting facilities in Berkeley and 180 m underground at Oroville, California.
How a CCD works

Metal-Oxide-Semiconductor capacitor

+V

Metal gate
Si oxide (insulator)
n-type Si (buried channel)

p-type Si

electron-hole pairs generated by a photon or ionizing particle (3.6 eV_{ee} / e-hole pair)

A CCD is an array of MOS capacitors
Amplifier

Output amplifier

Charge motion serial register

“horizontal clocks” (faster)

Charge motion serial register

“vertical clocks”

CCD in action
CCD pixel charge readout

Correlated Double Sampling (CDS)

(signal – pedestal) cancels the reset noise (and also other correlated noise)
Performed analogically in standard CCD readouts
Why Dark Matter in CCDs?

1) High-resistivity \((10^{11} \text{ donors/cm}^3)\) extremly pure silicon

2) Fully-depleted over several 100s \(\mu\text{m}\) (typical CCDs few tens of \(\mu\text{m}\))

- Detection of point-like energy deposits from nuclear recoils induced by WIMP interactions (10 keV Si ion range 200 A)
3) **Sizable mass**  

A DAMIC CCD 6 cm x 6 cm, 16 Mpixel (15 µm x 15 µm) has a record thickness of 675 µm and 5.9 g mass

- **DAMIC100**: 100 g detector (18 CCDs) at the SNOLAB underground laboratory
4) Unprecedented low energy threshold

- Negligible dark current $< 0.001 \, \text{e/pixel/day}$ (CCD cooled at 120 K). Readout noise dominant contribution
- Slow readout ($\approx 5 \, \text{min} / 8 \, \text{Mpix image}$) to achieve $\sigma \approx 2 \, \text{e-}$ noise
- Very long exposures (8 hours!) to minimize the n. of noise pixels above the energy threshold

Lower threshold, higher WIMP recoil rate (exponential), small mass detector competitive
5) **Unique spatial resolution:** 3D position reconstruction and particle ID

The charge diffuses towards the CCD pixels gates, producing a “diffusion-limited” cluster

![Diagram of pixel and coordinate system](image)

- **σ ≈ Z:** fiducial volume definition and surface event rejection

![Graph of single muon track](image)

- **6 keV front**
- **6 keV back**

**X-rays from \(^{55}\text{Fe}\)**

- A muon piercing a 675 \(\mu\)m thick DAMIC CCD
• “Worms” straggling electrons
• Straight tracks: minimum ionizing particles
• MeV charge blobs: alphas
• Diffusion-limited clusters: low-energy X-rays, nuclear recoils
• CCD spatial resolution provides a unique handle to the understanding of the background
6) Stable and reliable detectors

- Energy scale stable to < 1%
- Noise stable to 6% over 126 days.
- Duty cycle close to 100% (cf. superconducting detectors)
SNOLAB
Sudbury, Canada
Nickel-Copper active mine

in the cage, dropping at 50 km/h

2 km underground

out for a nice walk...

BBC documentary, Dancing in the Dark: the end of Physics
Abandon all hope, ye who enter here  Inferno, Canto III, Dante
entering the lab

got ready for a shower

nice dress!

get ready for a shower

coffee......
DAMIC R&D program in the J-Drift hall started in early 2013

CAB, FIUNA, Fermilab, LPNHE, SNOLAB, U Chicago, U Michigan, U Zürich, UFRJ, UNAM

strong collaboration with Fermilab (Estrada, Cancelo, Tiffenberg, Guardincerri)
DAMIC100 installation at SNOLAB

April 2016

4k x 4k CCD in low-bkg package

Cu box
Cu vessel
Cu box
Kapton cables
in-vacuum electronics

vacuum and cryo lines, electronics

8” lead shielding
20” thick poly shielding
Response to electrons

\[ \sigma \approx 21 \text{ eV} \]

Energy loss in gates and SiO\(_2\) < 2 µm / 675 µm

Tritium

Fluorescence X-rays from \(^3\text{H}\) source
Gamma-rays

CCD exposed to $^{57}$Co source at U Chicago

Very large dynamic range

Fluorescence

122 keV

photo-electric absorption

136 keV

Single-scatter Compton spectrum

39.5 keV

47.5 keV

Compton edges
Nuclear recoil calibration

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

$E_e \approx 0.2 \, E_r$ (Lindhard)
Event selection

• Fit a 2D gaussian model + background in a sliding 7x7 pixels window. Calculate the corresponding LL and subtract the LL of background only model $\Delta$LL.

$N_{e}(E) \times \text{Gaus}(x, y, \mu_{x}, \mu_{y}, \sigma(z))$

Number of ionized electrons
Best estimate for mean of energy deposition
Lateral spread

\begin{align*}
\Delta LL & \text{ for events with cdist } < 1.5 \text{ and } 60 \text{ ev } < E < 250 \text{ ev} \\
\text{data} & \quad \text{blank} \\
\text{50\% at } 90 \text{ eV}_{ee} & \text{ estimated by injecting simulated events on real images}
\end{align*}
Nuclear recoil spectrum

- “Neutron-on” with BeO (n+γ) “neutron-off” with Al (only γ)
- Clear signal from neutron-induced nuclear recoils

- Nuclear recoil ionization efficiency from adjusting MC $E_r$ to $E_e$ spectrum
- Single recoil spectrum
- Systematic uncertainties are small, dominated by 9% uncertainty on total predicted rate
Nuclear-recoil ionization efficiency in silicon

deviation from Lindhard theory observed – crucial for low-mass WIMP searches with silicon detectors

\[ 0.77 \pm 0.10 \text{ keV}_r \text{ at } 60 \text{ eV}_{ee} \]
• **Lead shielding** to stop environmental $\gamma$ rays
Inner 2” shielding made of ancient lead to avoid bremsstrahlung $\gamma$s from $^{210}$Pb $\beta$-decay (22 yrs half-life)

• **Material selection and cleaning:** copper machining, “secret” recipe etching (surface bkg)

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Spanish galleon (Collar)

Roman ship (Modane, France)

April 2016

<0.02 Bq/kg

50 Bq/kg

Radioactive!
Background tour-de-force

- Since 2013 background reduced by $>10^3$
- $\approx 5$ dru achieved before DAMIC100 installation (similar to competitors)

In the last year:
- Seven interventions at SNOLAB.
- Nitrogen purge installation (Radon).
- Improvements in treatment of copper surfaces.
- Suppression of background from thermal neutron captures in copper.
- Mitigation of background from condensation e.g. $^3$H.

- Background rate may be smaller in DAMIC100: new CCD box and packages, roman lead
Three α at the same location!

Powerful method to measure U/Th bkg in the bulk – ppt limits 2015 *JINST* 10 P08014
**Cosmogenic $^{32}$Si**

- **$^{32}$Si** → $^{32}$P → $^{32}$S
  - $T_{1/2} = 14$ d
  - 0.22 MeV → 1.7 MeV

- **Must be demonstrated to be low for any Dark Matter search in silicon without electron rejection**

  \[
  \approx 100 \text{ kg}^{-1} \text{ d}^{-1}
  \]

- **Search for sequences of $\beta$'s starting in the same pixel of the CCD in different images**

- **$^{32}$Si =** 80$^{+110}_{-65}$ kg$^{-1}$ d$^{-1}$ (95% CI)
  
  *2015 JINST 10 P08014*

  \[
  \approx 100 \text{ kg}^{-1} \text{ d}^{-1} \text{ corresponds to } \approx 1 \text{ dru at low energy!}
  \]

- **Statistically limited, will be measured precisely by DAMIC100. DAMIC unique spatial resolution and excellent duty cycle allows to reject this background (also other $\beta$-$\beta$ sequences e.g. $^{210}$Pb)**
Dark Matter search with R&D data

• R&D focused on background reduction and CCD operation.

• We also took a small amount of data to be used for a first limit. Background ≈ 30 dru (now 5 dru!). Exposure ≈ 0.6 kg day. Goal: develop search tools and demonstrate CCD science potential

• Part of exposure (0.23 kg day) taken with hardware binning

charge of several pixels can be added together before moving it to the readout node

some loss of spatial resolution but improved signal to noise (same readout noise but more charge in a binned pixel)

55Fe source: improved energy resolution
Event selection

Perform a hard cut on the ΔLL to exclude random fluctuations from noise. Noise leakage <0.01 event in final sample.

Evidence from surface events in data. Include in the signal extraction the likelihood that an event is from bulk or surface.
Detection efficiency

Binning data sensitive to events deeper in the bulk at low energies.
Unbinned likelihood fit to 1x1 and 1x100 data done independently, combined in a single exclusion limit.

Null (background-only) hypothesis consistent with both data sets.
Exclusion limit

WIMP 90% exclusion limits

- CDMSLite (2015) 70 kg-d
- SUPERCDMS (2014)
- DAMA/Na (2009)
- DAMIC (2016) 0.62 kg-d
- CDMSII-Si (2013)
- LUX (2015) 52 kg-d
DAMIC100 first “light”

eight 4k x 4k CCDs (≈ 50 g) installed this month
DAMIC100 commissioning

Light from 3

Light from amplifier
DAMIC100 commissioning
DAMIC100 commissioning

Gone after temperature cycling
DAMIC100 commissioning

also, too early for a background measurement, but no bad surprises....
Expected sensitivity

WIMP 90% exclusion limits

- CDMSLite (2015) - 70 kg-d
- SUPERCDMS (2014)
- CRESST (2015) - 52 kg-d
- CDMSII-Si (2013)
- DAMIC (2016) - 0.62 kg-d
- DAMIC100 (2017) - 30 kg-d
- DAMIC1K - 300 kg-d
  0.01 dru, 0.5 e\(^{-}\) noise
- LUX (2015)
Electron recoils

WIMP 90% exclusion limits

WIMP-electron cross-section / pb

WIMP Mass / GeV c^{-1}

XENON10 S2-ONLY (2012)

DAMIC100(2017) 30 kg-d

DAMIC1K
300 kg-d
0.01 dru, 0.5 e^{-} noise
Axion-like particles

ALP CDM exclusion limits

$g_{Ae} \times 10^{-9}$

Axion models

DAMIC100 (2017)

CoGeNT (2008)

XENON100 (2014)

Red giant

(Also millicharged particles)
Prospects for a kg-size DAMIC

- A kg-size DAMIC can be built with the existing technology in a short time.
  - Silicon wafer: 6k x 6k pixels, 1 mm thick
    - $\approx 20$ g / CCD
    - $\approx 50$ CCDs / 1 Kg
  - DAMIC100: one batch (24 wafers)
  - DAMIC1K: three batches

- Thicker CCDs development at the Pritzker Nanofabrication facility
  - up to 1” thickness (1 mm max at DALSA or LBNL)
  - Process flow for fabrication ok
  - Start with photodiode array (LBNL, S. Holland)

Strategic Initiative UChicago-Fermilab
• Noise reduction to < 1 e
  - Digital CDS: digital filtering

- Improve the CCD amplifier (3 µV /e) currently optimized for dynamic range of astronomy
  - Skipper CCD: multiple non-destructive charge readout, < 0.5 e noise (Fermilab)

• Background reduction

- One module being tested in DAMIC100

Realistic goal: 0.01 dru
 (dominated by $^{32}\text{Si}$ after coincidence rejection)

("underground" silicon for ultimate bkg; SuperCDMS)

Electroformed copper

PNRL
Conclusions and outlook

- DAMIC has successfully completed its R&D phase demonstrating the potential of CCDs as DM detectors:
  - stable, low noise, low background operation of large size, thick fully depleted CCDs at SNOLAB
  - unique spatial granularity to study backgrounds with unprecedented precision
  - nuclear-recoil ionization efficiency measured down to 60 eV$_{ee}$ threshold
  - low mass WIMP sensitivity with R&D data
- DAMIC100 installation and commissioning has started, 100 g detector ready for science data taking this summer. DAMIC100 will be a major player in the field in the next few years.
- A 1kg CCD detector can be built at low cost and fast. We will push for it....
- Other applications: nuclear forensics (PNNL), soft error (IBM)
Example of spatial resolution: Si K$_\alpha$

33 eV at 1.7 keV in bulk
Diffusion and 3-D reconstruction

$^{55}$Fe source 6 keV X ray (front and back)

Simulation
250 µm thick CCD

Data
675 µm thick CCD

$\sigma_{xy} = 1.4 \rightarrow z = 675 \ \mu m$
\(\alpha\) particles

\(\alpha - \beta\) discrimination based on shape of track.

Limits on contamination:

\(^{238}\text{U} < 5 \text{ kg}^{-1} \text{ d}^{-1} = 4 \text{ ppt}\)

\(^{232}\text{Th} < 15 \text{ kg}^{-1} \text{ d}^{-1} = 43 \text{ ppt}\)

arXiv:1506.02562 to appear in JINST
$^{32}\text{Si} - ^{32}\text{P}$ candidate

$E_1 = 114.5$ keV

$\Delta t = 35$ days

$E_2 = 328.0$ keV

$^{32}\text{Si} = 80^{+110}_{-65}$ kg$^{-1}$ day$^{-1}$ (95% CI)

arXiv:1506.02562 to appear in JINST
**DAMIC calibration (keV$_{nr}$)**

**Ionization efficiency in low E regime**

- Prediction, $k=0.15$, $Z_1=Z_2$ (Lindhard)
  - Ge, compiled (Jones)
  - Si (Dougherty)

**Examples**

eg. $^{28}\text{Si} + n \rightarrow ^{29}\text{Si} + \gamma$

Argonauta reactor (UFRJ, Rio de Janeiro)

340 Watt, thermal neutron flux few $10^5$/cm$^2$/s

**CCD activation with proton beam**

CDH proton center, Illinois

Nuclear recoil from EC of $^{22}\text{Na}$

Sb/Be “monochromatic” neutron source (24 keV), U. Chicago

University of Notre Dame