Recent Progress from the DMTPC Directional Dark Matter Experiment

Jocelyn Monroe,
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UCLA Dark Matter Conference
February 24, 2012
DMTPC Collaboration

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University of Hawai‘i at Manoa: I. Jaegle, S. Vahsen*

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Nov. 9, 2011
The Dark Matter Wind apparently “blows” from Cygnus

directional detection: search for a dark matter source

Daily direction modulation: asymmetry ~ 20-100% in forward-backward event rate.


Unambiguous proof: Correlation of WIMP-induced nuclear recoil signal with galactic motion
Signals in Directional Detectors

distribution of signal events determined by:

1. angular resolution of elastic scattering
2. dark matter velocity dispersion

need ~50 keV threshold for directional detectors, for 100 GeV WIMPs
Optimization

**Detector Properties:**
- detector resolution
- energy threshold
- background
- reconstruction (2D vs. 3D)
- vector or axial reconstruction

**Table:**

<table>
<thead>
<tr>
<th>No background, 3-d vector read-out, ( E_T = 20 ) keV</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_T = 50 ) keV</td>
<td>5</td>
</tr>
<tr>
<td>( E_T = 100 ) keV</td>
<td>3</td>
</tr>
<tr>
<td>( S/N = 10 )</td>
<td>8</td>
</tr>
<tr>
<td>( S/N = 1 )</td>
<td>17</td>
</tr>
<tr>
<td>( S/N = 0.1 )</td>
<td>99</td>
</tr>
<tr>
<td>3-d axial read-out</td>
<td>81</td>
</tr>
<tr>
<td><strong>2-d vector read-out in optimal plane, reduced angles</strong></td>
<td><strong>12</strong></td>
</tr>
<tr>
<td><strong>2-d axial read-out in optimal plane, reduced angles</strong></td>
<td><strong>190</strong></td>
</tr>
</tbody>
</table>


J. Billard, F. Mayet, D. Santos, *arXiv*:1009.5568

**do not need “zero background” for directional detectors**

simulation with 100 signal, 100 background
**Dark Matter Time Projection Chamber (DMTPC) Principle**

1. **primary ionization** encodes track direction via dE/dx profile

2. Drifting electrons preserve dE/dx profile if diffusion is small

3. Multiplication in amplification region produces e- + scintillation

**Minimum wetted materials**

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TPC Readout

Charge readout

Light readout

CCD

pixel X

pixel Y

Voltage

time (s)

goal: charge and light = 2->3D
TPC Readout

Charge readout

Light readout

Goal: charge and light = 2->3D
Amplification Plane

Copper Mesh, 256 um pitch

\[ e^{-}\]

CCD readout area

~28cm


SS or Cu mesh

G10

Resistive separators, dia=0.5mm, every 2.5cm

20x smaller pitch, 1E4-1E5 gain, 1->2D

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CCD Readout

Total light output:

Increasing gain + track length with lower pressure, but decreasing mass!

CF4 scintillation: $\gamma/e^- = 0.38 \pm 0.04$

Charge Readout

Multiplication calibrated with Fe-55, anode signal amplitude

\[ M \sim \frac{V_{\text{out}} \times 1.4\text{pC/V}}{5.9\text{keV/W}} \]

\[ W = 33.8 \pm 0.4 \text{ eV} \quad (\text{I. Wolfe thesis}) \]

Mesh signal readout with ns-risetime amplifier, to measure \( \Delta z \) and gamma rejection: \( <5.6 \times 10^{-6} \) (90\% CL)

\[ \text{arXiv:1109.3501} \]
illuminate with Co-57 (122, 137 keV) and Cs-137 (662 keV) for length calibration

measure optical plate scale by comparing spacer positions in gamma data with photo $= 136, 168$ um/pixel (top,bottom)

α sources for energy calibration (4.4 MeV)

measure gain (ADU/keVee) by comparing α energy measured in external solid state detector with energy in CCD, at track end: gain = 21,18 ADU/keV (top,bottom)
“WIMP” Calibration

Neutron elastic scattering mimics dark matter recoils, and most neutrons below ~4 MeV alpha production threshold.

Cf-252 (~mCi) and d-t sources at surface, AmBe (8.9 uCi) source underground minimum recoil energy detected: ~50 keV

Energy and recoil angle distributions similar to dark matter induced recoils

<table>
<thead>
<tr>
<th>Source</th>
<th>Recoil angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1 MeV neutrons</td>
<td>80deg</td>
</tr>
<tr>
<td>Neutrons from AmBe</td>
<td>~68 deg (avg)</td>
</tr>
<tr>
<td>Neutrons from Cf252</td>
<td>~57deg (avg)</td>
</tr>
<tr>
<td>200GeV WIMP</td>
<td>~43deg (avg)</td>
</tr>
</tbody>
</table>

10L Surface Cf-252 Data -- SRIM MC
Directionality

2D angle + head-tail from light asymmetry (measure skewness)

Signed cosine (E>200 keV), 5 cm drift

diffusion has a big impact on head-tail, working on 3D readout using charge signal

1D “sky map” for $^{252}$Cf, and “WIMP” data (80-200 keV)

20 cm drift (10L detector)

MC: 40° resolution at 80 keVr


Dujmic et al., NIM A584:327-333 (2008)

R&D Data

-- MC

Source

-2

0

2

-2

0

2

100

150

200

10L Data

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10^4 rejection of backgrounds from range vs. energy strategy, unique to directional detectors
Surface Run Results

nuclear recoil selection cuts, set using calibration data (note: no charge readout)

<table>
<thead>
<tr>
<th>Recoil Energy (keV)</th>
<th>counts / 10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>200</td>
<td>15</td>
</tr>
</tbody>
</table>

Nuclear Recoil Candidates in $80 < E_R < 200$ keV $5.0 \times 10^{-5}$

<table>
<thead>
<tr>
<th>Event Selection Cut</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Tracks</td>
<td>0.43</td>
</tr>
<tr>
<td>Residual Bulk Images</td>
<td>0.15</td>
</tr>
<tr>
<td>CCD Interactions</td>
<td>$4.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Alpha Candidates</td>
<td>$8.2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

observed 105 events above 80 keV threshold chosen for dark matter search (threshold chosen for max. recoil efficiency), consistent with neutron prediction (74 events)


Surface Run Result

$\sigma_p \ (cm^2)$

DMTPC limit (surface, 38 gm-day)

$S. \ Ahlen \ et\ al., \ Phys. \ Lett. \ B \ 695 \ (2011)$

Theory region:

Rozkowski et al JHEP 07 (2007) 075

Ellis et al PRD63 (2001) 065016

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Surface Run Result

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S. Ahlen et al.,

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DMTPC 10L surface
DMTPC, 10 L sensitivity
cMSSM theory

\( \sigma_p \) (cm\(^2\))
WIMP mass (GeV)
Surface Run Result

**NEWAGE** limit (Kamioka)


**DMTPC** limit (surface, 38 gm-day)


Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

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Surface Run Result

**NEWAGE** limit
(Kamioka)

K. Miuchi et al.,

DMTPC limit
(surface, 38 gm-day)

S. Ahlen et al.,

Theory region:
Rozkowski et al *JHEP* 07 (2007) 075
Ellis et al *PRD* 63 (2001) 065016

**Directional searches**

**DRIFT sensitivity**,

**1D results**

**COUPP**
PRL 106, 021303 (2011)
**SIMPLE**
arXiv:1106.3014
**PICASSO**
arXiv:1202.1240

Theory region:
Rozkowski et al *JHEP* 07 (2007) 075
Ellis et al *PRD* 63 (2001) 065016

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Surface Run Result

NEWAGE limit (Kamioka)


DMTPC limit (surface, 38 gm-day)


1m$^3$ at WIPP (DMTPCino) projected sensitivity

Next steps for DMTPC: low-background detector R&D, 2150’ underground at WIPP, DMTPCino at WIPP (1m$^3$)

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016
Yamamoto Laboratory at WIPP

Major effort at WIPP is to measure the in-situ detector backgrounds

“WIMP search” run started in 2011, typically 60-70% livetime (1 second exposure)

Blind analysis, selection cuts defined on AmBe and Cf-252 calibration data
Laboratory Conditions

measured backgrounds:

1. Esch PhD thesis

• 21.6x lower gamma rate (25 - 1600 keV)
• muon flux reduction of $10^5$ (1.6 km.w.e.)
• lower limit of 415x lower neutron flux (predict $x10^5$)
• upper limit on Rn rate of <7 Bq/m³
• particle count comparable to surface lab rate

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Spec.</th>
<th>Gamma Spec.</th>
<th>Avg</th>
<th>low</th>
<th>high</th>
<th>typical</th>
<th>Soil vs. WIPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[μg]</td>
<td>[μg]</td>
<td>[μg]</td>
<td>[μg]</td>
<td>[μg]</td>
<td>[μg]</td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>0.048</td>
<td>&lt;0.37</td>
<td>0.048</td>
<td>0.5</td>
<td>2.5</td>
<td>1.5</td>
<td>30</td>
</tr>
<tr>
<td>Thorium</td>
<td>0.08</td>
<td>0.25</td>
<td>0.25</td>
<td>1.2</td>
<td>3.7</td>
<td>2.4</td>
<td>10</td>
</tr>
<tr>
<td>Potassium</td>
<td>784</td>
<td>182</td>
<td>480</td>
<td>500</td>
<td>900</td>
<td>700</td>
<td>1.5</td>
</tr>
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</table>

Table 4.21: Natural Radioactivity at the WIPP underground [WEB98].
Move to back-illuminated CCDs (EMCCD here) to eliminate RBI backgrounds.
Redundant Readout R&D

for fiducialization, tracking in z (2D-> 3D) and background rejection

1. x-y fiducialization require no signal in veto ring of anode plane

x250 edge-crossing background rejection
Redundant Readout R&D

2. tracking in z (drift direction)

comparable tracking resolution in z (from charge) as in x-y (from CCD)

\[ \Delta z = \tan(27^\circ) \Delta x \]

- vertical error bars = RMS (spread due to track angles + detector resolution)
- Bias toward longer tracks in CCD at small \( \Delta z \) (due to search algorithm in CCD - not \( \Delta t \) issue)

\( \sigma_{\Delta z} \sim O(1\text{mm}) \)
at 10cm drift

Rise-time of charge signal (ns)
10L detector instrumented with charge readout of anode and mesh in December 2010 (WIPP) (surface run analysis used no charge data)
(no veto ring on 10L anode)

preliminary result:

<table>
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<tr>
<th>Cut</th>
<th>Pass CCD RBI</th>
<th>Pass CCD RBI &amp; Artifact</th>
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<tr>
<td>Fail NR Charge</td>
<td>400</td>
<td>244</td>
</tr>
<tr>
<td>Pass NR Charge</td>
<td>4</td>
<td>2</td>
</tr>
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require charge consistent with nuclear recoil in mesh rise time, and energy match to within 35 mV in anode amplitude, for $80 < E_{recoil} < 200$ keVr

x100 rejection of camera interaction backgrounds from charge readout
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require charge consistent with nuclear recoil in mesh rise time, and energy match to within 35 mV in anode amplitude, for $80 < E_{\text{recoil}} < 200$ keVr

$x_{100}$ rejection of camera interaction backgrounds from charge readout
DMTPC Next Steps: Deploy 4-Shooter Detector at WIPP

Goal: 
prototype for multi-camera readout, with CCDs, charge readout+veto, PMTs (20L) calibration data:

Installation 2012 at WIPP, surface calibration run suite underway now.
DMTPCino: 1m$^3$ Detector at WIPP

Goal: prototype for $O(10 \text{ kg})$ fiducial mass detector, with 1 m$^3$ (0.25 kg) instrumented now

4-shooter detector tests many design aspects:
   (i) multi-camera readout
   (ii) triggering with charge & PMTs
   (iii) directionality with charge
   (iv) low-background materials

dedicated 1 m$^3$ R&D on scalability:
   (i) amplification region
   (ii) optical system (1 lens, 1 camera?)

For a very large detector, build many 1m$^3$ modules because of diffusion limit.

Design underway, laboratory infrastructure ready, detector construction 2012.
Directional Detection Future

Eventually: large detector, $10^{-46}$ cm$^2$ sensitivity, how big is it?

- DMTPC Observatory: $16 \times 16 \times 16$ m$^3$
- MINOS: $15 \times 13 \times 30$ m$^3$
- SNO: $21 \times 21 \times 34$ m$^3$
- SuperK: $40 \times 40 \times 40$ m$^3$
- MiniBooNE: $6 \times 6 \times 6$ m$^3$
- 1 ton of CF$_4$ @ 50 Torr

Detector size for $10^{-44}$ cm$^2$ SI sensitivity
Conclusions and Outlook

Backgrounds make directional detection very attractive. Large low-energy, low-background tracking detectors have potential for confirmation of the astrophysical origin of a candidate direct detection dark matter signal.

DMTPC has published a surface limit, demonstrated background rejection from complementary optical and charge readout, established an underground laboratory at WIPP, dark matter run underground is underway, developing m$^3$ module for large detector.

There has been great progress since the last UCLA meeting... first limits from directional detectors!

Dark matter telescope: transition from discovery to observatory.
Backup Slides
Energy Resolution

$\sigma_E/E$ from CCD Readout:

- $15\%$ at $50$keV
- $\sim 10\%$ at $5.9$keV for charge readout

Expected fluctuation (avalanche + primary) $\sim 10\%$

Avalanche=Alkhazov, NIM89 (1970) 155,  primary=Poisson
CF$_4$ Electron Diffusion

Large impact on spatial resolution:

$$\sigma^2 = (D/\mu) \frac{2z}{E}$$

>10x discrepancy in measurements in our range-of-interest

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Large impact on spatial resolution:
\[ \sigma^2 = \left( \frac{D}{\mu} \right) \frac{2z}{E} \]

or?

>10x discrepancy in measurements in our range-of-interest

(D. Dujmic, T. Caldwell)

Large impact on spatial resolution:

$$\sigma^2 = \frac{D}{\mu} \frac{2z}{E}$$

>10x discrepancy in measurements in our range-of-interest

DMTPC maximum drift length for <1 mm diffusion ~20 cm.
CF$_4$ Electron Attenuation

Attachment to CF$_4$:

e.g.

$e^- + \text{CF}_4 \rightarrow \text{CF}_4^- \rightarrow \text{CF}_3^- + \text{F}^-$

$e^- + \text{CF}_4 \rightarrow \text{CF}_4^- \rightarrow \text{CF}_3^- + \text{F}$

$e^- + \text{CF}_4 \rightarrow \text{CF}_4^* \rightarrow \text{F}^- + \text{CF}_2 + \text{F}$

From previous measurements, 0% loss, or 70% loss after 20cm drift length?

(D. Dujmic, T. Caldwell)
CF$_4$ Electron Attenuation

Attachment to CF$_4$:

e.g.

$e^- + CF_4 \rightarrow CF_4^- \rightarrow CF_3^- + F^-$

$e^- + CF_4 \rightarrow CF_4^- \rightarrow CF_3^- + F$

$e^- + CF_4 \rightarrow CF_4^- \rightarrow F^- + CF_2 + F$

From previous measurements, 0% loss, or 70% loss after 20 cm drift length?

DMTPC measures ~0 charge loss over 20 cm drift length.

$T. \text{ Caldwell, et al., arXiv:0905.2549}$