Dark Matter Search with CCDs - DAMIC

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Rome, Italy
Dark Energy Camera (DECam)

New wide field imager (3 sq-deg) for the Blanco 4m telescope to be delivered in 2010 in exchange for 30% of the telescope time during 5 years. Being built at FNAL.
Science goal requires DES to reach $z \sim 1$

we want to spend ~50% of time in $z$-filter (825-1100nm)
Astronomical CCDs are usually thinned to 30-40 microns (depletion):
Good 400nm response
Poor 900nm response

**LBNL full depletion CCD are the choice for DECam:**

- 250 microns thick
- high resistivity silicon
- QE > 50% at 1000 nm

DECam wafer
New opportunities with these CCDs

Two features:

CCDs are readout serially (2 outputs for 8 million pixels). When readout slow, these detectors have a noise below 2e- (RMS). This means an **RMS noise of 7.2 eV in ionization energy!**

The devices are “massive”, 1 gram per CCD. Which means you could easily build ~10 g detector. DECam would be a 70 g detector.

Interesting for a low threshold DM search.

- 7.2 eV noise ⇔ low threshold (~0.036 keVee)
- 250 μm thick ⇔ reasonable mass (a few gram detector)
clear difference between tracks and diffusion limited hits.

nuclear recoils will produce diffusion limited hits.
X-ray $^{55}\text{Fe}$ (5.9 keV)

Point like hits (diffusion limited)

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

Compton electrons (worms) and point like hits.
X-ray $^{55}\text{Fe}$ (5.9 keV)

point like hits (diffusion limited)

all hits diffusion limited

%99.9 efficiency in for selecting diffusion limited hits
low noise readout for Fe55

energy resolution:
RMS = 64 eV

effective fano factor:
$F_{\text{eff}} = \frac{(18^2 - 2^2)}{1620}$. 
$F_{\text{eff}} \approx 0.17$
this typical for CCDs (CTI, clustering)
in silicon: 0.10
Charge diffusion with X-rays

- **Energy (keV)**
- **Size (pix)**

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**Graph:**
- Title: Diffusion on DECam CCD pb-22-27 vs Vsub.
- Data points for different substrate voltages:
  - T = 133 K
  - T = 173 K
  - T = 188 K
  - T = 203 K

- X-axis: Substrate Voltage (Volts)
- Y-axis: Diffusion (microns)
Charge diffusion with X-rays

we operate them at 40V for the moment.
Nuclear Recoils in CCDs

**Neutrons $^{252}$Cf**

We have measured nuclear recoils from a neutron source and fitted an ionization yield of \(~13.9\text{ eV/e}^-\) ("Q=3.8"). This is not a real calibration, just first check for the response to nuclear recoils. Now setting up for collecting more data to attempt a real calibration.
DAMIC (FNAL MOU T987)

Underground test of CCDs for DM

CPA people:
DES: T. Diehl, J. Estrada, B. Flaugher, D. Kubik, V. Scarpine
COUPP: E. Ramberg, A. Sonnenschein
CDF: Ben Kilminster

Visitors:
J. Molina (CIEMAT), J. Jones (Purdue)

Engineering (mostly DECam people and spares when available)
Mech: H. Cease, K. Schultz
Electrical: T. Shaw, W. Stuermer, K. Kuk

Support:
> Detectors and electronics are DECam engineering parts
> PPD: shield + tent underground
> CPA: some electronics boards (VIB)

setting up a 4CCD array here. ~350 foot depth
Moved CCDs to Minos in January

built a tent in the near detector hall and installed our detectors inside

all parts used were spares from other FNAL projects... not designed for low background.
tracks:
- surface
- Minos (350’ underg.)
- Minos + 8” lead shield
I apologize for showing this result in a conference where everybody shows low backgrounds.

to become competitive we need to reduce another 2 orders of magnitude.
cross section (cm$^2$)

DM mass (GeV)

Q=10
Q=3.8

GREGOR 2001 spin indep., 1.5 kg-days, 262g sapphire
CAMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
XENON10 2007 (Net 136 kg-d)
To reduce background we are building this new dewar for a 21 gr detector. We still have to do a better job selecting the cold electronics.

- **Vacuum Interface Board**
- **Al-63 Cryocooler**
- **Vacuum**
- **Cold Finger**
- **6 Inch Lead cast in copper container**
- **8 Pack CCD picture frames (-160C)**
- **Cu shield**
- **Lead shield**

**Vessel**
- OFHC Cu
- 9” OD
- 30” length
CCD readout: lowering noise

CDS: the amount of charge on each pixel is given by the difference between signal and pedestal levels inside an integration window. **High frequencies are suppressed by the integration window, low frequencies are suppressed by the double sampling.** Working on digital filtering of the intermediate frequencies by looking at the signal over many pixels...
Conclusions

• We started an R&D program to investigate **CCDs as candidates for direct DM searches at low threshold**.

• First test (without low background design) indicates that **we need x100 background reduction to become competitive**.

• Next:
  • Built a **low background setup** (new design almost done).
  • A **new readout system** to filter the low frequency noise remaining after CDS.
  • Real calibration **nuclear recoils**.

• There are other efforts to get low threshold in DM searches. If this works it has potential extremely low threshold. **With 0.5e of noise a 5 sigma threshold on 10 eVee is possible**. Right now have no reason to believe that this is impossible, so we will try it.
END
charge is clocked to a serial register (SR) and the shifted to the readout node. You can continue shifting the SR after you are done reading out physical pixels and this produces the overscan region.
the $1/f$ noise component produces increase the noise of the CDS result when the pixel time becomes too slow.

We are working on a digital filtering algorithm to improve the low frequency filtering... maybe this will allow us to go below $1e-$ of noise.
4000 sec exposures

\[ \sigma = 2.4 \text{ e-} \]

\[ \sigma = 2.7 \text{ e-} \]
40000 sec exposures

\[ \sigma = 2.4 \text{ e-} \]
noise

\[ \sigma = 3.4 \text{ e-} \]
noise + dark current
runs at Lab-A gave $10^6$ cpd/keV... too high!
Shield studies: Ge detector at LAB-A

FNAL lead is bad, it had Bi-207 from exposure to beam.

Peanut lead was available at FNAL for these test, but not enough for the experiment.

Ge detector from surplus!
Purchased new lead before the price went down... and made a shield at Minos for the Ge detector.

Test indicated we could get about 2 orders of magnitudes.
... thanks!

T. Nebel (inside)

J. Tweed

S. Jakubowski

K. Schultz

J. Voirin

J. Delao (and lead workers)

M. Watson

K. Kuk
Finished shield with new lead in March

“clean tent”

no more tape... FNAL lead painted with “german sport car” clear coat. New lead naked.
how low could we go?

DAMIC

Current DAMIC background levels

Two to four orders of magnitude reduction seem possible based on other experiments

FIG. 4: The measured spectrum of ULEGe with 0.338 kg-day of data, after CRV, ACV and PSD selections. Background spectra of the CRESST-I experiment [9] and the HPGe [13] are overlaid for comparison. The expected nuclear recoil spectra for two cases of \((m_\chi, \sigma_{\chi N}^{SI})\) are superimposed onto the spectrum shown in linear scales in the inset.
result from our fit to neutrons

```
<table>
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<tr>
<th>Silicon recoil energy (keV)</th>
<th>Ratio of ionization Si/e (%)</th>
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<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
<td>4</td>
<td>10</td>
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<tr>
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<td>40</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
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</tbody>
</table>
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PRD 42(1990) 3211
Each detector in our setup sees a different spectrum.

X rays:
- Si (Silicon)
- Mn (Manganese)
- Co (Cobalt)
- Zn (Zinc)
- As (Arsenic)
- Sr (Strontium)
Each detector in our setup sees a different spectrum.

A sees a lot of steel:
- Mn (Manganese)
- Co (Cobalt)

B sees a lot of electronics:
- As (Arsenic) - transistors
- Zn (Zinc) - flex circuits

C sees a lot of cables:
- Zn (Zinc) - flex circuits

Sr (Strontium) in A?
neutrino coherent scattering spectrum at 28m of a 3GW reactor (Texono Collaboration)

\[ Q = 10 \]

\[ Q = 3.8 \]

now!
neutrino coherent scattering spectrum at 28m of a 3GW reactor (Texono Collaboration)

\[ Q = 10 \]
\[ Q = 3.8 \]

Events (kg^{-1} day^{-1} keV^{-1})

\[ {\bar \nu}_e N(\text{SM}) \]
\[ {\bar \nu}_e e(\text{MM}) \]
\[ {\bar \nu}_e e(\text{SM}) \]

1/100 back.

Recoil Energy (keV)
neutrino coherent scattering spectrum at 28m of a 3GW reactor (Texono Collaboration)

\begin{align*}
&\bar{\nu}_e N(\text{SM}) \\
&\bar{\nu}_e e(\text{MM}) \\
&\bar{\nu}_e e(\text{SM}) \\
\end{align*}

$Q = 10$

$Q = 3.8$

I/100 back.

I/10 thr
DM search results

limited by detector threshold, typically a few keV. This limitation comes in part from the readout noise.

from Petriello & Zurek 0806.3989

minimal SUSY likes heavy WIMPs, and most experiments are trying to cover that area.

given our low noise, we can set a much lower threshold and scan the low energy region.
**Galaxy Cluster counting**
(collaboration with SPT, see next slides)
20,000 clusters to \( z = 1 \) with \( M > 2 \times 10^{14} M_{\odot} \)

**Spatial clustering of galaxies (BAO)**
300 million galaxies to \( z \sim 1 \)

**Weak lensing**
300 million galaxies with shape measurements over 5000 sq deg

**Supernovae type Ia (secondary survey)**
\( \sim 1100 \) SNe Ia, to \( z = 1 \)
5.9 keV X-ray from Fe55 gives 1620e-

**FIG. 4:** Spectrum obtained for the reconstructed X-ray hits in an $^{56}$Fe exposure of a DECam CCD. The arrows mark the direct X-rays from the source $K\alpha=5.9$ keV and $K\beta=6.5$ keV, the $K\alpha$ and $K\beta$ escape lines at 4.2 and 4.8 keV, and the Si X-ray at 1.7 keV. The factor 3.64 eV/e is used to convert from charge to ionization energy.
DAMIC started at SiDet

BTev/SNAP dewar adapted for DECam CCDs. 4CCD array pin compatible with DECam prototype.

DECam prototype electronics used