DMTPC: a new approach to directional detection of Dark Matter

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Outline:
- Introduction to Dark Matter
- Why directional detection of DM
- DMTPC: detector concept
- Recent results: first evidence of “head-tail” effect
- Next step: toward a full-scale detector
- Conclusion

UPenn, March 24, 2009
First hints of Dark Matter

Fritz Zwicky (1933)

- Applying virial theorem to study of Coma cluster, he concluded that mass of galaxies in cluster was $O(10^2)$ what inferred from luminosity
- Explanation: substantial amount of matter not emitting light (Dark) must exist

Coma Cluster in ultraviolet and visible light from Sloan Digital Sky Survey/Spitzer Space Telescope

DM-TPC: a new approach to dir
Strong evidence for DM

Vera Rubin et al. (1979)

- Study of rotational curve of spiral galaxies
  - Newtonian prediction for orbital velocity of galaxies
    \[
    \frac{GMm}{r^2} = \frac{mv^2}{r} \implies v \propto \frac{1}{\sqrt{r}}
    \]
  - Observation: orbital velocity is flat outside central bulge

- Explanation: substantial amount of matter far from the center of the galaxy that is not emitting light (Dark Matter)
Even more convincing evidence...

**Bullet Cluster (2006)**

- Two colliding clusters of galaxies
- Its components (stars, gas, and DM) behave differently during collision
  - Stars (optical) not greatly affected: small gravitational slow down
  - Hot gas (X-rays), larger mass, EM interactions: more dramatic slow down
  - DM (gravitational lensing), largest mass, minimally affected
- Conclusion: most of the mass in the cluster pair is in the form of weakly interacting Dark Matter

*X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
What is Dark Matter made of?

- Astronomy and cosmology tell us that Dark Matter accounts for a huge fraction of our Universe:
  - 23% of the energy
  - 82% of the mass

- What is Dark Matter?
  - Many candidates:
    - Baryonic DM (e.g.: non-luminous gas)
    - Non baryonic DM --- hot or cold
  - CMB data favor cold non-baryonic Dark Matter
    - Cold: large mass --> non-relativistic velocities
    - Non-baryonic: gravity and weak interactions --> new particle
    - Stable: maybe LSP?
  - Weakly Interacting Massive Particles (WIMPs) are the most likely candidates
Direct detection of WIMPs

- Basic principle: detect recoil of matter after elastic scatter with WIMP
- Different experiments use different techniques and materials
  - Ionization, scintillation, phonons
  - Si, Ge, CsI, Xe, Ar, CF₄, ...
- Very challenging measurements
  - Very low-energy recoils (10-100 keV), very weak interactions, many backgrounds

Signal:
\[ \chi \ N \rightarrow \chi \ N' \]

Backgrounds:
\[ \gamma \ e^- \rightarrow \gamma \ e^-' \]
\[ N \rightarrow N' + \alpha, e^- \]
\[ n \ N \rightarrow n \ N' \]
\[ \nu \ N \rightarrow \nu \ N' \]
Present DM searches

Current best limits on spin-independent interactions

- Many experiments engaged in direct detection of DM
  - Recent progress: improved cross-section limits $\sigma_{SI} < 10^{-44} - 10^{-43}$ cm$^2$
- Intrinsic limitation of mainstream DM experiments
  - Counting experiments: zero-background assumed
  - Larger detectors will start to see several (irreducible) backgrounds

It may be very hard for a counting experiment to provide unambiguous positive observation of Dark Matter
Situation similar to neutrino oscillations...

Oscillation of solar $\nu$ first observed by Davis in the 60’s in counting experiment, but decisive proof came in 2001 with water Cherenkov directional results.
DM in our galaxy: the Dark Halo Model

The decisive proof of positive observation of DM requires correlation with astrophysical phenomena.
A wind of Dark Matter from Cygnus

The decisive proof of positive observation of DM requires correlation with astrophysical phenomena.

| DM halo’s reference frame | Solar system’s reference frame |

Dark Matter wind from Cygnus of 220 Km/s
Why not yearly asymmetry?

First observation of WIMPS??

Yearly asymmetry:
- Small rate asymmetry: 2-10%
- Hard to disentangle from temperature dependent phenomena
Unambiguous signature of Dark Matter

Daily asymmetry~30-100%!

Only directional detection can correlate with Cygnus: unambiguous positive observation of Dark Matter in presence of backgrounds

Spergel PRD 37,1353 (1988)
Directional Detectors

- Direction of incoming WIMP is encoded in direction of nuclear recoil

How to detect the direction of recoils?
  - Low-pressure gaseous detectors
    - A 50 keV F in CF$_4$ @ 40 torr recoils ~2 mm
Spin-dependent interactions

- WIMPs can scatter elastically on nuclei via
  - Spin-independent interactions
    - cross-section scales with the mass of the nucleus squared: $\sigma \sim A^2$
  - Spin-dependent interactions
    - cross-section is nonzero only if the nucleus has a nonzero spin

- Spin-dependent interactions may be enhanced by orders of magnitude compared to spin-independent
  - E.g.: in models in which LSP has substantial Higgsino contribution

- Weaker limits for spin-dependent interactions
  - Limits on spin-independent x-section: $\sim 10^{-44} - 10^{-43} \text{ cm}^2$
  - Limits on spin-dependent x-section: $\sim 10^{-37} - 10^{-36} \text{ cm}^2$

SD searches are promising and complementary to other DM efforts

Murakami B. and J.D. Wells, Phys. Rev. D 64 (2001) 15001

7 orders of magnitude!
Current directional DM detectors

- **DRIFT (Boulby, UK)**
  - CS, low-pressure negative ion TPC using MWPCs

- **NewAge (Kamioka, Japan)**
  - Low-pressure CF$_4$ TPC using μPIC 2D readout

- **MIMAC (France)**
  - 2D electronic readout
  - 2D electronic readout with Micromegas

Question: can we have both?
- **Full reconstruction of nuclear recoil**
- **Low cost/unit volume**

Drift-II

NewAge

MIMAC
Our goal

Develop a novel detector for direct detection of Dark Matter with the following characteristics:

- **Directionality**
  - Unambiguous observation of DM in presence of backgrounds
  - Test DM models in our Galaxy ("DM astronomy")
- **Spin-dependent interactions**
  - Can be much enhanced wrt spin-independent interactions

To make this feasible we need:

- **Low cost/unit volume**
  - Directionality requires gaseous detectors: large volumes
- **Easy to maintain**
  - Very stable, safe, easy to operate underground
- **Scalability**
  - Modular structure
The DM-TPC Collaboration

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DM-TPC: detector concept

- Low-pressure CF\textsubscript{4} TPC
  - 50 torr: 40 keV F recoil \approx 2\text{mm}
- Optical readout (CCD)
  - Image scintillation photons produced in amplification region
  - 2D, low-cost, proven technology
- Amplification region
  - Wire planes \rightarrow mesh detector
  - Woven mesh 25\text{\mu m}, 250\text{\mu m} pitch
- CF\textsubscript{4} is ideal gas
  - F: spin-dependent interactions
  - Good scintillation efficiency
  - Low transverse diffusion
  - Non flammable, non toxic

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The amplification region

Original design: wire planes

- Ground wire plane
  - 50 µm, 2 mm pitch

- Anode wire plane
  - 30-100 µm wire
  - 2-5 mm pitch
  - $V_{anode} \sim 2kV$

Pros: simplicity, high gains ($\sim 10^4$-$10^5$)
Limitations of wire-based amplification

- Wire-based detectors have serious limitations....

- 1D reconstruction of the recoil: not enough!
New amplification region: meshes

- Additional coordinate at no additional readout cost

a) Mesh-copper

b) Triple mesh

Stainless steel woven mesh
- 28 μm, 256 μm pitch, optical transmittance 77%
  Uniform spacing
- Fishing wire 0.54 mm Ø, Pitch 2 cm
What we measure

CCD cameras measure
- $E_{\text{recoil}}$ from total scintillation light
  - Integral of CCD signal ($\sigma_E/E \sim 10\%$)
- Reconstruct direction of recoil track (in 2D)
  - Pattern recognition in CCD
- Sense of direction (“head-tail”)
  - Gains an additional order of magnitude
    - Green&Morgan ’06, Alenazi&Gondolo ’08
  - $dE/dx$ decreases along recoil track
    - Low energy, below Bragg peak

Additional info from PMTs
- 3$^{\text{rd}}$ coordinate of recoil ($// v_{\text{drift}}$) through timing
- Trigger

Bragg curve for 80 keV F recoil from WIMP in CF$_4$
Background rejection

- Excellent rejection of gammas
  - 8 hours run with 8 µCi $^{137}$Cs inside prototype: no evts
  - Rejection factor $\sim 2/10^6$ or better

- Excellent discrimination against $\alpha$ and $e^-$
  - By measuring both energy and length of recoil

- Neutrons
  - Underground cavern
  - Neutron shielding
    - Passive and active
    - Directionality!

- Solar neutrinos
  - Directionality!

![Graph showing track length vs. energy for different particles.](image)
First generation prototype

Drift distance: 2.6 cm, 
$E=580 \text{ V/cm}$
Wire plane: $10 \times 10 \text{ cm}^2$
Anode: 5 mm pitch, 100 $\mu$m
Ground: 2 mm pitch, 50 $\mu$m

CCD Camera
Kodak KAF0401 chip
768x512 (9x9mm)
Cooled (-20°C)
Photographic lens (55mm)
Finger Lakes Instrumentation

Window

Cathode grid
-1.5 kV

$\text{CF}_4$ (100-380 Torr)

Grounded wire plane

Anode wire plane +3 kV

Grounded plate

10 cm

Lens
DM-TPC: 2\textsuperscript{nd} generation prototype

- Drift up to 25 cm
- Image view 16 cm Ø
- Mesh detector 23 cm Ø
  - 256 um pitch
  - 30 um wire Ø
  - 79% transparency
Bragg curve for 5.5 MeV $\alpha$ from $^{241}$Am

- Alphas emitted parallel to anode wires
  - Wire plane oriented at 45 degrees
- Compare measured $dE/dx$ vs range of the track with SRIM simulation
  - Excellent DATA-MC agreement!

Well understood detector
Effect of diffusion on resolution

- Dark Matter recoils $\sim 1-2$ mm
  - Resolution $\ll 1$ mm; diffusion must be contained
- Resolution vs drift distance measured with 4 $\alpha$ sources

\[ \sigma[\mu m] = 324 \oplus 36 \sqrt{\Delta z} \]

<table>
<thead>
<tr>
<th>Drift distance</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>340 $\mu$m</td>
</tr>
<tr>
<td>25 cm</td>
<td>670 $\mu$m</td>
</tr>
</tbody>
</table>
Light yield calibration with alphas

Photon yield/keV as a function of anode voltage

Stable operations for gas gain $\sim 10^4$-$10^5$
Recoils from low-energy neutrons

- Nuclear recoils by low-energy neutrons mimic Dark Matter
  - DM: F has lower energy but is better aligned with WIMP direction
- Neutron source #1: 14 MeV neutrons from D-T tube

Fluorine recoil energy

Fluorine recoil angle wrt wires

Blue band = spread in WIMP direction

President: Gabriella Sciolla

DM-TPC: a new approach to directional Recoils from low-energy neutrons
Neutron beam setup

- Anode wires // neutrons
- F recoils ~2 mm in CF₄ at 180 torr
Observation of “head-tail” in F recoils

Wires at 0 deg:

Wires at 180 deg:

Direction of neutrons

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ICHEP ’07, CYGNUS ’07
More quantitative results (DT)

We measure skewness of light yield along wire

\[ \gamma(x) = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\langle (x - \langle x \rangle)^3 \rangle}{\langle (x - \langle x \rangle)^2 \rangle^{3/2}} \]

\( \gamma > 0 \): neutron travels L to R
\( \gamma < 0 \): neutron travels R to L

- Black dots: wires @ 0 deg
- Open circles: wires @ 180 deg

\# L to R (24±3)%
\# R to L (76±3)%

NIM A584:327-333,2008

MC 50 torr

% correct sense

Recoil energy (keV)
α particles with meshes

\[ V_{\text{anode}} = 2\text{kV} \ (E \sim 1.5 \cdot 10^5 \text{ V/cm}) \]
\[ 300\mu\text{m gap, 200Torr} \]

NB: 1D --> 2D at no additional cost!
252Cf run with mesh detector @ 75 torr

- Softer spectrum, closer to WIMP recoils
- Mesh-based detector: 1D→2D projection of recoil
- Stable data-taking at 75 torr
  - “Head-tail” effect down ~ 100 keV
- Excellent data-MC agreement
Mesh detector: $^{252}\text{Cf}$ run @ 75 torr

- 100 keV $\leftrightarrow$ 2 mm
- Head-tail at 100 keV
- Angular resolution $15^\circ$ at 100 keV
- Excellent data-MC agreement

Next step: DM-TPC (10 liters)

- Active volume: 10 liters
  - Each drift volume: 23 cm $\varnothing$, 25 cm drift
  - 2 CCD cameras (top and bottom)
  - 1 year underground at WIPP (NM)
- $P \approx 100$ torr; 1 year underground
  - Exposure of 2-4 kg-days
Goals of DM-TPC (10 liters)

- Ready for underground run as early as Spring 2009
  - Surface run at MIT: completed -- data analysis under way
  - Neutron run: next few months
  - Some components being replaced (radiopurity)

- DM study -- 1 year run with CF$_4$
  - Prove backgrounds-free operation underground
  - Set our first limit on SD WIMP interactions
    - Surprisingly good limits given limited mass due to large spin-factor of F and isotopic abundance
    - Directionality provides additional n rejection

- Study neutrons underground -- phase II
  - Gas mixture $^4\text{He-CF}_4$ to enhance n interactions
  - Measure neutron spectrum and direction in underground cavern
    - Can identify 10% point source over bkg
    - Useful input for nearby DM experiments!

NB: DMTPC as neutron detector for Homeland Security applications
DMTPCino: 1-m$^3$ detector

- Prove detector technology on a more realistic scale
- Set best limit on spin-dependent interactions with directionality

Current design:
- 2 amplification planes
- 2 drift regions / plane
- 10 CCD cameras/plane
- 10 PMTs/plane

- Mass ~0.25-0.5 kg/m$^3$
- 1 year: ~100-200 kg d

arXiv:0811.2764
**Assumptions:**
- 1 year data taking at 3,000 mwe
- Threshold 50 keV, P=100 torr
- Negligible background from detector material

**Future detector:**
- 100 kg-year at 3,000 mwe
- Threshold 50 keV
- Negligible background from detector material


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Sensitivity 1 m³ underground
Can we find space for it?

- Large DUSEL cavern at 6,000 mwe is ideal for our needs

From J. Kotcher’s presentation at HEPAP meeting on 7/14/2007
Conclusion

- DM-TPC collaboration is making rapid progress toward development of new Dark Matter detector
  - Directionality, spin-dependent interactions, optical readout (<$)
- 2007
  - First prototype proved detector concept using wire planes (1D)
  - First observation of head-tail effect in low-energy nuclear recoils
- 2008
  - Much superior detector images recoils in 2D
  - 10-liter module ready for underground operation
- 2009?
  - DMTPCino 1-m$^3$ design and construction; x50 improvement on $\sigma_p^{SD}$
- Large $O(10^3 \text{ kg})$ DM-TPC detector ideal candidate for DUSEL
  - Directionality: unambiguous observation of WIMPs
  - DM detector --> DM observatory for underground WIMP astronomy
WIMP Astronomy: Sky Map

Background (isotropic)

Dark halo - no head-tail

Sikivie’s model (Gelmini, Gondolo 2001)

With head-tail
Announcement

The second CYGNUS meeting on directional dark matter direct detection will be held at MIT in Cambridge, Massachusetts, from June 11-13, 2009. This meeting will bring together the international scientific community working on both theoretical and experimental aspects of directional dark matter detection and the galactic dark matter distribution. In so doing, we hope to coordinate efforts toward a large directional dark matter experiment that is capable of providing an unambiguous detection of Galactic dark matter.