Searching for low mass dark matter with DAMIC

Ben Kilminster
Fermilab

Identification of Dark Matter
IDM 2012

Naturalness of Dark Matter Mass scale

1. “Wimp miracle” scale :
   - Why do SUSY cross-sections provide correct relic DM density ?
     \[ M_{DM} \sim 100 \text{ GeV} \]
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2. “Baryon-DM coincidence” scale:
   • Why is the DM abundance so close to matter?
     \[ \rho_{DM} \sim 5 \cdot \rho_M \]
   • What if dark matter is more baryon-like?
   • Assume \( N_{DM} \sim N_{baryon} \) in early universe
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\[ M_{DM} \sim 5 \text{ GeV} \]
Status of DM searches

- DAMA
- CoGeNT
- DAMA (with channeling)

Trotta et al. CMSSM 95% CL
Trotta et al. CMSSM 68% CL

Cross Section [cm²]

Mass [GeV/c²]
CMSSM prefers heavy WIMPs ~200 GeV
But ... increasingly ruled out by LHC
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Hints of signal at lower masses
**Status of DM searches**

- **Hints of signal at lower masses**
- **Limited by threshold, typically a few keV** (need lower energy detection)
- **Limited by exposure mass** (need bigger detector, multi-kg-sized detectors)

**CMSSM** prefers heavy WIMPs \(\sim 200\) GeV

But ... increasingly ruled out by LHC
DArk Matter In CCDs (DAMIC)

- Fermilab experiment - T987 DAMIC
- DM collides with nuclei in silicon pixel detectors of CCDs
- Goal is to extend sensitivity for low mass dark matter, $M_{DM} < 5$ GeV
  ($< 1$ GeV, $< 100$ MeV ?)
  - Focus on low noise, low threshold nuclear recoil detection
The Dark Energy Camera (DECam) for Dark Energy Survey (DES)

Optical Lenses

Blanco 4m Telescope
Cerro Tololo, Chile
The Dark Energy Camera (DECam) for Dark Energy Survey (DES)

Images collected on 
~60 CCDs ~600 Mpix 
Developed by LBNL
Energy threshold for DM search

- CCDs cooled to -150 C to reduce noise
- 50 μs / pixel
  - RMS of 2 e-
  - 7.2 eV equivalent ionizing in Silicon
- Threshold of 40 eVee
- Lowest of current DM experiments
- We are pushing energy threshold even further
- RMS of 0.2 e- may be possible

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMIC</td>
<td>0.04 keVee</td>
</tr>
<tr>
<td>COGENT</td>
<td>0.5 keVee</td>
</tr>
<tr>
<td>CDMS II</td>
<td>3 keVee</td>
</tr>
<tr>
<td>Xenon 100</td>
<td>8.4 keVnr</td>
</tr>
</tbody>
</table>

Noise decreases as integration time increases.
DECam CCDs for DM

Instead of exposing CCD to light on its back surface, we shield it, and look for nuclear recoils in silicon volume.

Advantages of DECam CCDs
- 10x thicker than most CCDs (250 μm)
- Relatively massive ~ 1g / CCD
- High resistivity silicon, allows high bias voltage
  - Limits diffusion
(This background is a CCD image)
Nuclear recoils produce small, diffusion-limited hits

Clear difference between **tracks** (gamma rays, cosmics) and **diffusion-limited hits** (X-rays, nuclear recoils)
X-ray $^{55}$Fe (5.9 keV)

Point like hits (diffusion limited)

Gammas $^{60}$Co (1.33 & 1.77 MeV)

Alphas

plasma effect creates large hits

Compton electrons (worms) and point like hits.
Calibration - X-rays

Expose CCD to X-ray $^{55}$Fe

5.9 KeV X-ray line yields 1620 e$^-$
So : 3.64 eV / e$^-$ converts charge to ionization energy
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5.9 KeV X-ray line yields 1620 e$^-$
So : 3.64 eV / e$^-$
converts charge to ionization energy

We can select diffusion-limited hits from tracks with 99.9% efficiency
“Calibration” of quenching factor with Neutrons

\[ Q = \frac{\text{signal from X-rays}}{\text{signal from neutrons}} \]

Neutrons $^{252}\text{Cf}$

What we measure with CCDs
“Calibration” of quenching factor with Neutrons

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Neutrons \(^{252}\text{Cf}\)

Neutron energy spectrum with GEANT-simulated detector effects

What we measure with CCDs
“Calibration” of quenching factor with Neutrons

Q = signal from X-rays / signal from neutrons

Neutrons $^{252}$Cf

What we measure with CCDs

Neutron energy spectrum with GEANT-simulated detector effects

Can’t fit energy dependence since neutrons have energy distribution

Unfold these distributions to determine ionization yield from nuclear recoils of 13.9 ev/e$^-$
Quenching Factor

- Comparison to Lindhard theory assuming constant detection efficiency

Lindhard Theory
Flat Q Factor

Neutrons $^{252}$Cf

Lindhard used to produce more conservative limits - we are following up with a dedicated low energy neutron calibration this year.
Nuclear recoil selection

- Diffusion varies as a function of depth
Nuclear recoil selection

- Diffusion varies as a function of depth

Narrower end - front of CCD - minimal diffusion

Thicker end - back of CCD - maximal diffusion
Nuclear recoil selection

- Diffusion varies as a function of depth
  - Narrower end - front of CCD - minimal diffusion
  - Thicker end - back of CCD - maximal diffusion

- Can apply fiducial cuts based on hit size to select recoils consistent with bulk
Selection

- Energy threshold 0.04 keVee to suppress readout noise
- Fiducial cuts based on RMS of hits to suppress X-rays

Flat cut to reject large diffusion hits

Parabolic cut to reject small diffusion hits based on RMS as a function of hit position

Red = front x-rays
Green = back x-rays
Black = neutrons

\[ \sigma^2_x \]
DAMIC

CCD Inside a cold Cu box

Lead Bucket

Cylindrical Cu Dewar
DAMIC

![Image showing DAMIC setup](image)

1. Al-63 Cryocooler
2. Vacuum
3. Cold Finger
4. 6 Inch Lead cast in copper container
5. 8 Pack CCD picture frames (-160C) we will have to design a low background package and cable
6. Cu shield
7. Lead shield
NuMI Tunnel Project
DAMIC
Energy Spectrum

![Energy Spectrum Diagram]

- **All Hits**
- **Selected Hits**

**events/150 eV**

**Energy (keVee)**
X-Ray Contamination

![Graph showing X-Ray Contamination](image)

- All Hits
- Selected Hits

- Mn
- Cu
- Au
- Ge
- Br
- Sr

Energy (keVee)

Occurrences per 150 eV
Energy Spectrum

Region from 0.05 keVee to 2.0 keVee
used for search
Results from First Run

- Wimp density $\rightarrow 0.3 \text{ GeV/cm}$
- $V_{\text{earth}} = 244 \text{ km/s}$
- $V_{\text{escape}} = 650 \text{ km/s}$

Assumes Lindhard quenching factor for conservative limits
Results from First Run

Direct Search for Low Mass Dark Matter Particles with CCDs


$^1$Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
$^2$Fermi National Accelerator Laboratory, Batavia, Illinois, USA
$^3$Facultad de Ingeniería, Universidad Nacional de Asunción (FIUNA), Asunción, Paraguay
$^4$University of California at Davis, USA.

(Dated: August 17, 2011)

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (RMS~7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (~5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

PACS numbers: 93.35.+d, 95.55.Aq

I. INTRODUCTION

There have been several direct-detection experiments searching for dark matter (DM) performed in recent years, and several more in development. [1]. Most of these experiments have been optimized for detecting the electron recoil of very low fiducial mass. The recent design of thick, fully-depleted CCDs is an order of magnitude more sensitive than conventional CCDs. This is the first demonstration of thick, fully-depleted CCDs for dark matter detection. The Dark Matter in Cambridge (DMiC) experiment is the first DM search to use this technology.
Ramping Up!

Adding Mass and Going Deeper

- Adding 10x more mass by adding CCD’s (8 CCD’s/10g)
- Moving to SNOLAB within months (2km deep)
- 1 year, 3.5 kg-day @ 40 eV threshold
Ramping Up!

Better Shielding, Better Materials

- Re-using 6500 lbs of lead shielding
- Adding 9800 lbs of polyethylene shielding
- Removed connectors and colored cables with some unknown materials
Ramping Up!

Better Background Predictions

- In-situ measurement of neutron contamination
- Layer of Boron-10 on polyethylene
- Poly slows down neutrons - B10 produces alpha radiation (2 protons & 2 neutrons) from the interacting neutrons
- Alphas have a distinct signature in DAMIC CCD’s
Ramping Up!

Better Background Predictions

- In-situ measurement of neutron contamination
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- Alphas have a distinct signature in DAMIC CCDs

Plasma effect in Silicon Charge Coupled Devices (CCDs)

J. Estrada(1), J. Molina(2), J. Blostein(3), G. Fernández(4)
1Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
2Facultad de Ingeniería, Universidad Nacional de Asunción, Asunción, Paraguay
3Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica, Universidad Nacional de Cuyo, (R8402AGP) Bariloche, Argentina
4Universidad Nacional del Sur, Bahía Blanca, Argentina

(Dated: May 31, 2011)

Plasma effect is observed in CCDs exposed to heavy ionizing α-particles with energy 0.5 - 5.5 MeV. The results obtained for the size of the charge clusters reconstitute the pixel size with previous measurements in the high energy region (≥ 3.5 MeV). The results were extended to lower energies using α-particles produced by (n,α) reactions of the target. The effective linear charge density for the plasma column is measured as energy. The results demonstrate the potential for high position resolution in the readout of α alpha particles, which opens an interesting possibility for using these detectors in space.
Ramping Up!
Calibrating to Lower Energy

- Using a mono-energetic beam of neutrons to calibrate quenching factor to very low energies
Ramping Up!

Adding People Mass

J. Estrada
FNAL
Project Lead

B. Kilminster
FNAL

J. Molina
UNA

K. Chinetti
IMSA

G. Cancelo
FNAL

T. Schwarz
Univ. Michigan

P. Privitera
U. Chicago

Adding
Students

+2
Projecting Sensitivity for Next Run

- Expected sensitivity from
  - Adding mass
    8 CCD’s (x10 more mass)
  - Going deeper and better shielding
    SNOLab ~ 2km
    Polyethylene
    Better Materials
  - Increase sensitivity
    Better calibration
    Bkg Predictions

http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Long Term Goal

- 100g of CCD @ SNOLab ~ $50K per 10g
- Lower energy thresholds
  - Skipper CCD & Digital Filters
- DAMIC-SOUTH  UNAM (Mexico) CNEA (Argentina) UTFSM (Chile)
  - Will construct and install a DAMIC over the next 3 years in ANGRA
  - Cancel systematic effects when combined with DAMIC-NORTH
Conclusions

- DAMIC @ NuMI 2011-12 data (Fermilab tunnel)
  - Demonstrated sensitivity to low mass DM
    - 107 g-days set best limits below 4 GeV

- DAMIC @ Snolab
  - Will significantly reduce cosmogenic neutron backgrounds
  - Some other improvements planned
  - Improve limits by ~50

- DAMIC in the future
  - Will focus on pushing lower energy thresholds
    - Requires better neutron calibrations
  - Larger mass when bkgs are under control